American
Gear Manufacturers
Association

Technical Publications Catalog

June 2017

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American Gear Manufacturers Association

AGMA is a voluntary association of companies, consultants and academicians with a direct interest in the design, manufacture, and application of gears and flexible couplings. AGMA was founded in 1916 by nine companies in response to the market demand for standardized gear products; it remains a member- and market-driven organization to this day. AGMA provides a wide variety of services to the gear industry and its customers and conducts numerous programs which support these services. Some of these services and programs are:

- **STANDARDS:** AGMA develops all U.S. gear related standards through an open process under the authorization of the American National Standards Institute (ANSI).
- **ISO PARTICIPATION:** AGMA is Secretariat to TC60, the technical committee responsible for developing all international gear standards. TC60 is an ISO (International Organization of Standardization) committee.
- **MARKET REPORTS AND STATISTICS:** AGMA's Operating Ratio Report, Wage & Benefit Survey, and Monthly Market Trend Reports help you stay competitive by giving you up-to-date information on the gear industry.
- **GEAR EXPO:** This is the only trade show dedicated solely to the gear industry.
- **TECHNICAL COMMITTEE MEETINGS** are the core of the open AGMA standard writing process keeping members abreast of new developments while ensuring that AGMA standards are kept current.
- **THE AGMA TRAINING SCHOOL FOR GEAR MANUFACTURING** uses current technology to offer hands-on training in hobbing, shaping, and inspection. At the "Gear School," operators learn how to maximize their productivity. Enrollment is open to all.
- AGMA's two e-newsletters, offer you timely, useful information you can use immediately.

If you would like additional information about our programs, or on how to become a member of AGMA, please contact AGMA Headquarters.

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ANSI/AGMA 6000 *Specification for Measurement of Linear Vibration on Gear Units*

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Style Manual

AGMA 900 *Style Manual for the Preparation of Standards and Editorial Manuals*

Thermal

AGMA ISO 14179-1 *Gear Reducers – Thermal Capacity Based on ISO/TR 14179-1*

Vehicle

ANSI/AGMA 6002 *Design Guide for Vehicle Spur and Helical Gears*

ANSI/AGMA 6102 *Design Guide for Vehicle Spur and Helical Gears (Metric)*

Wind Turbine Units

ANSI/AGMA/AWEA 6006 *Standard for Design and Specification of Gearboxes for Wind Turbines*

Wormgears

ANSI/AGMA 6034 *Practice for Enclosed Cylindrical Wormgear Speed Reducers and Gearmotors*

ANSI/AGMA 6035 *Design, Rating and Application of Industrial Globoidal Wormgearing*

ANSI/AGMA 6135 *Design, Rating and Application of Industrial Globoidal Wormgearing (Metric)*

AGMA Standards and Information Sheets

Many standards require additional documents for their proper use. A list of these standards is normally supplied after the scope, in the normative references section of a document. Be sure to inquire whether the standard you need requires other documents listed herewith.

AGMA 900-I11 Style Manual for the Preparation of Standards, Information Sheets and Editorial Manuals

Presents the requirements for preparing AGMA standards, editorial manuals, and other technical literature. A new annex, "ISO symbols used in metric documents," has been added, which includes a comprehensive listing of the symbols used in ISO gear rating standards. **Revision of AGMA 900-H06.**

ISBN: 1-55589-775-4 Pages: 38

AGMA 901-A92 A Rational Procedure for the Preliminary Design of Minimum Volume Gears

Presents a simple, closed-form procedure as a first step in the minimum volume spur and helical gearset design. It Includes methods for selecting geometry and dimensions, considering maximum pitting resistance, bending strength, and scuffing resistance, and methods for selecting profile shift. **Reaffirmed March 2015.**

ISBN: 1-55589-579-4 Pages: 37

AGMA 904-C96 Metric Usage

Serves as a guide in preparing AGMA metric standards. **Reaffirmed January 2017.**

ISBN: 1-55589-681-2 Pages: 20

AGMA 905-A17 Inspection of Molded Plastic Gears

Due to their specification, design, and manufacture, plastic gears have unique issues that can affect the measurement methods and results obtained. This information sheet describes industry accepted practices to inspect molded plastic gears. It identifies the unique characteristics of molded plastic gears that influence the accuracy and/or repeatability of gear measurements.

ISBN: 1-55589-735-2 Pages: 84

AGMA 908-B89 Geometry Factors for Determining the Pitting Resistance and Bending Strength of Spur, Helical and Herringbone Gear Teeth

Gives the equations for calculating the pitting resistance geometry factor, I, for external and internal spur and helical gears, and the bending strength geometry factor, J, for external spur and helical gears that are generated by rack-type tools (hobs, rack cutters or generating grinding wheels) or pinion-type tools (shaper cutters). Includes charts which provide geometry factors, I and J, for a range of typical gear sets and tooth forms. **Reaffirmed March 2015.**

ISBN: 1-55589-525-5 Pages: 78

AGMA 909-A06 Specifications for Molded Plastic Gears

The objective of this information sheet is to inform the plastic gear designer of the importance to clearly and thoroughly define the gear specifications to the plastic gear producer. It discusses the specifications for gear tooth geometry, inspection, other gear features and manufacturing considerations for involute external and internal spur and helical gears. Suggested data forms are provided in the annexes.

ISBN: 1-55589-889-8 Pages: 25

AGMA 910-D12 Formats for Fine-Pitch Gear Specification Data

This information sheet consists of a series of printed forms for gear drawings that contain the appropriate data to be tabulated by the gear designer for the gear manufacturer. It also includes a series of definitions of the various tabulated items. **Replaces AGMA 910-C90**.

ISBN: 1-55589-999-8 Pages: 32

AGMA 911-A94 Guidelines for Aerospace Gearing

Covers current gear design practices as they are applied to air vehicles and spacecraft. Goes beyond the design of gear meshes. Presents the broad spectrum of factors which combine to produce a working gear system, whether it be a power transmission or special purpose mechanism. Covers only spur, helical and bevel gears. (Does not cover wormgears, face gears, and various proprietary tooth forms). **Replaces AGMA 411.02.**

ISBN: 1-55589-629-4 Pages: 97

AGMA 913-A98 Method for Specifying the Geometry of Spur and Helical Gears

Provides information to translate tooth thickness specifications which are expressed in terms of tooth thickness, center distance or diameter into profile shift coefficients. It describes the effect that profile shift has on the geometry and performance of gears. Annexes are provided which contain practical examples on the calculation of tool proportions and profile shift. **Reaffirmed May 3, 2016.**

ISBN: 1-55589-714-2 Pages: 25

AGMA 914-B04, Gear Sound Manual – Part I: Fundamentals of Sound as Related to Gears; Part II: Sources, Specifications and Levels of Gear Sound; Part III: Gear Noise Control

This information sheet discusses how noise measurement and control depend upon the individual characteristics of the prime mover, gear unit, and driven machine, as well as their combined effects in a particular acoustical environment. It indicates certain areas that might require special attention. This document is a revision of AGMA 299.01 to include updated references and a discussion of Fast Fourier Transform analysis. **Replaces AGMA 299.01.**

ISBN: 1-55589-820-3 Pages: 37

AGMA 915-1-A02 Inspection Practices – Part 1: Cylindrical Gears – Tangential Measurements

Provides a code of practice and measuring methods dealing with inspection relevant to tangential element and composite deviations of cylindrical involute gears (measurements referred to single flank contact). Replaces elemental measurement section of AGMA 2000-A88.

ISBN: 1-55589-798-3 Pages: 39

AGMA 915-2-A05 Inspection Practices – Part 2: Cylindrical Gears – Radial Measurements

This information sheet discusses inspection of cylindrical involute gears using the radial (double flank) composite method, with recommended practices detailed. Also included is a clause on runout and eccentricity measurement methods. This information sheet is a supplement to the standard ANSI/AGMA 2015-2. It replaced AGMA ISO 10064-2 and replaces double flank composite measurement section of AGMA 2000-A88.

ISBN: 1-55589-843-2 Pages: 24

AGMA 915-3-A99 Inspection Practices – Gear Blanks, Shaft Center Distance and Parallelism

Provides recommended numerical values relating to the inspection of gear blanks, shaft center distance and parallelism of shaft axes. Discussions include such topics as methods for defining datum axes on components; the use of center holes and mounting surfaces during manufacturing and inspection; and, recommended values of in-plane and out-of-plane deviations of shaft parallelism. **Modified adoption of ISO/TR 10064-3:1996.**

ISBN: 1-55589-738-3 Pages: 9

AGMA 917-B97 Design Manual for Parallel Shaft Fine-Pitch Gearing

Provides guidance for the design of spur and helical gearing of 20 through 120 diametral pitch including internal and rack forms. Manual contains such specialized subjects as inspection, lubrication, gear load calculation methods, materials, including a wide variety of plastics. **Replaces AGMA 370.01.**

ISBN: 1-55589-694-4 Pages: 84

AGMA 918-A93 A Summary of Numerical Examples Demonstrating the Procedures for Calculating Geometry Factors for Spur and Helical Gears

Provides numerical examples for calculating the pitting resistance geometry factor, I, and bending strength geometry factor, J, for typical gearsets that are generated by rack-type tools (hobs, rack cutters or generating grinding wheels) or pinion-type tools (disk-type shaper cutters). **Supplement to AGMA 908-B89. Reaffirmed March 2015.**

ISBN: 1-55589-617-0 Pages: 42

AGMA 919-1-A14 Condition Monitoring and Diagnostics of Gear Units and Open Gears: Part 1 – Basics

The new information sheet provides basic overviews of key approaches to establishing a condition monitoring and diagnostics program for open gearing and enclosed gear units. This information sheet attempts to inform the reader of the common techniques used and parameters measured for condition monitoring of a gear unit allowing the reader to build a program based on individual needs.

ISBN: 1-61481-087-2 Pages: 20

AGMA 920-B15 Materials for Plastic Gears

The purpose of this document is to aid the gear designer in understanding the unique physical, mechanical and thermal behavior of plastic materials. The use of plastic materials for gear applications has grown considerably due to cost and performance issues. Growing markets include the automotive, business machine, and consumer-related industries. Topics covered include general plastic material behavior, gear operating conditions, plastic gear manufacturing, tests for gear related material properties, and typical plastic gear materials. There are no quantitative details on material properties or any comparative evaluations of plastic types. Such specific information is left to be provided by material suppliers and gear manufacturers. **Revision of AGMA 920-A01.**

ISBN: 1-55589-048-3 Pages: 50

AGMA 922-A96 Load Classification and Service Factors for Flexible Couplings

This Information Sheet provides load classifications and related service factors that are frequently used for various flexible coupling applications. Typical applications using smooth prime movers and special considerations involving unusual or more severe loading are discussed. **Replaces AGMA 514.02. Reaffirmed May 2015.**

ISBN: 1-55589-680-4 Pages: 6

AGMA 923-B05 Metallurgical Specifications for Steel Gearing

This document identifies metallurgical quality characteristics which are important to the performance of steel gearing. The AGMA gear rating standards identify performance levels of gearing by heat treatment method and grade number. For each heat treatment method and AGMA grade number, acceptance criteria are given for various metallurgical characteristics identified in this document. **Revision of AGMA 923-A00.**

ISBN: 1-55589-848-3 Pages: 31

AGMA 925-A03 Effect of Lubrication on Gear Surface Distress

This document provides currently available information pertaining to oil lubrication of industrial gears for power transmission applications. It is intended to serve as a general guideline and source of information about gear oils, their properties, and their tribological behavior in gear contacts. Equations provided allow the calculation of specific film thickness and instantaneous contact (flash) temperature for gears in service, and to help assess the potential risk of surface distress (scuffing, micropitting and macropitting, and scoring) involved with a given lubricant choice. **Supplement to ANSI/AGMA 2001-D04.**

ISBN: 1-55589-815-7 Pages: 51

AGMA 926-C99 Recommended Practice for Carburized Aerospace Gearing

Establishes recommended practices for material case and core properties, microstructure and processing procedures for carburized AISI 9310 aerospace gears. This document is not intended to be a practice for any gears other than those applied to aerospace. **Replaces AGMA 246.02a.**

ISBN: 1-55589-758-4 Pages: 9

AGMA 927-A01 Load Distribution Factors – Analytical Methods for Cylindrical Gears

Describes an analytical procedure for the calculation of face load distribution factor. The iterative solution that is described is compatible with the definitions of the term face load distribution of AGMA standards and longitudinal load distribution of the ISO standards. The procedure is easily programmable and flow charts of the calculation scheme, as well as examples from typical software are presented. **Supplement to ANSI/AGMA 2001-D04.**

ISBN: 1-55589-779-7 Pages: 31

AGMA 929-A06 Calculation of Bevel Gear Top Land and Guidance on Cutter Edge Radius

Has the calculations for bevel gear top land and guidance for selection of cutter edge radius for determination of tooth geometry. It integrates various publications with modifications to include face hobbing. It adds top land calculations for non-generated manufacturing methods. It is intended to provide assistance in completing the calculations requiring determination of top lands and cutter edge radii for gear capacity in accordance with ANSI/AGMA 2003-B97. **Supplement to standard ANSI/AGMA 2005-D03**

ISBN: 1-55589-873-4 Pages: 38

AGMA 930-A05 Calculated Bending Load Capacity of Powder Metallurgy (P/M) External Spur Gears

This information sheet describes a procedure for calculating the load capacity of a pair of powder metallurgy external spur gears based on tooth bending strength. Two types of loading are considered: 1) repeated loading over many cycles; and 2) occasional peak loading. It also describes an essentially reverse procedure for establishing an initial design from specified applied loads. As part of the load capacity calculations, there is a detailed analysis of the gear teeth geometry, including tooth profiles and various fillets.

ISBN: 1-55589-845-9 Pages: 78

AGMA 932-A05 Rating the Pitting Resistance and Bending Strength of Hypoid Gears

This information sheet provides a method by which different hypoid gear designs can be compared. The formulas are intended to establish a uniformly acceptable method for calculating the pitting resistance and bending strength capacity of both curved and skewed tooth hypoid gears. They apply equally to tapered depth and uniform depth teeth. Annexes contain graphs for geometry factors and a sample calculation to assist the user. **Supplement to ANSI/AGMA 2003-B97.**

ISBN: 1-55589-869-6 Pages: 18

AGMA 933-B03 Basic Gear Geometry

This information sheet illustrates important geometrical relationships which provide a sound basis for a thoroughly logical and comprehensive system of gear geometry. **Replaces AGMA 115.01.**

ISBN: 1-55589-814-9 Pages: 18

AGMA 935-A05 Recommendations Relative to the Evaluation of Radial Composite Gear Double Flank Testers

The condition and alignment of gear measuring instruments can greatly influence the measurement of product gears. This information sheet provides qualification procedures for double flank testers that are used for the evaluation of radial composite deviations of gears. It discusses guidelines for alignment of double flank tester elements such as centers, ways, probe systems, etc. It also covers the application of artifacts to determine instrument accuracy. **Supplement to standard ANSI/AGMA 2116-A05. Reaffirmed June 2015.**

ISBN: 1-55589-872-6 Pages: 11

AGMA 937-A12 Aerospace Bevel Gears

This information sheet covers aerospace bevel gears for power, accessory and actuation applications. It provides additional information on the design, manufacturing and quality control unique to the aerospace environment. The new information sheet was developed to fill the void following the withdrawal of AGMA 431.01. It expands the scope to include all applications of aerospace bevel gearing.

ISBN: 1-61481-030-8 Pages: 142

AGMA 938-A05 Shot Peening of Gears

This information sheet provides a tool for gear designers interested in the residual compressive stress properties produced by shot peening and its relationship to gearing. It also discusses shot media materials, delivery methods and process controls.

ISBN: 1-55589-847-5 Pages: 14

AGMA 939-A07 Austempered Ductile Iron for Gears

This information sheet gives the background and basic guidelines to consider the feasibility of austempered ductile iron (ADI) for gear applications. It contains experimental, experiential and anecdotal information to assist in the specification, purchase and manufacture of ADI components. The metallurgy of ADI, relevant factors in its production, allowable stress numbers, and stress cycle curves are reviewed. It also has references, relevant standards, and evaluation methods used in the manufacture of ADI components.

ISBN: 1-55589-901-1 Pages: 10

AGMA 940-A09 Double Helical Epicyclic Gear Units

This information sheet addresses epicyclic gear drives which utilize double helical type gearing on the planetary elements. It is intended to be a supplement to and used in conjunction with ANSI/AGMA 6123-B06, *Design Manual for Enclosed Epicyclic Gear Dives*. It covers only those topics which are unique to double helical gear arrangements in epicyclic gear drives.

ISBN: 1-55589-953-0 Pages: 28

AGMA 942-A12 Metallurgical Specifications for Powder Metallurgy, PM, Steel Gearing

This information sheet recommends powder metallurgy, PM, steel materials and metallurgical quality characteristics for use in specifying PM gearing. It identifies specifications and requirements for various PM steel materials for as-sintered, through hardened or sinter hardened, carburized case hardened, and induction hardened gearing. Requirements are coded by process and class number, the latter based on the density of the PM gear teeth. Characteristics covered include material composition, density, sinter processing (conventional, high temperature and sinter hardening), secondary heat treatments and post heat treatment processing, and their associated inspections. **Reaffirmed May 25, 2017.**

ISBN: 1-61481-031-5 Pages: 17

ANSI/AGMA 1003-H07 Tooth Proportions for Fine-Pitch Spur and Helical Gears

Tooth proportions for fine-pitch gearing are similar to those of coarse pitch gearing except in the matter of clearance. This standard is applicable to external spur and helical gears with diametral pitch of 20 through 120 and a profile angle of 20 degrees. It provides a system of enlarged pinions which use the involute form above 5 degrees of roll. Data on 14-1/2 and 25-degree profile angle systems, and a discussion of enlargement and tooth thicknesses are provided in annexes. In addition, it addresses, in a new annex, an analysis of comparative systems of selecting tooth thicknesses of pinions. **Revision of ANSI/AGMA 1003-G93. Reaffirmed March 2014.**

ISBN: 1-55589-902-8 Pages: 25

ANSI/AGMA 1006-A97 Tooth Proportions for Plastic Gears

Presents a new basic rack, AGMA PT, which, with its full round fillet, may be preferred in many applications of gears made from plastic materials. It contains a description, with equations and sample calculations, of how the proportions of a spur or helical gear may be derived from the design tooth thickness and the basic rack data. In several annexes, there are discussions of possible variations from the basic rack and also a procedure for defining tooth proportions without using the basic rack concept. **Reaffirmed May 2009.**

ISBN: 1-55589-684-7 Pages: 47

ANSI/AGMA 1010-F14 Appearance of Gear Teeth – Terminology of Wear and Failure

This standard provides nomenclature for general modes of gear tooth wear and failure. It classifies, identifies and describes the most common types of failure and provides information which will, in many cases, enable the user to identify failure modes and evaluate the degree or progression of wear. **Revision of ANSI/AGMA 1010-E95.**

ISBN: 1-61481-089-6 Pages: 40

ANSI/AGMA 1012-G05 Gear Nomenclature, Definitions of Terms with Symbols

This standard lists terms and their definitions with symbols for gear nomenclature. **Revision of ANSI/AGMA 1012-F90. Reaffirmed March 2011.**

ISBN: 1-55589-846-7 Pages: 89

ANSI/AGMA 1102-B13 Tolerance Specification for Gear Hobs

The standard provides specifications for nomenclature, dimensions, tolerances, and inspection for gear hobs for modules 0.63 to 40 mm. It establishes a basis for understanding the use and manufacture of these tools. **Replaces ANSI/AGMA 1102-A03.**

ISBN: 1-55589-816-5 Pages: 49

ANSI/AGMA 1103-H07 Tooth Proportions for Fine-Pitch Spur and Helical Gears (Metric Edition)

Tooth proportions for fine-pitch gearing are similar to those of coarse pitch gearing except in the matter of clearance. This standard is applicable to external spur and helical gears with diametral pitch of 1.25 through 0.2 and a profile angle of 20 degrees. It provides a system of enlarged pinions which use the involute form above 5 degrees of roll. Data on 14-1/2 and 25-degree profile angle systems, and a discussion of enlargement and tooth thicknesses are provided in annexes. In addition, it addresses, in a new annex, an analysis of comparative systems of selecting tooth thicknesses of pinions. **Metric version of ANSI/AGMA 1003-H07. Reaffirmed March 2014.**

ISBN: 1-55589-903-5 Pages: 25

ANSI/AGMA 1104-A09 Tolerance Specification for Shaper Cutters

The purpose of this standard is to provide specifications for nomenclature, dimensions, tolerances, and inspection of shaper cutters, and thereby establish a basis for mutual understanding in this respect in the use and manufacture of these tools. **Reaffirmed February 2015.**

ISBN: 1-55589-974-5 Pages: 54

ANSI/AGMA 1106-A97 Tooth Proportions for Plastic Gears

Presents a new basic rack, AGMA PT, which, with its full round fillet, may be preferred in many applications of gears made from plastic materials. It contains a description, with equations and sample calculations, of how the proportions of a spur or helical gear may be derived from the design tooth thickness and the basic rack data. In several annexes, there are discussions of possible variations from the basic rack and also a procedure for defining tooth proportions without using the basic rack concept. **Metric edition of ANSI/AGMA 1006-A97. Reaffirmed May 2009.**

ISBN: 1-55589-685-5 Pages: 47

ANSI/AGMA ISO 1328-1-B14 Cylindrical gears – ISO system of flank tolerance classification – Part 1: Definitions and allowable values of deviations relevant to flanks of gear teeth

This standard establishes a tolerance classification system relevant to manufacturing and conformity assessment of tooth flanks of individual cylindrical involute gears. It specifies definitions for gear flank tolerance terms, the structure of the flank tolerance class system, and allowable values. **Replaces ANSI/AGMA 2015-1-A01.**

ISBN: 1-61481-114-5 Pages: 47

ANSI/AGMA 2001-D04 Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth

Presents a comprehensive method for rating the pitting resistance and bending strength of spur and helical involute gear pairs. Contains detailed discussions of factors influencing gear survival and calculation methods. Revisions reflected in this version include incorporating the latest AGMA accuracy standard (ANSI/AGMA 2015-1-A01) into the determination of dynamic factor, and change to the relationship between service factor and stress cycle factor. **Revision of ANSI/AGMA 2001-C95. Reaffirmed March 2016.**

ISBN: 1-55589-839-4 Pages: 56

ANSI/AGMA 2002-C16, Tooth Thickness and Backlash Measurement of Cylindrical Involute Gearing

Establishes the procedures for determining the specification limits for tooth thickness of external and internal cylindrical involute gearing. Includes equations and calculation procedures for the commonly used measuring methods. A specific tooth thickness specification limit can be established from the design thickness or from another tooth thickness measurement. The procedures can be used with an established design tooth thickness, or with actual tooth thickness dimensions. The effect of tooth geometric quality variations on tooth thickness dimensions is discussed. Calculations for backlash are included, and are based on the specified tooth thickness, center distance, and tolerances. **Revision of ANSI/AGMA 2002-B88.**

ISBN: 1-55589-056-8 Pages: 151

ANSI/AGMA 2003-C10 Rating the Pitting Resistance and Bending Strength of Generated Straight Bevel, Zerol Bevel and Spiral Bevel Gear Teeth

This standard specifies a method for rating the pitting resistance and bending strength of generated straight bevel, zerol bevel and spiral bevel gear teeth. A detailed discussion of factors influencing gear survival and a calculation method are provided. **Revision of ANSI/AGMA 2003-B97. Reaffirmed December 2015.**

ISBN: 1-55589-975-2 Pages: 71

ANSI/AGMA 2004-C08 Gear Materials, Heat Treatment and Processing Manual

This standard provides information pertaining to ferrous and nonferrous materials used in gearing. Factors in material selection, including material forms, properties, and associated processing and heat treatments are discussed. Manufacturing procedures to prepare materials for machining and final heat treatment are included. Heat treating procedures used for gearing are covered in detail, including process description, product specifications, process controls, and characteristics of heat treated gearing. Post-heat treatment processes to meet gearing requirements are discussed. Product inspection methods and documentation are covered. Term definitions, test methods, distortion and residual stress, sources for additional information and bibliography are included. **Revision of ANSI/AGMA 2004-B89. Reaffirmed March 2014.**

ISBN: 1-55589-904-2 Pages: 68

ANSI/AGMA 2007-C00 Surface Temper Etch Inspection after Grinding **[Same as ISO 14104:1995]**

Explains the materials and procedures to determine and evaluate localized overheating on ground surfaces. Includes a system to describe and classify the indications produced during this inspection. However, does not provide specific acceptance or rejection criteria. **Revision of ANSI/AGMA 2007-B92. Reaffirmed August 2013.**

ISBN: 1-55589-761-4 Pages: 6

ANSI/AGMA 2008-D11 Assembling Bevel Gears

This Standard was prepared for the assembly man in the factory and for the service man in the field. Each definition, explanation, and instruction is directed toward the physical appearance of the gears as they are inspected and assembled by these personnel. The definitions are simple. The explanations are thorough. An Annex provides detailed instructions on performing contact pattern checks. **Reaffirmed December 27, 2016.**

ISBN: 1-55589-998-1 Pages: 49

ANSI/AGMA 2011-B14 Cylindrical Wormgearing Tolerance and Inspection Methods

This standard describes and defines variations that may occur in unassembled wormgearing. It displays measuring methods and practices, giving suitable warnings if a preferred probe cannot be used. The applicability of single or double flank composite testing is discussed, using a reference gear. Tooth thickness measurement is shown using direct measurement as well as the use of measurements over wires or pins. Equations for the maximum variations are given for the stated ranges, as a function of size, pitch and tolerance grade. **Revision of ANSI/AGMA 2011-A98.**

ISBN: 1-61481-090-2 Pages 51

ANSI/AGMA 2015-2-B15 Gear Tooth Flank Tolerance Classification System – Definitions and Allowable Values of Double Flank Radial Composite Deviations

This standard establishes a classification system for double flank radial composite tolerances—allowable values of deviations—of individual cylindrical involute gears, sector gears, racks, cylindrical worms, worm gears and hypoid or bevel gears. It serves as a concise means of specifying allowable gear geometry deviations and simplifies discussions between the gear manufacturer and purchaser. It specifies the appropriate definitions of double flank radial composite gear tooth geometry deviations, the structure of the tolerance system and the tolerances. **Revision of ANSI/AGMA 2015-2-A06.**

ISBN: 1-55589-005-6 Pages: 26

ANSI/AGMA 2101-D04 Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth (Metric Edition)

Presents a comprehensive method for rating the pitting resistance and bending strength of spur and helical involute gear pairs. Contains detailed discussions of factors influencing gear survival and calculation methods. Revisions reflected in this version include incorporating the latest AGMA accuracy standard (ANSI/AGMA 2015-1-A01) into the determination of dynamic factor, and change to the relationship between service factor and stress cycle factor. **Revision of ANSI/AGMA 2101-C95. Reaffirmed March 2016.**

ISBN: 1-55589-840-8 Pages: 56

ANSI/AGMA 2111-A98 Cylindrical Wormgearing Tolerance and Inspection Methods

Establishes a classification system for the geometrical accuracy specification of wormgearing. It also provides uniform measurement procedures including discussions on single and double flank composite testing and tooth thickness measurements. The standard establishes ten accuracy grades, W3 through W12, based on the relative effect of geometrical errors on conjugate action for wormgear sets. **Metric edition of ANSI/AGMA 2011-A98. Reaffirmed July 2010.**

ISBN: 1-55589-717-7 Pages: 43

ANSI/AGMA 2116-A05 Evaluation of Double Flank Testers for Radial Composite Measurement of Gears

This standard provides the evaluation criteria for double flank testers. Recommended artifact sizes and geometry are provided along with measurement system conditions. Annexes contain methods for estimating calibration uncertainty and specifying artifact. **Reaffirmed February 2, 2017.**

ISBN: 1-55589-871-8 Pages: 9

ANSI/AGMA 6000-B96 Specification for Measurement of Linear Vibration on Gear Units

Presents a method for measuring linear vibration on a gear unit. Recommends instrumentation, measuring methods, test procedures and discrete frequency vibration limits for acceptance testing. Annexes list system effects on gear unit vibration and system responsibility. The ISO vibration rating curves from ISO 8579-2, *Acceptance code for gears – Part 2: Determination of mechanical vibrations of gear units during acceptance testing* are introduced. **Reaffirmed March 2016.**

ISBN: 1-55589-666-9 Pages: 21

ANSI/AGMA 6001-E08 Design and Selection of Components for Enclosed Gear Drives

This standard outlines the basic practices for the design and selection of components, other than gearing, for use in commercial and industrial enclosed gear drives. Fundamental equations provide for the proper sizing of shafts, keys, and fasteners based on stated allowable stresses. Other components are discussed in a manner to provide an awareness of their function or specific requirements. This standard applies to the following types of commercial and industrial enclosed gear drives, individually or in combination: spur, helical, herringbone, bevel and worm. **Revision of ANSI/AGMA 6001-D97. Reaffirmed March 2014.**

ISBN: 1-55589-951-6 Pages: 44

ANSI/AGMA 6002-C15 Design Guide for Vehicle Spur and Helical Gears

This standard provides the engineer, who is familiar with gear designing, a guide to sound design approaches for vehicle gear applications. Through this standard, the engineer is guided to selecting design considerations paramount to the parallel axis gear sets required in vehicle drive lines. These include tooth and blank proportions, metallurgy, lubrication, profile and lead modification requirements, and gear tooth tolerances. Properties of the commonly used steels and processes for their heat treatment are outlined, as well as details for calculating design limits for bending and contact stresses. **Replaces ANSI/AGMA 6002-B93.**

ISBN: 1- 55589-001-8 Pages: 69

ANSI/AGMA/AWEA 6006-A03 Standard for Design and Specification of Gearboxes for Wind Turbines

This standard is intended to apply to wind turbine gearboxes. It provides information for specifying, selecting, designing, manufacturing, procuring operating and manufacturing reliable speed increasing gearboxes for wind turbine generator system service.

Annex information is supplied on: wind turbine architecture, wind turbine load description, quality assurance, operation and maintenance, minimum purchaser gearbox manufacturing ordering data, lubrication selection and monitoring, determination of an application factor from a load spectrum using equivalent torque, and bearing stress calculations. **Replaces AGMA 921-A97. Reaffirmed June 29, 2016.**

ISBN: 1-55589-817-3 Pages: 94

ANSI/AGMA 6008-A98 Specifications for Powder Metallurgy Gears

Defines the minimum detailed information to be included in the powder metallurgy gear specifications submitted by the gear purchaser to the gear producer. Specifications on gear tooth geometry are described in detail for external spur and helical gears and for straight bevel gears. In addition, there are discussions on specifications for gear drawings and gear material data. The standard applies to gears made by the conventional P/M process consisting of compaction followed by sintering and, in some cases, by post sintering treatments. **Reaffirmed August 2012.**

ISBN: 1-55589-713-4 Pages: 17

ANSI/AGMA 6011-J14 Specification for High Speed Helical Gear Units

This standard includes design, lubrication, bearings, testing and rating for single and double helical external tooth, parallel shaft speed reducers or increasers. Units covered include those operating with at least one stage having a pitch line velocity equal to or greater than 35 meters per second or rotational speeds greater than 4500 rpm and other stages having pitch line velocities equal to or greater than 8 meters per second. **Revision of ANSI/AGMA 6011-I03.**

ISBN: 1-61481-088-9 Pages: 69

ANSI/AGMA 6013-B16 Standard for Industrial Enclosed Gear Drives

This standard includes design, rating, lubrication, testing, and selection information for enclosed gear drives, including foot mounted, shaft mounted, screw conveyor drives, and gearmotors. These drives may include spur, helical, herringbone, double helical, or bevel gearing in single or multistage arrangements as either parallel, concentric, or right angle configurations. **Revision of ANSI/AGMA 6013-A06.**

ISBN: 978-1-55589-049-0 Pages: 85

ANSI/AGMA 6014-B15 Gear Power Rating for Cylindrical Shell and Trunnion Supported Equipment

This standard specifies a method for rating the pitting resistance and bending strength of open or semi-enclosed gearing for use on cylindrical shell and trunnion supported equipment such as grinding mills, kilns, coolers, and dryers. This includes spur, self-aligning spur, single helical, double helical, and herringbone gears made from steel, ductile iron, and austempered ductile iron. Annexes cover installation, alignment, maintenance, combination drives, and lubrication. **Revision of ANSI/AGMA 6014-A06.**

ISBN: 1-55589-045-2 Pages: 82

ANSI/AGMA 6015-A13 Power Rating of Single and Double Helical Gearing for Rolling Mill Service

This Standard provides a method for determining the power rating of gear sets used in main mill drives, pinion stands, and combination units used for the reduction of material size in metal rolling mills. Applications include, but are not limited to, hot mills and cold mills, roughing and finishing stands: reducing, increasing, and 1:1 ratio sets. Auxiliary drives, including drives listed in ANSI/AGMA 6013-A06, such as bridles, coilers, uncoilers, edge trimmers, flatteners, loopers (accumulators), pinch rolls, scrap choppers, shears, and slitters are not covered by this document. This standard includes a method by which different gear tooth designs can be rated and compared at extended life cycles typical for these applications, up to 175 000 hours.

ISBN: 1-61481-056-8 Pages: 67

ANSI/AGMA 6022-C93 Design Manual for Cylindrical Wormgearing

Covers the design of general industrial coarse-pitch cylindrical worms and throated gears mounted with axes at a 90-degree angle and having axial pitches of 3/16 inch and larger. **Reaffirmed May 2014.**

ISBN: 1-55589-041-5 Pages: 10

ANSI/AGMA 6025-D98 Sound for Enclosed Helical, Herringbone and Spiral Bevel Gear Drives

Describes a recommended method of acceptance testing and reporting of the sound pressure levels generated by a gear speed reducer or increaser when tested at the manufacturer’s facility. The results obtained through the use of this standard should represent only the sound of the gear unit, as other system influences, such as prime mover or driven equipment are minimized. Annexes to the standard present sound power measurement methods for use when required by specific contract provisions between the manufacturer and purchaser. **Revision of ANSI/AGMA 6025-C90. Reaffirmed March 2016.**

ISBN: 1-55589-718-5 Pages: 21

ANSI/AGMA 6032-B13 Standard for Marine Gear Units: Rating and Application for Spur and Helical Gear Teeth

This document considers rating practices for marine main propulsion, power take-off and auxiliary propulsion service. **Revision of ANSI/AGMA 6032-A94.**

ISBN: 1-61481-084-1 Pages: 52

ANSI/AGMA 6033-C08 Materials for Marine Propulsion Gearing

This standard identifies commonly used alloy steels, heat treatments and inspection requirements for through hardened and surface hardened gearing for main propulsion marine service over 1500 hp. Forged and hot rolled alloy steel bar stock are specified to two metallurgical quality grades (1 and 2) according to cleanliness and test requirements. Cast steel gearing is specified to a single metallurgical quality level. Mechanical, metallurgical and nondestructive test requirements are provided for various heat treatment processes and metallurgical quality grades of gearing. **Revision of ANSI/AGMA 6033-B98. Reaffirmed March 2014.**

ISBN: 1-55589-929-5 Pages: 34

ANSI/AGMA 6034-B92 Practice for Enclosed Cylindrical Wormgear Speed Reducers and Gearmotors

Covers the design and rating of cylindrical-wormgear speed reducers, having either solid or hollow output shafts of the following specific types: single reduction; double reduction incorporating cylindrical wormgearing for each reduction; and double reduction incorporating cylindrical wormgearing as final and helical gearing as initial reduction. **Reaffirmed March 31, 2016.**

ISBN: 1-55589-494-1 Pages: 37

ANSI/AGMA 6035-A02 Design, Rating and Application of Industrial Globoidal Wormgearing

This standard provides guidelines for the design, rating and application of globoidal wormgearing mounted at a 90-degree angle. Specific definitions for globoidal wormgearing terms are presented, along with formulas for determining the geometric sizes of the major features for the worm and gear. Design considerations, design procedures, gear blanks and self-locking conditions are also discussed. Procedures for rating the load capacity of globoidal wormgearing are included. **Replaces ANSI/AGMA 6017-E86 and ANSI/AGMA 6030-C87. Reaffirmed August 2013.**

ISBN: 1-55589-792-4 Pages: 45

ANSI/AGMA 6101-E08 Design and Selection of Components for Enclosed Gear Drives (Metric Edition)

This standard outlines the basic practices for the design and selection of components, other than gearing, for use in commercial and industrial enclosed gear drives. Fundamental equations provide for the proper sizing of shafts, keys, and fasteners based on stated allowable stresses. Other components are discussed in a manner to provide an awareness of their function or specific requirements. This standard applies to the following types of commercial and industrial enclosed gear drives, individually or in combination: spur, helical, herringbone, bevel and worm. **Metric Edition of ANSI/AGMA 6001-E08. Reaffirmed March 2014.**

ISBN: 1-55589-952-3 Pages: 42

ANSI/AGMA 6102-C15 Design Guide for Vehicle Spur and Helical Gears (Metric Edition)

This standard provides the engineer, who is familiar with gear designing, a guide to sound design approaches for vehicle gear applications. Through this standard, the engineer is guided to selecting design considerations paramount to the parallel axis gear sets required in vehicle drive lines. These include tooth and blank proportions, metallurgy, lubrication, profile and lead modification requirements, and gear tooth tolerances. Properties of the commonly used steels and processes for their heat treatment are outlined, as well as details for calculating design limits for bending and contact stresses.

ISBN: 1-55589-003-2 Pages: 69

ANSI/AGMA 6113-B16 Standard for Industrial Enclosed Gear Drives (Metric Edition)

This standard includes design, rating, lubrication, testing, and selection information for enclosed gear drives, including foot mounted, shaft mounted, screw conveyor drives, and gearmotors. These drives may include spur, helical, herringbone, double helical, or bevel gearing in single or multistage arrangements as either parallel, concentric, or right angle configurations. **Metric version of ANSI/AGMA 6013-B16. Replaces ANSI/AGMA 6113-A06.**

ISBN: 978-1-55589-051-3 Pages: 84

ANSI/AGMA 6114-B15 Gear Power Rating for Cylindrical Shell and Trunnion Supported Equipment (Metric Edition)

This standard specifies a method for rating the pitting resistance and bending strength of open or semi-enclosed gearing for use on cylindrical shell and trunnion supported equipment such as grinding mills, kilns, coolers, and dryers. This includes spur, self-aligning spur, single helical, double helical, and herringbone gears made from steel, ductile iron, and austempered ductile iron. Annexes cover installation, alignment, maintenance, combination drives, and lubrication. Revision of ANSI/AGMA 6014-A06. **Replaces 6114-A06. Metric edition of ANSI/AGMA 6014-B15.**

ISBN: 1-55589-047-6 Pages: 82

ANSI/AGMA 6115-A13 Power Rating of Single and Double Helical Gearing for Rolling Mill Service (Metric Edition)

This Standard provides a method for determining the power rating of gear sets used in main mill drives, pinion stands, and combination units used for the reduction of material size in metal rolling mills. Applications include, but are not limited to, hot mills and cold mills, roughing and finishing stands: reducing, increasing, and 1:1 ratio sets. Auxiliary drives, including drives listed in ANSI/AGMA 6113-A06, such as bridles, coilers, uncoilers, edge trimmers, flatteners, loopers (accumulators), pinch rolls, scrap choppers, shears, and slitters are not covered by this document. This standard includes a method by which different gear tooth designs can be rated and compared at extended life cycles typical for these applications, up to 175 000 hours.

ISBN: 1-61481-057-5 Pages: 67

ANSI/AGMA 6123-C16 Design Manual for Enclosed Epicyclic Gear Drives

This is a design manual for drives employing epicyclic gear arrangements. It includes descriptions of epicyclic drives, nomenclature, application information and design guidelines with reference to other AGMA standards. **Replaces ANSI/AGMA 6123-B06.**

ISBN: 1-55589-059-9 Pages: 136

ANSI/AGMA 6132-B13 Standard for Marine Gear Units: Rating and Application for Spur and Helical Gear Teeth (Metric Edition)

This document considers rating practices for marine main propulsion, power take-off and auxiliary propulsion service. **Metric edition of ANSI/AGMA 6032-B13.**

ISBN: 1-61481-085-8 Pages: 52

ANSI/AGMA 6133-C08 Materials for Marine Propulsion Gearing

This standard identifies commonly used alloy steels, heat treatments and inspection requirements for through hardened and surface hardened gearing for main propulsion marine service over 1500 hp. Forged and hot rolled alloy steel bar stock are specified to two metallurgical quality grades (1 and 2) according to cleanliness and test requirements. Cast steel gearing is specified to a single metallurgical quality level. Mechanical, metallurgical and nondestructive test requirements are provided for various heat treatment processes and metallurgical quality grades of gearing. **Metric version of ANSI/AGMA 6033-C08. Reaffirmed March 2014.**

ISBN: 1-55589-930-1 Pages: 34

ANSI/AGMA 6135-A02 Design, Rating and Application of Industrial Globoidal Wormgearing (Metric Version)

This standard provides guidelines for the design, rating and application of globoidal wormgearing mounted at a 90-degree angle. Specific definitions for globoidal wormgearing terms are presented, along with formulas for determining the geometric sizes of the major features for the worm and gear. Design considerations, design procedures, gear blanks and self-locking conditions are also discussed. Procedures for rating the load capacity of globoidal wormgearing are included. **Replaces ANSI/AGMA 6017-E86 and ANSI/AGMA 6030-C87. Metric edition of ANSI/AGMA 6035-A02. Reaffirmed August 2013.**

ISBN: 1-55589-793-2 Pages: 45

ANSI/AGMA ISO 6336-6-A08 Calculation of Load Capacity of Spur and Helical Gears ISO 8579-2 Part 6: Calculation of Service Life under Variable Load

This standard specifies the information and standardized conditions necessary for the calculation of the service life (or safety factors for a required life) of gears subject to variable loading. While the method is presented in the context of ISO 6336 and the calculation of load capacity for spur and helical gears, it is equally applicable to other types of stress. **Identical adoption of ISO 6336-6:2006. Reaffirmed March 2014. Warning: Users are advised that there is a corrigendum to Clause C.6 of Annex C; see ISO 6336-6:2006/Cor.1:2007(E).**

ISBN: 1-55589-928-8 Pages: 20

ANSI/AGMA 9000-D11 Flexible Couplings – Potential Unbalance Classification

This standard defines classes of flexible coupling potential unbalance, one of which the user must select in order to meet the needs of their system. The classes are established using weight and speed and system sensitivity to arrive at a mass displacement value that defines the potential unbalance. The standard defines types of unbalance, provides a method of selecting balance class, identifies contributors to potential unbalance, and provides a method of determining potential coupling unbalance. The balance classes are derived from consideration of the potential unbalance of the coupling. **Reaffirmed December 8, 2016.**

ISBN: 1-55589-995-0 Pages: 69

ANSI/AGMA 9001-B97 Flexible Couplings – Lubrication

Examines proper lubrication and why it is an essential element for satisfactory performance and long life. Looks at the requisites for proper lubrication, including: selection of proper lubricant, a well-designed lubrication system, and an adequate maintenance program, are discussed in this standard. **Revision of ANSI/AGMA 9001-A86. Reaffirmed May 2014.**

ISBN: 1-55589-686-3 Pages: 6

ANSI/AGMA 9002-C14 Bores and Keyways for Flexible Couplings (Inch Series)

This standard describes sizes and tolerances for straight and tapered bores and the associated keys and keyways, as furnished in flexible couplings. The data in the standard considers commercially standard coupling bores and keyways, not special coupling bores and keyways that may require special tolerances. Annexes provide material on inspection methods and design practices for tapered shafts. **Revision of ANSI/AGMA 9002-B04.**

ISBN: 1-61481-091-9 Pages: 28

ANSI/AGMA 9003-B08 Flexible Couplings – Keyless Fits

This standard presents information on design, dimensions, tolerances, inspection, mounting, removal, and equipment that is in common use with keyless tapered and keyless straight (cylindrical) bore hubs for flexible couplings. Example calculations of important design issues are provided in an annex. **Revision of ANSI/AGMA 9003-A91. Reaffirmed June 2014.**

ISBN: 1-55589-572-7 Pages: 21

ANSI/AGMA 9004-B08 Flexible Couplings – Mass Elastic Properties and Other Characteristics

This standard provides calculation methods related to mass elastic properties of flexible couplings. Properties discussed include coupling mass, polar mass moment of inertia (WR2), center of gravity, axial stiffness, axial natural frequency, lateral stiffness, lateral natural frequency, and torsional stiffness. Calculation examples are provided in informative annexes. **Revision of ANSI/AGMA 9004-A99. Reaffirmed May 2014.**

ISBN: 1-55589-973-8 Pages: 33

ANSI/AGMA 9005-F16 Industrial Gear Lubrication

This standard provides lubrication guidelines for enclosed and open gearing installed in general industrial power transmission applications. It is not intended to supplant specific instructions from the gear manufacturer. **Revision of ANSI/AGMA 9005-E02.**

ISBN: 978-1-55589-052-0 Pages: 46

ANSI/AGMA 9006-A16 Flexible Couplings – Basis for Rating

This standard presents criteria and guidelines for the establishment of the basis for ratings of standard flexible couplings. Due to the diversity of coupling types, details of design such as formulas and analysis used to derive the stresses, etc. are often considered proprietary and are not considered in this standard. This standard is of importance to coupling manufacturers, users and equipment designers for the proper selection, comparison and application of flexible couplings.

ISBN: 978-1-55589-057-5 Pages: 18

ANSI/AGMA 9008-B00 Flexible Couplings – Gear Type – Flange Dimensions, Inch Series

Defines the North American industry practice for the interface dimensions of the sleeve and rigid hubs of both shrouded and exposed bole, inch series, gear type couplings. **Reaffirmed May 2012.**

ISBN: 1-55589-736-3 Pages: 3

ANSI/AGMA 9009-D02 Flexible Couplings – Nomenclature for Flexible Couplings

Presents the nomenclature common to flexible couplings as used in mechanical power transmission drives. It was prepared to reduce the language barriers that arise between designers, manufacturers and users when attempting to designate various types of flexible couplings and their elements. It does not address nomenclature for flexible shafts, quill shafts, universal joints or devices which exhibit slip such as clutches, fluid couplings, magnetic couplings or torque converters. **Reaffirmed July 2014.**

ISBN: 1-55589-796-7 Pages: 17

ANSI/AGMA 9103-B08 Flexible Couplings – Keyless Fits (Metric Edition)

This standard presents information on design, dimensions, tolerances, inspection, mounting, removal, and equipment that is in common use with keyless tapered and keyless straight (cylindrical) bore hubs for flexible couplings. Example calculations of important design issues are provided in an annex. **Metric version of ANSI/AGMA 9003-B08. Reaffirmed June 2014.**

ISBN: 1-55589-925-7 Pages: 22

ANSI/AGMA 9104-A06 Flexible Couplings – Mass Elastic Properties and Other Characteristics (Metric Edition)

This standard provides calculation methods related to mass elastic properties of flexible couplings. Properties discussed include coupling mass, polar mass moment of inertia, center of gravity, axial stiffness, axial natural frequency, lateral stiffness, lateral natural frequency, and torsional stiffness. Calculation examples are provided in informative annexes. **Metric edition of ANSI/AGMA 9004-A99. Reaffirmed May 2012.**

ISBN: 1-55589-900-4 Pages: 32

ANSI/AGMA 9110-A11 Flexible Couplings – Potential Unbalance Classification (Metric Edition)

This metric standard defines classes of flexible coupling potential unbalance, one of which the user must select in order to meet the needs of their system. The classes are established using mass and speed and system sensitivity to arrive at a mass displacement value that defines the potential unbalance. The standard defines types of unbalance, provides a method of selecting balance class, identifies contributors to potential unbalance, and provides a method of determining potential coupling unbalance. The balance classes are derived from consideration of the potential unbalance of the coupling. **Metric edition of ANSI/AGMA 9000-D11. Reaffirmed December 8, 2016.**

ISBN: 1-55589-996-7 Pages: 69

ANSI/AGMA 9112-B15 Bores and Keyways for Flexible Couplings (Metric Series)

This standard describes sizes and tolerances for straight and tapered bores and the associated keys and keyways, as furnished in flexible couplings. The data in the standard considers commercially standard coupling bores and keyways, not special coupling bores and keyways that may require special tolerances. Annexes provide material on inspection methods and design practices for tapered shafts. **Metric edition of ANSI/AGMA 9002-C14.**

ISBN: 1-61481-092-6 Pages: 36

AGMA ISO 10064-5-A06 Code of Inspection Practice – Part 5: Recommendations Relative to Evaluation of Gear Measuring Instruments

This information sheet provides methods and examples to support the implementation of ANSI/AGMA ISO 18653-A06. It includes evaluation and calibration procedures for involute, helix, runout, and tooth thickness measurement processes. Methods are given for the evaluation of condition and alignment of instrument elements such as centers, guideways, probe systems, etc. Recommendations include statistical data evaluation procedures. Guidance is given on the application of measurement processes to the inspection of product gears, including fitness for use and the recommended limits of U95 uncertainty based on the accuracy tolerances of product gears to be inspected. Many of its recommendations could be applied to the measurement of worms, worm wheels, bevel gears and gear cutting tools. **Replaces AGMA 931-A02.**

ISBN: 1-55589-881-5 Pages: 62

AGMA ISO 10064-6-A10 Code of Inspection Practice – Part 6: Bevel Gear Measurement Methods

This document provides information on measuring methods and practices of unassembled bevel and hypoid gears and gear pairs. Tolerances are provided in ISO 17485:2006, for calculating the maximum values allowed by the specific tolerance grade. These methods and practices are intended to promote uniform inspection procedures which are accurate and repeatable to a degree compatible with the specified tolerance grade. **Replaces ANSI/AGMA 2009-B01.**

ISBN: 1-55589-994-3 Pages: 28

AGMA ISO 14179-1 Gear Reducers – Thermal Capacity Based on ISO/TR 14179-1

This information sheet utilizes an analytical heat balance model to provide a means of calculating the thermal transmittable power for a single- or multi-stage gear drive lubricated with mineral oil. The calculation is based on standard conditions of 25C maximum ambient temperature and 95C maximum oil sump temperature in a large indoor space, but provides modifiers for other conditions. Differences from ISO/TR 14179-1 are: a) errors were identified and corrected, b) text was added to clarify the calculation methods, and c) an illustrative example was added to assist the reader. **Modified adoption of ISO/TR 14179-1.**

ISBN: 1-55589-821-1 Pages: 26

ANSI/AGMA ISO 17485-A08 Bevel Gears – ISO System of Accuracy

This standard establishes a classification system that can be used to communicate geometrical accuracy specifications of unassembled bevel gears, hypoid gears, and gear pairs. It defines tooth accuracy terms, specifies the structure of the gear accuracy grade system, and provides allowable values. The standard provides the gear manufacturer and the gear buyer with a mutually advantageous reference for uniform tolerances. Ten grades are defined, numbered 2 to 11 in order of decreasing precision. Equations for tolerances and their ranges of validity are provided for bevel and hypoid gearing. **Identical adoption of ISO 17485:2006. Replaces ANSI/AGMA 2009-B01. Reaffirmed March 2014.**

ISBN: 1-55589-926-4 Pages: 23

Supplemental Tables for ANSI/AGMA ISO 17485-A08 Bevel Gears – ISO System of Accuracy – Tolerance Tables

This information sheet contains tolerance tables dealing with the measurements of bevel gear tooth flanks. While the tables may be used to estimate the tolerance, the actual tolerances are provided in ANSI/AGMA ISO 17485-A08.

ISBN: 1-55589-950-9 Pages: 39

ANSI/AGMA ISO 18653-A06 Gears – Evaluation of Instruments for the Measurement of Individual Gears

This International Standard specifies methods for the evaluation of measuring instruments used to measure cylindrical gear involute, helix, pitch and runout. It includes instruments that measure runout directly, or compute it from index measurements. Of necessity, it includes the estimation of measurement uncertainty with the use of calibrated gear artifacts. It also gives recommendations for the evaluation of tooth thickness measuring instruments. The estimation of product gear measurement uncertainty is beyond its scope (see AGMA ISO 10064-5-A06 for recommendations). This standard is an identical adoption of ISO 18653:2006. **Replaces ANSI/AGMA 2010-A94, ANSI/AGMA 2110-A94, ANSI/AGMA 2113-A97 and ANSI/AGMA 2114-A98.**

ISBN: 1-55589-882-3 Pages: 14

ANSI/AGMA ISO 23509-A08 Bevel and Hypoid Gear Geometry

This standard specifies the geometry of bevel gears. The term bevel gears is used to mean straight, spiral, zerol bevel and hypoid gear designs. The standard integrates straight bevel gears and the three major design generation methods for spiral bevel gears into one complete set of formulas. The formulas of the three methods are developed for the general case of hypoid gears and calculate the specific cases of spiral bevel gears by entering zero for the hypoid offset. **Replaces ANSI/AGMA 2005-D03.**

ISBN: 1-55589-927-1 Pages: 145

AGMA ISO 22849-A12 Design Recommendations for Bevel Gears

This information sheet provides information for the application of bevel and hypoid gears using the geometry in ANSI/AGMA ISO 23509, the capacity as determined by ISO 10300 (all parts), or ANSI/AGMA 2003-C10 and AGMA 932-A05, and the tolerances in ANSI/AGMA ISO 17485. This information sheet provides additional information on the application, manufacturing, strength and efficiency of bevel gears for consideration in the design stage of a new bevel gear set. **Replaces ANSI/AGMA 2005-D03.**

ISBN: 1-61481-029-2 Pages: 40

ISO Standards by Technical Committee 60

Technical Committee 60 is responsible for the development of all international gear-related standards.

Many standards require additional documents for their proper use. A list of these standards are normally supplied after the scope, in the normative references section of a document. Be sure to inquire whether the standard you need requires other documents listed herein.

53:1998 *Cylindrical gears for general and heavy engineering – Standard basic rack tooth profile*

54:1996 *Cylindrical gears for general engineering and for heavy engineering – Modules*

677:1976 *Straight bevel gears for general engineering and heavy engineering – Basic rack*

678:1976 (1996) *Straight bevel gears for general engineering and heavy engineering – Modules and diametral pitches*

701:1998 *International gear notation – Symbols for geometric data*

1122-1:1998 *Glossary of gear terms – Part 1: Definitions related to geometry*

1122-2:1999 *Vocabulary of gear terms – Part 2: Definitions related to worm gear geometry*

1328-1:2013 *Cylindrical gears – ISO system of accuracy – Part 1: Definitions and allowable values of deviations relevant to corresponding flanks of gear teeth*

1328-2:1997 *Cylindrical gears – ISO system of accuracy – Part 2: Definitions and allowable values of deviations relevant to radial composite deviations and runout information*

1340:1976 *Cylindrical gears – Information to be given to the manufacturer by the purchaser in order to obtain the gears required*

1341:1976 *Straight bevel gears – Information to be given to the manufacturer by the purchaser in order to obtain the gears required*

2203:1973 *Technical drawings – Conventional representation of gears*

2490:2007 *Single-start solid (monoblock) gear hobs with tenon drive or axial keyway, 1 to 40 module – Nominal dimensions*

TR4467:1982 *Addendum modification of the teeth of cylindrical gears for speed-reducing and speed-increasing gear pairs*

4468:2009 *Gear hobs – Accuracy requirements*

6336-1:2006 *Calculation of load capacity of spur and helical gears – Part 1: Basic principles, introduction and general influence factors*

6336-2:2006 *Calculation of load capacity of spur and helical gears – Part 2: Calculation of surface durability (pitting)*

6336-3:2006 *Calculation of load capacity of spur and helical gears – Part 3: Calculation of tooth bending strength*

6336-5:2016 *Calculation of load capacity of spur and helical gears – Part 5: Strength and quality of materials*

6336-6:2006 *Calculation of load capacity of spur and helical gears – Part 6: Calculation of service life under variable load*

8579-1:2002 *Acceptance code for gears – Part 1: Determination of airborne sound power levels emitted by gear units*

8579-2:1993 *Acceptance code for gears – Part 2: Determination of mechanical vibration of gear units during acceptance testing*

9083:2001 *Calculation of load capacity of spur and helical gears – Application to marine gears*

9084:2000 *Calculation of load capacity of spur and helical gears – Application to high-speed gears and gears of similar requirements*

9085:2002 *Calculation of load capacity of spur and helical gears – Application for industrial gears*

TR10064-1:1992 *Cylindrical gears – Code of inspection practice – Part 1: Inspection of corresponding flanks of gear teeth*

TR10064-2:1996 *Cylindrical gears – Code of inspection practice – Part 2: Inspection related to radial composite deviations, runout, tooth thickness and backlash*

TR10064-3:1996 *Cylindrical gears – Code of inspection practice – Part 3: Recommendations relative to gear blanks, shaft centre distance and parallelism of axes*

TR10064-4:1998 *Cylindrical gears – Code of inspection practice – Part 4: Recommendations relative to surface texture and tooth contact pattern checking*

TR10064-5:2005 *Code of inspection practice – Part 5: Recommendations relative to evaluation of gear measuring instruments – Technical Corrigendum 1*

TR10064-6:2009 *Code of inspection practice – Part 6: Bevel gear measurement methods*

10300-1:2014 *Calculation of load capacity of bevel gears – Part 1: Introduction and general influence factors*

10300-2:2014 *Calculation of load capacity of bevel gears – Part 2: Calculation of surface durability (pitting)*

10300-3:2014 *Calculation of load capacity of bevel gears – Part 3: Calculation of tooth root strength*

10347:1999 *Worm gears – Geometry of worms – Name plates for worm gear units, center distances, information to be supplied to gear manufacturer by the purchaser*

TR10495:1997 *Cylindrical gears – Calculation of service life under variable load – Conditions for cylindrical gears in accordance with IS0 6336*

10825:1995 *Gears – Wear and damage to gear teeth – Terminology*

TR10828:2015 *Worm gears – Worm profiles and gear mesh geometry*

TR13593:1999 *Enclosed gear drives for industrial applications*

13691:2001 *Petroleum and natural gas industries – High speed special-purpose gear units*

TR13989-1:2000 *Calculation of scuffing load capacity of cylindrical, bevel and hypoid gears – Part 1: Flash temperature method*

TR13989-2:2000 *Calculation of scuffing load capacity of cylindrical, bevel and hypoid gears – Part 2: Integral temperature method*

14104:2017 *Gears – Surface temper etch inspection after grinding, chemical method*

TR14179-1:2001 *Gears – Thermal capacity – Part 1: Rating gear drives with thermal equilibrium at 95°C sump temperature*

TR14179-2:2001 *Gears – Thermal capacity – Part 2: Thermal load-carrying capacity*

14635-1:2000 *Gears – FZG test procedures – Part 1: FZG method A/8, 3/90 for relative scuffing load carrying capacity of oils*

14635-2:2004 *Gears – FZG test procedures – Part 2: FZG step load test A10/16, 6R/120 for relative scuffing load-carrying capacity of high EP oils*

14635-3:2005 *Gears – FZG test procedures – Part 3: FZG test method A/2,8/50 for relative scuffing load-carrying capacity and wear characteristics of semifluid gear greases*

TR15144-1:2014 *Calculation of micropitting load capacity of cylindrical spur and helical gears – Part 1: Introduction and basic principles*

TR15144-2: 2014 *Calculation of micropitting load capacity of cylindrical spur and helical gears – Part 2: Examples of calculation for micropitting*

17485:2006 *Bevel gears – ISO system of accuracy*

18653:2003 *Gears – Evaluation of instruments for the measurement of individual gears*

TR18792:2008 *Lubrication of industrial gear drives*

21771:2007 *Gears – Cylindrical involute gears and gear pairs – concepts and geometry*

TR22849:2011 *Design recommendations for bevel gears*

23509:2006 *Bevel and hypoid gear geometry*

Fall Technical Meeting Papers: 2000–2016

2016 PAPERS

16FTM01. Efficient Hard Finishing of Asymmetric Tooth Profiles and Topological Modifications by Generating Grinding

Authors: **Andreas Mehr & Scott Yoders**

New possibilities of modifications with the continuous generating grinding method will be presented, such as Deviation Free Topological grinding (DFT), Generated End Relief (GER), Noise Excitation Optimized modification (NEO), and hard finishing of asymmetric gears. The focus is on the explanation of the technical challenges, their solutions, and the principle function of the dressing and grinding processes.

ISBN: 1-55589-060-5 Pages: 13

16FTM02. The Whirling Process in a Company that Produces Worm Gear Drives

Authors: **Dr. Massimiliano Turci, Dr. Giampaolo Giacomozzi**

This paper looks at the benefits that can be realized with the introduction a whirling machine into the wormgear manufacturing facility. The benefits include time and cost savings, especially in regard to the need for grinding, increased quality, and environmental considerations due to not needing cutting oils.

ISBN: 1-55589-061-2 Pages: 22

16FTM03. Worm Screw High-Speed Manufacturing

Author: **Jean-Laurent Feutren**

The conventional set-up of on a gear hobbing machine for the production of helical gears has the hob axis perpendicular (±30°) to the workpiece. This set-up does not allow for conventional manufacturing of wormgears. To solve this problem, a high speed method will be presented that reverses the axis between the workpiece and tool, and utilizes a high speed spindle (up to 16 000 rpm). This method can produce wormgears eight times faster than conventional methods.

ISBN: 1-55589-063-6 Pages: 15

16FTM04. Twist Control Grinding (TCG)

Author: **Walter Graf**

This paper introduces the latest process developments for the hard-finishing of gears in regards to controlling flank twist. Flank twist occurs as a matter of course when machining helical gears that feature lead modifications, and is brought about by the geometries and kinematics inherent in the continuous generating grinding of helical gears. Controlling the flank twist on gears, using twist control grinding (TCG), can either eliminate twist completely, or introduce a counter-twist to counteract the deformation of gears under load.

ISBN: 1-55589-064-3 Pages: 13

16FTM05. Review of Microstructure and Properties of Non-Ferrous Alloys for Worm Gear Application and Advantages of Centrifugally Cast Gears

Authors: **Giri Rajendran & Jason Hassen**

This paper reviews the microstructure and properties of tin bronze, manganese bronze, and aluminum bronze material that make them suitable for specific wormgear applications. The advantages of centrifugally cast bi-metal gear blanks, and some common causes of worm gear failures are discussed.

ISBN: 1-55589-065-0 Pages: 11

16FTM06. Pre-Nitriding: A Means of Significantly Increasing Carburizing Throughput

Author: **Thomas Hart**

Higher carburizing temperatures allow end users to use shorter cycle times and significantly increase production rates, but can lead to grain growth. Pre-nitriding is a relatively new technology that addresses grain growth and allows carburizing end users to carburize at higher temperatures. Real life case studies show how carburizing productivity has doubled, and sometimes tripled, using pre-nitriding.

ISBN: 1-55589-066-7 Pages: 10

16FTM07. Performance and Machining of Advanced Engineering Steels in Power Transmission Applications – Continued Developments

Authors: **Lily Kamjou, Nicklas Bylund, Brent Marsh, Joakim Fagerlund, Thomas Björk**

This paper discusses the potential gain for the power transmissions industry by making use of the material properties of Advanced Engineering Steels to support more demanding applications. Machining the Advanced Engineering Steels is discussed based on a number of recent studies. All studies indicate that by optimizing machining parameters and tools, the productivity and efficiency of these processes can be maintained, or even improved.

ISBN: 1-55589-067-4 Pages: 16

16FTM08. Gear Design Relevant Cleanness Metrics

Authors: **Dr. E. Buddy Damm, Peter Glaws**

This paper describes the methods used to characterize premium quality clean steels through the use of statistics of extreme values (SEV), and the use of these data to perform gear design relevant engineering analysis of the potential for a gear failure due to bending fatigue in the root or flank. Literature evaluation, modeling results, and experimental results are presented in order to validate the approach.

ISBN: 1-55589-068-1 Pages: 17

16FTM09. Development of High Hardness-Cast Gears for High-Power Applications in the Mining Industry

Author: **Fabrice Wavelet**

Multiple solutions are available to increase the transmissible power of girth gears, including using a larger module, increasing the gear diameter, enlarging the face width, and increasing the hardness of the base material. Base material hardness, the only parameter that is not limited by cutting machine size, is being increased to meet higher power needs. This paper will review the related design and manufacturing impact of the high-hardness gears needed to meet today's industry demands.

ISBN: 1-55589-069-8 Pages: 14

16FTM10. Computerized Design of Straight Bevel Gears with Optimized Profiles for Forging, Molding, or 3D Printing

Authors: **Alfonso Fuentes, Ignacio Gonzalez-Perez, and Harish Pasapula**

Research will be presented on whether there is a reference profile that will yeild the same advantages for bevel gears as the involute for cylindrical gears. The spherical involute and octoidal profiles will be studied, and the virtual generation of bevel gears with the different profiles will be developed, and simulated, using advanced tools such as tooth contact analysis and finite element analysis.

ISBN: 1-55589-111-4 Pages: 21

16FTM11. Contact Fatigue Characterization of Through-Hardened Steel for Low-Speed Applications Like Hoisting

Authors: **Dr. Michel Octrue, Antoine Nicolle, and Remy Genevier**

Lubrication by grease is often employed on open gears that transmit power at low speeds. The rating methods found in ISO 6336 has shown that ISO is very conservative for grease lubricated, through hardened steel gears running with case hardened pinions, specifically when considering service life. Fatigue SN curves resulting from tests will be compared and discussed with values given in ISO and AGMA gear rating standards.

ISBN: 1-55589-112-1 Pages: 18

16FTM12. Determination of Load Distributions on Double Helical-Geared Planetary Gear Boxes

Author: **Dr. Tobias Schulze**

The optimization and effective utilization of planetary gearbox designs require a detailed consideration of the loads on the gears. This paper presents a computer aided calculation method that has been developed for planetary gearboxes with spur and helical gears that considers the most important influences on the load distribution. Using this information, a detailed load distribution is possible to reach the maximum capability of the gears.

ISBN: 1-55589-113-8 Pages: 14

16FTM13. Designing Very Strong Gear Teeth by Means of High Pressure Angles

Author: **Richard Miller**

This paper will show a method of designing and specifying gear teeth with much higher bending and surface contact strength than that of conventional gear teeth. The primary means of achieving this is by specifying gear teeth with significantly higher pressure angles. This paper will show calculation procedures, mathematical solutions, and the theoretical background and equations to achieve this.

ISBN: 1-55589-114-5 Pages: 22

16FTM14. Impact of Surface Condition and Lubricant on Effective Gear Tooth Friction Coefficient

Authors: **Aaron Isaacson, Matthew Wagner, Suren Rao, and Gary Sroka**

Using a four-square, power re-circulating gear test rig with high accuracy torque transducers, losses due to operating speed, surface roughness, and torque level, including two different lubricants, were compared, and measurements of the effective coefficient of friction at the gear tooth flanks are provided. This paper summarizes the results obtained.

ISBN: 1-55589-118-3 Pages: 12

16FTM15. Surface Structure Shift for Ground Bevel Gears

Author: **Sebastian Strunk**

A process is presented that improves the excitation behavior of a ground bevel gear set by altering the surface structure of a generated member along the path of contact from slot to slot. This process addresses this objectionable harmonic excitation by influencing each axis position in each line of the axis position table with small predetermined or random amounts.

ISBN: 1-55589-119-0 Pages: 20

16FTM16. Developing an Energy-Efficient Industrial Gear Oil

Authors: **Shubhamita Basu, Daniel Wilkerson, and James Vinci**

This paper describes a laboratory test rig, test procedure, and results that are focused on quantifying increased operating efficiency with various synthetic lubricant formulations. Fluid evaluations were conducted in an industrial-scale worm gear efficiency rig. Operating under a wide range of speeds and loads, the rig produced sharp differentiation among fluids for their impact on power loss and operating temperature.

ISBN: 1-55589-120-6 Pages: 14

16FTM17. Analysis of Excitation Behavior of a Two-Stage Gearbox Based on a Validated Simulation Model

Authors: **Marius Schroers, Christian Brecher, and Christoph Löpenhaus**

In order to reduce development and production costs of a gearbox, simulation models have been set up to predict the noise and vibration behavior of a gearbox before the prototype phase. A simulation model, verified by experimental results, is presented that is able to calculate the dynamic excitation behavior of a two-stage gearbox.

ISBN: 1-55589-121-3 Pages: 16

16FTM18. An Experimental and Analytical Comparison of the Noise Generated by Gears of Austempered Ductile Iron (ADI) and Steel Materials

Authors: **Dr. Donald Houser, Samuel Shon, Kathy Hayrynen, Justin Lefevre**

Many have made claims concerning the relative noise performance of Austempered Ductile Iron (ADI) versus steel as a gearing material. Predictions based on measured tooth topographies of the transmission error and "sum of forces" gear noise metrics show that the iron gears should be slightly quieter than the steel gears at loads beneath the transmission error optimization "notch" torque and slightly louder above this torque. This paper presents results from a systematic experimental study to ascertain these differences.

ISBN: 1-55589-122-0 Pages: 25

16FTM19. Numerical Thermal 3D Model to Predict the Surface and Body Temperature of Spur and Helical Plastic Gears

Authors: **Niranjan Raghuraman, Donald Houser, and Zachary Wright**

Tooth surface wear is an important failure mode in plastic gears and this primarily caused by the surface temperature increasing to a value close to the melting point of the material. Thus, it is critical to compute the temperature of the gear pair in an accurate fashion. This paper will focus on the prediction of gear temperature of plastic gears using a numerical heat transfer model based on 3D finite difference method.

ISBN: 1-55589-123-7 Pages: 17

16FTM20. Influence of the Defect Size on the Tooth Root Load Carrying Capacity

Authors: **Jens Brimmers, Christian Brecher, Christoph Löpenhaus, and Jannik Henser**

Conventional calculation methods for the flank and tooth root load carrying capacity are well-established, but models that consider the defect size on the tooth root strength have not yet been applied in fatigue models for gears. This paper will introduce a method for calculating the tooth root load carrying capacity for gears while considering the influence of the defect size on the endurance fatigue strength of the tooth root.

ISBN: 1-55589-176-3 Pages: 14

16FTM21. Influence of Contact Conditions on the Onset of Micropitting in Rolling-Sliding Contacts Pertinent to Gear Applications

Authors: **Dr. Amir Kadiric & Dr. Pawel Rycerz**

Recently, increased sliding has been one of the factors suggested to be responsible for the onset of micropitting, with the proposed underlying mechanism being the potential reduction of film thickness through increased sliding speed. This paper attempts to shed light on the tribological conditions that may lead to the onset of micropitting in lubricated, concentrated contacts representative of those occurring between gear teeth. In particular, the effect of slide-roll-ratio, surface roughness and film thickness is studied.

ISBN: 1-55589-480-1 Pages: 19

16FTM22. Comparison of Tooth Interior Fatigue Fracture Load Capacity to Standardized Gear Failure Modes

Authors: **Baydu Al, Paul Langlois, Rupesh Patel**

This study aims to improve the existing understanding of Tooth Interior Fatigue Fracture (TIFF) load capacity and compare calculated load capacity to the allowable loading conditions for bending and pitting fatigue failure, based on standard calculation procedures. Possible methods that could be used to mitigate TIFF risk are presented, and the effect of these methods on the performance with respect to the other failure modes are quantified.

ISBN: 1-55589-497-9 Pages: 19

16FTM23. A New Approach to Repair Large Industrial Gears Damaged by Surface Degradation – The Refurbishment Using the Modification of Both the Profile Shift Coefficient and the Pressure Angle

Authors: **Horacio Albertini, Carlo Gorla, Francesco Rosa**

Superficial degradation of industrial gears, and a lack of approaches to repair them, have resulted in many gears being discarded prematurely. This paper presents a computer program and method for repairing industrial gears, enabled by the recent advances in multi-axis CNC machine centers, and gear grinding, that considers the modification of both the profile shift coefficient and the pressure angle.

ISBN: 1-55589-234-0 Pages: 20

2015 PAPERS

15FTM01. Influence of Surface Finishing on the Load Capacity of Coated and Uncoated Spur Gears

Authors: **P. Konowalczyk, C. Brecher**

In order to increase the power density of tribologically stressed drive train components, different approaches are being pursued in material and production technology. In addition to the development of efficient base materials, especially the optimization of surface finishing processes and the application of coating systems are promising. By combining mechanically highly stressable substrate materials and tribologically effective, extremely thin coatings, the components show modified wear and friction properties, which often lead to an increase of tooth flank load carrying capacity. A major advantage of this approach is that the highly accurate component geometry is only slightly changed by the coating.

The influence of PVD/PECVD hard coatings on the load carrying capacity of cylindrical gears made of alloy steel is the subject of scientific research since the nineties. Several reports show that diamond-like carbon (DLC) coating systems reduce the occurrence of specific forms of gear damages, such as pitting or scuffing, and optimize the frictional behavior of gears. Despite the good results, PVD/PECVD coating technology could not be established in gear transmission technology yet. The use of a PVD/PECVD coating leads to higher component costs and longer manufacturing time. Furthermore, the surface finishing process before coating can influence the resulting tooth flank load capacity, and in some studies, a reduction of tooth root strength by the application of a coating can be observed. An extensive research concerning the influence of specific surface finishing processes on the tooth flank load capacity of uncoated and coated gears have not been focused in existing works. Furthermore, the existing works focus on the coating of both gears in contact and not on the coating of just one gear combined with optimized surface finishing processes.

Therefore, the aim of this work is the investigation and determination of the influence of surface finishing processes on the impact of PVD/PECVD coatings concerning the pitting load capacity of gears. By means of running tests, the influence of different surface finishing processes on the pitting resistance is examined for the uncoated and coated tooth flank contact. The coated tooth flank contact will be further separated in the cases with just one or two coated gears in contact. By coating only one gear, a possible reduction of coating costs with simultaneous increase of the pitting resistance is targeted. As a DLC coating, a modified tungsten carbide coating (a-C:H:W (WC/C)) will be applied. Due to an optimized coating process, consistent coating adhesion without loss of hardness of the substrate material will be achieved. The result of this optimization will additionally be proven by the investigation of tooth root strength by means of pulsator testing.

ISBN: 1-55589-006-3 Pages: 11

15FTM02. Improved Materials and Enhanced Fatigue Resistance for Gear Components

Authors: **Dr. Volker Heuer, Dr. Klaus Loeser, Gunther Schmitt**

This paper shows the latest progress in steel grades and in case hardening technology for gear components.

To answer the demand for fuel-efficient vehicles, modern gear boxes are built much lighter. Improving fatigue resistance is a key factor to allow for the design of thin components to be used in advanced vehicle transmissions. The choice of material and the applied heat treat process are of key importance to enhance the fatigue resistance of gear components.

By applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ), the tooth root bending strength can be significantly enhanced, compared to traditional heat treatment with atmospheric carburizing and oil quenching.

Besides heat treatment, significant progress has been made over the past years on the steels being used for gear components. The hardenability of case hardening steels such as 5130H, 5120H, 20MnCr5, 27MnCr5, 18CrNiMo7-6 etc. has been stepwise increased in recent years. An important factor for fatigue resistance is the grain size after heat treatment. Therefore, grain size control is a key goal when developing new modifications of steel grades.

After enhancing grain size control, it was possible to increase the carburizing temperatures over the past years from 930°C to 980°C (1700°F to 1800°F) which resulted in shorter heat treatment cycles and thus in significant cost savings.

With the introduction of new microalloyed steels for grain size stability, carburizing temperatures can now be even further increased to temperatures of up to 1050°C (1920°F), leading to even more economic process cycles. By adding microelements such as Niobium or Titanium in the ppm-range, nitride and carbonitride-precipitates are formed. These precipitates effectively limit the grain-growth during the heat treatment process.

ISBN: 1-55589-008-7 Pages: 16

15FTM03. Practical Approach to Determining Effective Case Depth of Gas Carburizing

Author: **March Li**

Effective case depth is an important factor and goal in gas carburizing, involving complicated procedures in the furnace and requiring precise control of many thermal parameters. Based upon diffusion theory and years of carburizing experience, this paper calculates the effective case depth governed by carburizing temperature, time, carbon content of steel, and carbon potential of atmosphere. In light of this analysis, carburizing factors at various temperatures and carbon potentials for steels with different carbon content were calculated to determine the necessary carburizing cycle time. This methodology provides simple (without computer simulation) and practical guidance of optimized gas carburizing and has been applied to plant production. It shows that measured effective case depth of gear parts covering most of the industrial application range (0.020 inch to over 0.250 inch) was in good agreement with the calculation.

ISBN: 1-55589-010-0 Pages: 7

15FTM04. Single-Piece, High-Volume, Low-Distortion Case Hardening of Gears

Authors: **Maciej Korecki, Emilia Wolowiec-Korecka, Doug Glenn**

Global output of gears in the automotive industry is estimated to be in excess of 1 billion units per year.

While carburizing and quenching of steel gears for the automotive industry provides the surface-hardened teeth and flexible core necessary for a long-lasting gear, heat treating, and especially the quenching process, produces distortion. Distortion is most often corrected by the costly process of post-heat treat machining. The main goal of every high-volume gear heat treating process is the elimination of distortion. If distortion is not eliminated, the goal is significant reduction, predictability, and repeatability of distortion.

This article looks at the major causes of deformation during heat treatment and methods for controlling, correcting, and eliminating distortion. A new concept—a single-piece flow case hardening system—will be presented. This system adjusts to the size and shape of the particular gear in order to minimize distortion and ensures ideal repeatability of results, gear after gear. It is a compact system designed for high-volume gear heat treating, is ideal for lean manufacturing configurations, and can easily be integrated into machining centers.

ISBN: 1-55589-011-7 Pages: 15

15FTM05. Innovative Steel Design and Gear Machining of Advanced Engineering Steel

Authors: **Lily Kamjou, Patrik Ölund, Erik Claesson, Joakim Fagerlund, Garry Wicks, Mats Wennmo, Hans Hansson**

The basis for high fatigue performance in high hardness steel originates in precise inclusion engineering. In addition, recent research shows that by changing the alloying strategy, an increase in the bending fatigue limit can be achieved similar to an additional shot-peening process. Therefore, the near surface structure will exhibit excellent mechanical properties and compressive residual stresses in the as-carburized condition.

The current paper describes the potential of clean steel for new approaches in transmission gear box manufacturing and possibilities to meet the future demands of being smaller, lighter and managing higher torque. One important factor is the bending fatigue performance of the gear teeth where an increasing fatigue strength is required. The paper discusses how shot peening might be eliminated in high-cleanliness, as-carburized steel components using an alternative composition. The fatigue performance of such a solution is compared to conventional grades used today, both with and without shot peening.

The full benefit of this new steel design can be obtained by using a high-quality steel with a decreased number of critically-sized inclusions in the loaded volume. Results from extensive testing support how this type of steel compares to commonly used carburizing steels. The effect of material cleanliness on contact fatigue is also examined through FZG pitting testing.

To address potential machining issues of clean steels, the paper also deals with the production process, including quantitative machining trials and the importance of tooling selection. The study is focused on the production of gears, dealing mainly with turning and hobbing. Initial results show how these clean steels can be machined in full scale production in standard conditions with equal or better efficiency and cost.

ISBN: 1-55589-016-2 Pages: 12

15FTM06. Powder Metal Gear Technology: A Review of the State of the Art

Author: **Anders Flodin**

During the past 10 years, the PM industry has put a lot of focus on how to make Powder Metal gears for automotive transmissions a reality. To reach this goal, several hurdles had to be overcome, such as fatigue data generation on gears, verification of calculation methods, production technology, materials development, heat treatment recipes, design development, and cost studies.

All of these advancements will be discussed, and a number of vehicles with powder metal gears in their transmissions will be presented. How the transmissions have been redesigned in order to achieve the required stress levels while minimizing weight and inertia, thus increasing efficiency, will also be discussed.

ISBN: 1-55589-017-9 Pages: 11

15FTM07. Industry 4.0 and its Implication to Gear Manufacturing

Author: **Hermann J. Stadtfeld**

The Industry 4.0 is an initiative of leading German industrial corporations and scientific institutions, supported with funding from the German government, which promotes the computerization of traditional industries such as manufacturing. This paper reviews the four industrial periods from the viewpoint of gear manufacturing and points out the special character of the fourth industrial period, which has just begun. The main part of the paper reports about the techniques and elements of the so-called cyber physical production systems and how they will change the way of industrial manufacturing. In the proceeding sections, the paper relates the features of Industry 4.0 to the Gleason achievements regarding machining process design, machine networking, expert systems, machine self-diagnosis, and cycle optimization, as well as remote diagnosis. The conclusion points out that the new movement will enhance manufacturing capabilities, improve product quality, and will create very flexible manufacturing. Gleason products today already show a significant content of smart features and modern data processing, which together with a leading strategy for future developments, is represented with the name Gleason 4.0.

A concern of manufacturing personnel is the missing transparency and traceability of the action that a smart manufacturing control is executing. The concern, that chaotic situations can occur if the smart manufacturing system has to react to unexpected input information, is justified; the concern about missing traceability is, in most cases, not justified. For example, in the early days of G-AGE corrections, gear engineers liked to understand why the combination of five or more delta settings would correct a certain flank form error. However, the mathematics behind those corrections are rather complex and would require many hours—or even days—to verify a single set of correction data. After the first years of practice with G-AGE, gear engineers learned to trust the results and applied them without questioning. In the few cases when the theory failed and the corrections made the gear worse, the gear engineer used common sense and either applied simple manually calculated corrections or eliminated a critical input or output variable in order to unarm the unstable part of the originally computed results.

This example shows that it is efficient to have the thousands of decisions or actions which are constantly reoccurring done by the smart manufacturing system. Its strength is to execute reoccurring operating tasks very fast. The human skill is to concentrate on all out-of-the-ordinary situations, in which the computerized intelligence is not very strong. The artificial neurons don't take anyone's workplace. Quite the contrary—future manufacturing will only exist if it follows the smart movement. Workplaces in factories will be sophisticated and interesting, and humans will be in control…probably in more control than they have been in the past.

ISBN: 1-55589-018-6 Pages: 24

15FTM08. Proposed Pre-Finish Cylindrical Gear Quality Standard

Author: **Peter E. Chapin**

It is quite common to specify a gear class for in-process quality requirements, usually calling for a lower quality class than is required for the finished gear quality. Although it is appropriate to have lower expectations for a pre-finish gear condition, it is not appropriate to subject the pre-finish gear to the same level of scrutiny as a finished gear. Gears in a pre-finish condition may have large feed scallops or generating flats, which are desirable for productivity and may be conducive to the finishing process. However, such features will be evaluated as errors when subjected to the full analysis as required by the finished gear class inspection. Therefore, the use of a finished gear quality specification is not recommended or even appropriate for pre-finish gear quality evaluation, even if the quality class has been adjusted to pre-finish expectations. Additionally, in-process requirements often require non-zero target helix and profile slopes, which necessitate a new method of analysis to determine the achieved quality class. Therefore, a pre-finish evaluation method and standard is proposed. This proposed standard would not make any recommendations regarding the required quality for any application. The intent is to establish standard pre-finish quality classes for typical finishing operations, which only include the inspection elements that are important to properly evaluate pre-finish gear quality as it applies to the finishing operation.

ISBN: 1-55589-019-3 Pages: 19

15FTM10. Influence of Hobbing Tool Generating Scallops on Root Fillet Stress Concentrations

Authors: **Benjamin S. Sheen, Matthew Glass**

In the design of gear and spline teeth, the root fillet area and its maximum tensile stress are of primary concern for the gear designer. In general terms, the tensile stress in the root fillet is based on specific geometries of the design: minor diameter, fillet radius, etc. However, additional concerns regarding the manufacturing method, cutting tool geometry, and process parameters can greatly influence the impact of stress concentration factors in the root fillet area.

For a hobbed tooth manufacturing process, the root fillet geometry is controlled by the rack design of the cutter, but also by the number of generating scallops produced by the tool. For a shaping process, the generating scallops are close together and can produce a surface with almost no visible signs of root fillet generating scallops. However, for a hobbing process, the number of threads, number of gashes, and tip radius can create multiple variations of generated scallops. These can create stress concentrations, which can increase the tensile bending stress and potentially impact the service life of the component. For this discussion, stress concentrations caused by root fillet generating scallops will be reviewed.

This paper will discuss a specific example regarding parallel-sided splines manufactured with a finish hobbing process and their effects on generating root fillet stress concentrations. To estimate the value of the stress concentrations, Finite Element Analysis was performed on the components for two unique hobbing tool designs. The FE results are compared to actual component field service histories.

ISBN: 1-55589-021-6 Pages: 10

15FTM11. Selecting the Proper Gear Milling Cutter Design for the Machining of High Quality Parallel Axis, Cylindrical Gears and Splines

Author: **Brent Marsh**

Gear milling cutters offer a versatile and timesaving solution for milling of high-quality gear profiles. Application methods vary. There are many ways to utilize these cutters. Machines range from traditional gear hobbing machines with single indexing capability to horizontal and vertical CNC machining centers with 4- or 5-axis capability, modern multi-task turning and milling centers, CNC lathes with live milling capability, and dedicated special-purpose machines.

Tool selection will depend on a number of factors, such as module size, work piece material, gear quality level desired, spur or helical design, tooth count, size of gear blank, and available equipment options. The desired post-milling operations needed—such as hardening, grinding, honing, and shaving—also have an influence on the milling tool design.

When planning for successful process methods, rigidity, tool holding (arbor supported vs. unsupported), and material removal rate, all must be addressed.

Power and torque requirements as related to gear material, number of passes, cutter design, and diameter, are very important in the planning phase. Tool selection has a significant impact on this. Rake angles and cutter geometry are important. Tools are designed according to rough, semi-finish, and finish requirements. Tandem, multi-cutter designs will improve productivity but bring on specific challenges to the process engineer.

Surface finish requirements are also very important. Milling methods can vary from climb cutting to conventional milling. Both methods have their place and impact surface finish and tool life. Radial infeed and reduced or increased feed rate on entry are other factors. Wet-versus-dry machining and oil-versus-water-soluble coolants impact tool life, part quality, and environmental concerns. Proper chip thickness and calculations for feed rate compensation must be considered.

This paper takes a comprehensive view of all of the above mentioned topics to assist the manufacturing engineer or process planner in successfully choosing the design of gear milling cutters to make cost-effective cylindrical gears to the appropriate quality desired.

ISBN: 1-55589-022-3 Pages: 12

15FTM12. Simulation of Hobbing and Generation Grinding to Solve Quality and Noise Problems

Author: **Günther Gravel**

Due to increasing tolerance requirements for gearboxes and gears, it has become more and more important to establish quality circles in production. A quick detection and correction of the causes of tolerance violation is essential for high quality. This paper shows the possibilities and procedures of searching for the root cause in general, especially with problems in hobbing and generation grinding using multi-start tools.

A new simulation tool has been developed, which allows for the simulation of typical faults that occur during hobbing and generation grinding. The calculated contour on the workpiece is treated as a measured curve, making it easy to compare workpiece measurements and simulations. In this way, possible error causes can be simulated and compared with the real gear surface.

This paper uses practical examples to demonstrate the following applications for simulation. The influence of the tool parameter's "number of starts" and "number of flutes" on the cutting result is shown in connection with the axial feed parameter. Protuberance and tooth tip rounding on the tool influence the profile form generated on the workpiece. Wobble and eccentric in the tool clamping creates an s-shaped pattern on the profile, based on the number of starts on the tool. The form of the pattern changes with different parameters.

In high-speed gearboxes, ripples on the gear surfaces are frequently the cause of noise problems. Simulation of a tool error and a subsequent evaluation of the ripples enable conclusions to be drawn about the excitations caused by the tool error during the cutting process. A practical comparison between the ripple measurement of a hobbed and subsequently honed gear and the simulation shows that the noise-related ripples on the finished part arises already in the pre-machining stage.

The applications presented in this paper show that the results of the simulation are a very good match with practical tests. Thus, the simulation software is a highly precise tool for determining and eliminating the causes of deviations in production. At the same time, design engineers and planners can quickly and easily develop new process and tool designs, thereby significantly reducing the costs involved in testing.

ISBN: 1-55589-023-0 Pages: 11

15FTM13. Thermal Capacity of a Multi-Stage Gearbox

Authors: **Albertus Willem Wemekamp, A. Doyer**

In many industrial gearbox applications, thermal rating is a key factor in the practical utilization of the gearbox. The thermal capacity is affected by the efficiency (power loss) of the gearbox and heat dissipation within the environment. Methods, as found in ISO Technical Reports (ISO/TR 14179), help to estimate quasi-stationary temperature in the oil sump.

To further increase the understanding, SKF has incorporated power loss prediction and thermal equilibrium in its validated simulation tool. It goes beyond ISO methods: it includes the interaction between heat losses, thermal expansions, and (bearing) pre-loading. With this simulation tool, all these interactions can be analyzed by solving the mechanical and thermal problem simultaneously.

When changing operating conditions (e.g., during starting up), temperature differences between rotating parts (e.g., shafts) and the exterior parts (e.g., housing) may differ considerably from the steady state conditions. These effects are extremely difficult to anticipate, or complex measurements would be required. The developed method allows engineers to perform transient calculation in which the momentary temperature differences (affecting the bearing loading) are taken into account. In this way, the whole gearbox behavior can be analyzed in more detail.

In the paper, the methodology used to obtain the interaction between mechanical and thermal equilibrium will be explained. Using the simulation tool capabilities, the performance of the bearings and gears in a multi-stage gearbox will be analyzed and presented.

ISBN: 1-55589-025-4 Pages: 12

15FTM14. Gear Backlash Analysis of Unloaded Gear Pairs in Transmissions

Author: **Carlos Wink**

A best practice in gear design is to limit the amount of backlash to a minimum value needed to accommodate manufacturing tolerances, misalignments, and deflections, in order to prevent the non-driving side of the teeth to make contact and rattle. Industry standards, such as ANSI/AGMA 2002 and DIN3967, provide reference values of minimum backlash to be used in the gear design. However, increased customers' expectations in vehicle noise reduction have pushed backlash and allowable manufacturing tolerances to even lower limits. This is especially true in the truck market, where engines are quieter because they run at lower speeds to improve fuel economy, but they quite often run at high torsional vibration levels. Furthermore, gear and shaft arrangements in truck transmissions have become more complex, for an increased number of speeds and to improve efficiency. Determining the minimum amount of backlash is quite a challenge. This paper presents an investigation of minimum backlash values of helical gear teeth applied to a light-duty pickup truck transmission. An analytical model was developed to calculate backlash limits of each gear pair when not transmitting load, and thus susceptible to generate rattle noise, through different transmission power paths. A statistical approach (Monte Carlo) was used since a significant number of factors affect backlash, such as tooth thickness variation, center distance variation, lead, runout and pitch variations, bearing clearances, spline clearances, and shaft deflections and misalignments. Analytical results identified the critical gear pair, and power path, which was confirmed experimentally on a transmission. The approach presented in this paper can be useful to design gear pairs with a minimum amount of backlash, to prevent double flank contact and to help reduce rattle noise to lowest levels.

ISBN: 1-55589-026-1 Pages: 7

15FTM15. New Refinements to the Use of AGMA Load Reversal and Reliability Factors

Author: **Ernie Reiter**

AGMA standards use load reversal and reliability factors in the calculation of the rated load capacity for gear teeth. ANSI/AGMA 2101-D04 recommends the use of a load reversal factor of 1.0 for most gears which see one-way bending, and 0.7 for gears such as idler gears and planet gears that see a fully reversing bending condition. Likewise, the standard uses a table format to assign a reliability factor based on a desired reliability level in an application.

This paper suggests two ways to calculate a load reversal factor which would be material specific, based either on Modified Goodman or Gerber Failure Theories. This paper further provides a method of calculating the reliability factors which very closely match the AGMA tables found in ANSI/AGMA 2101-D04.

ISBN: 1-55589-028-5 Pages: 15

15FTM17. Homogeneous Geometry Calculation of Arbitrary Tooth Shapes – Mathematical Approach and Practical Applications

Authors: **Maximilian Zimmer, M. Otto, Karsten Stahl,**

As an extensive machine element to transfer and convert rotational movement, gears meet high requirements for construction and assembly. Due to existing modern production techniques, more sophisticated gear types can be produced with high precision and maintainable financial effort. The benefits of traditional gear profiles, such as an involute, are thus no longer of major importance. In particular, for gear types such as bevel, worm, and hypoid gears, but also for non-standard gear types (e.g., beveloid gears, crown gears, or spiroid gearings), modern gear production systems ensure high quality and reliability to the operator. Depending on the context of application, different gear types have advantages and disadvantages concerning load carrying capacity, effectiveness, or noise excitation. Supported by various calculation software tools for the particular gear type, it is possible to create the optimal gear design, depending on the respective application. A homogeneous calculation software for ubiquitous gear geometries—irrespective of the gear type, and especially for analyzing non-standard gears—would be preferable.

This paper provides a mathematical framework and its implementation for calculating the tooth geometry of arbitrary gear types, based on the basic law of gear kinematics. The rack or gear geometry can be generated in two different ways: by calculating the conjugate geometry and the line of contact of a gear to the given geometric shape of a known geometry (e.g., a cutting hob), or by prescribing the surface of action of two gears in contact and calculating the correspondent flank shapes. Besides so-called standard gears like involute spur and helical gears, bevel or worm gears, it is possible to analyze the tooth geometry of non-standard gears (e.g., non-involute spur, conical, or spiroid gears). Depending on the type of gear, a distinction is made between tool-dependent and tool-independent geometry calculation.

The described mathematical algorithms are summarized in implemented software modules for the particular gear types. Two practice-oriented examples are presented to illustrate the calculation model: beveloid gears for use in vehicle or marine gear boxes as well as rack-and-pinion meshing with variable ratio, as it is used for steering systems on automobiles. Since the geometry is exported as a point cloud, a further analysis of the generated gear types is possible, e.g., by computer-aided design or finite-element software tools as well as manufacturing on 5-axis CNC or forging machines. Thus, a detailed analysis—especially of non-standard gears—is feasible that currently cannot be calculated and evaluated with common industrial gear calculating software.

ISBN: 1-55589-029-2 Pages: 17

15FTM18. Rating of Asymmetric Tooth Gears

Author: **Alexander L. Kapelevich**

The benefits of gears with asymmetric tooth profiles for unidirectional torque transmission are well known. The design objective of asymmetric tooth gears is to improve performance of the primary drive flank profiles at the expense of the opposite coast profiles' performance. The coast flanks are unloaded or lightly loaded during a relatively short work period. Asymmetric tooth profiles make it possible to simultaneously increase the contact ratio and operating pressure angle of drive tooth flanks beyond those limits achievable with conventional symmetric tooth gears. The main advantage of asymmetric tooth gears is drive flank contact stress reduction, which allows one to considerably amplify power transmission density, increase load capacity, and reduce size and weight. However, asymmetric tooth gears and their rating are not described by existing gear design standards.

This paper presents a rating approach for asymmetric tooth gears by their bending and contact stress levels in comparison with symmetric tooth gears, whose rating is defined by standards. This approach applies finite element analysis (FEA) for bending stress definition and the Hertz equation for contact stress definition. It defines equivalency factors for practical asymmetric tooth gear design and rating.

The paper illustrates the rating of asymmetric tooth gears with numerical examples.

ISBN: 1-55589-030-8 Pages: 15

15FTM19. Worm Gear Efficiency Estimation and Optimization

Authors: **Massimiliano Turci, E. Ferramola, F. Bisanti, G. Giacomozzi**

This paper outlines the comparison of efficiencies for worm gearboxes with a center distance ranging from 28 to 150 mm that have single reduction from 5 to 100:1. Efficiencies are calculated using several standards (AGMA, ISO, DIN, BS) or by methods defined in other bibliographic references.

It also deals with the measurement of torque and temperature on a test rig, required for the calibration of an analytical model to predict worm gearbox efficiency and temperature.

There are also examples of experimental activity (wear and friction measurements on a block-on-ring tribometer and the measurements of dynamic viscosity) regarding the effort of improving the efficiency for worm gear drivers by adding nanoparticles of fullerene shape to standard PEG lubricant.

ISBN: 1-55589-031-5 Pages: 15

15FTM20. Efficiency of Worm Gear Drives

Authors: **Eva-Maria Mautner, W. Sigmund, J.-P. Stemplinger, Karsten Stahl**

Due to a wide range of properties, worm gears are an indispensable element on the current transmission market. Next to a huge gear ratio field in one gear stage of $i = 5$ to $i = 80$, operation with low noise and vibration is realizable. Furthermore, worm gears provide the opportunity of self-locking, respectively self-braking. Despite these benefits, as a result of greater energy awareness, the efficiency of worm gears is in the focus. Because of high sliding velocities, especially at high gear ratios, gearing losses are a main topic of interest. Other gearbox concepts with combined spur and bevel gear sets show smaller gear ratio fields, and therefore the realization of high gear ratios in only one stage is not possible. Consequently, fewer components are necessary for worm gearboxes, which allows savings of assembly and maintenance costs.

In the scope of recent research projects, the efficiency and the load-carrying capacity of worm gears is examined. Therefore, experimental investigations on different worm gears were conducted on several test rigs. Generally, the pairing of bronze worm wheel with case-hardened worm is used in center distances between $a = 65$ and 315 mm. Additionally, the influence of different gear ratios, worm wheel materials, lubricants, and contact pattern on efficiency and load-carrying capacity are considered. In the course of these investigations, overall worm gearbox efficiencies of up to $\eta = 96\%$ are reached.

The paper describes the conducted tests in detail and shows basic examples of experimental test results. On the basis of the experimental investigations and theoretical examinations, recommendations for an increase in efficiency are given.

ISBN: 1-55589-032-2 Pages: 22

15FTM21. Polish Grinding of Gears for Higher Transmission Efficiency

Author: **Walter Graf**

This paper introduces a new gear polish grinding process and describes its multiple benefits to makers of automotive transmissions. First, based on independent scientific studies and customer trials, it will be shown that improved surface finishes increase the overall efficiency of transmissions, which translates into a reduction in torque loss, lower fuel consumption, and lower CO_2 output. The resulting higher bearing ratios reduce micro-pitting, and thus increase the longevity of gears. Secondly, the paper introduces a cost-efficient manufacturing method adapted for large-scale manufacture, as automotive transmission manufacturers need a more suitable method than the time-consuming vibration finishing used in aerospace applications today.

ISBN: 1-55589-033-9 Pages: 13

15FTM22. A New Class of Industrial Gear Oil

Authors: **David B. Gray, René Koschabek, Aidan Rose**

Industrial gear oils are a critical component in the efficient operation of modern equipment. More than 800 000 tons of these industrial gear oils are sold each year, which accounts for 5–6% of the total industrial lubricants market.

While industrial gear oils have not traditionally been the leading focus for lubricant development, the recent strong growth of wind turbines and field service performance has shifted the focus significantly in the direction of the industrial gear oils.

The challenging application for gearboxes in wind turbines has created demand for new high performance synthetic gear oils that provide both good equipment protection and longer drain intervals. While recent years have seen lubricant performance improvements, the highly fragmented landscape of OEM requirements and the complex approval processes have limited the application's attractiveness to those developing new lubricant formulations.

Today, however, the leading synthetic gear oils are based principally on polyalphaolefins (PAO), and while these lubricants are very effective and durable, they come at a significant cost penalty when compared to conventional mineral oils.

This has created an opportunity for a new class of industrial gear lubricants, based on alternative synthetic materials. These new industrial gear oils have been developed to satisfy critical market performance expectations, ensure global supply chain security, and to address economic as well as performance challenges.

This paper describes the technical aspects of this novel synthetic gear oil lubricant approach.

ISBN: 1-55589-034-6 Pages: 11

15FTM23. Noise Reduction in an EV Hub Drive Using a Full Test and Simulation Methodology

Authors: **Owen J. Harris, P.P. Langlois, G.A. Cooper**

With the current trend towards Electric Vehicles (EVs), there is likely to be increasing focus on the noise impact of the gearing required for the transmission of power from the electric motor (high speed) to the road. Current automotive Noise, Vibration and Harshness (NVH) understanding and methodologies for total in-vehicle noise presuppose relatively large Internal Combustion (IC) contributions compared to gear noise. Further, it may be advantageous to run the electric motors at significantly higher rotational speed than conventional automotive IC engines putting the gear trains into higher speed ranges. Thus, the move to EV or Hybrid Electric Vehicles (HEV) places greater or different demands on gear train noise.

This work combines both a traditional NVH approach (in-vehicle and rig noise, waterfall plots, Campbell diagrams, and Fourier analysis)—with highly detailed transmission error measurement and simulation of the complete drivetrain—to fully understand noise sources within an EV hub drive.

The transmission error testing has been performed on both the full assembly with the three-stage gear train and on individual gear pairs using a dedicated transmission error measurement rig. Highly accurate rotary encoders are used to measure transmission error through different stages of the gear train in order to identify sources of excitation.

For comparison, a full Computer-Aided Engineering (CAE) model has been built, which includes the flexibilities of all components, gears, shafts, bearings, and casing. Standard analysis is used to simulate the system deflection under input loads with corresponding gear misalignments, contact patches, and transmission errors. Contact patches are compared to tooth marking test results. Further, a novel advanced calculation is performed which iteratively couples deflections of the full system model with detailed tooth contact analysis at the gear meshes. This analysis shows how the gear meshes and the deflections of the full transmission change through the gear meshing cycles. This analysis can include detailed, measured, manufactured gear geometry, and various tolerances and errors within the system and calculate both the associated individual mesh and system transmission errors and their harmonic content.

Detailed test and simulation identifies the noise sources to be the meshes of the three gear sets and captures a full understanding of them. Methods are presented to accurately derive and compare the individual gear mesh transmission errors from test and simulation of the complete unit. Further analysis of the individual results indicates both gear design and manufacturing considerations to be optimized to reduce noise. The results of prototype testing of design changes are given showing significant in-vehicle noise reductions.

A detailed methodology is presented, combining both a full series of tests and advanced simulation to troubleshoot and optimize an EV hub drive for noise reduction.

ISBN: 1-55589-035-3 Pages: 22

15FTM24. Tribological Coating Wear and Durability Performance Guideline for Gear Applications

Authors: **Randy Kruse, Carl Hager, Ryan D. Evans**

Diamond-like carbon (DLC) tribological coatings have demonstrated the ability to provide gear and bearing performance enhancements in an initially narrow but increasing range of applications. These experiences have heightened awareness and curiosity in industry about the potential of DLC coatings to enhance the performance of gear train systems. Valuable benefits may include reducing the probability of micropitting wear and increasing scuffing resistance, perhaps even to enable improved oil-out performance in aerospace applications. The application of these coatings may be used to increase gearbox efficiency, not by reducing friction within tooth contacts, but by increasing tooth surface durability to allow for less viscous lubricants and reduced lubricant quantities.

It is generally known that extreme contact pressure and sliding velocity operating conditions can lead to coating wear. However, a better understanding of the thresholds that constrain coating durability and usefulness are needed so that gear and bearing engineers can more accurately specify and predict system life. This paper reports the results of testing a tungsten carbide-reinforced diamond-like carbon coating (W-DLC) as applied to AISI 4320 and AMS6308 gear materials using a rotating ball-on-disk tribology test rig under a range of conditions that simulate the contact stresses and sliding velocities of gears.

ISBN: 1-55589-036-0 Pages: 13

15FTM25. An Experimental Evaluation of the Procedures of the ISO/TR 15144 Technical Report for the Prediction of Micropitting

Authors: **Donald R. Houser, Samuel Shon**

This paper presents the results of several experimental analyses to explore some of the features and methodologies of ISO 15144. A summary of ISO 15144 is first discussed, as is a spreadsheet that has been written, to accept contact stresses calculated from load distribution analyses. Sample load distribution analyses and subsequent ISO predictions are made for several experimental results that are reported in the literature. Following these analyses, a series of experimental durability tests were run using the AGMA tribology gears running with Dexron 6 automatic transmission fluid as the lubricant. An FVA 54 test was run to obtain the lubricant pass/fail level and the permissible value of Lambda needed to calculate the safety factor for micropitting.

ISBN: 1-55589-037-7 Pages: 18

15FTM26. Calculating the Risk of Micropitting Using ISO Technical Report 15144-1:2014 – Validation with Practical Applications

Authors: **Burkhard Pinnekamp, Michael Heider**

Micropitting is a surface fatigue phenomenon on highly loaded gears with case-hardened gear flanks. Main contributors are local stress, surface roughness, sliding speed, and lube oil properties.

General influence factors, testing, and earlier calculation methods were described in 11FTM15 [1]. Meanwhile, a new version of the ISO Technical Report, TR 15144-1:2014 [2], was issued. It is intended to become an ISO Standard within the next years.

This paper describes the definition of micropitting, the actual calculation method, and its application to practical examples where micropitting has either occurred or not. The examples give evidence that the Technical Report reliably predicts the risk of micropitting where it is later found on the gear flanks. For cases where no micropitting occurs, the calculated safety factors are sufficiently high. Operating conditions for some examples are out of the validated range of the Technical Report.

ISBN: 1-55589-038-4 Pages: 16

15FTM27. Wear: A New Approach for an 'Old' Failure Phenomenon of Gears

Authors: **Ulrich Kissling, Sandro Hauri**

Wear is a well-known criterion of failure for gears. Wear is a result of metallic contact between the tooth flanks. But when a lubricant is involved, the wear-generating mechanism can be quite different. If the pitch line velocity is 0.5 m/s or higher, the lubrication film still has a dominant effect, the metallic contact is only partial, and the gears are running in the mixed-film or full EHL regime. At very low pitch line velocities (less than 0.5–1.0 m/s), the boundary lubrication prevails, and the metallic contact is dominant. The wear behavior in this case is completely different from wear occurring in mixed-film regime. Wear occurring at very slow speed is called in U.S. literature 'slow-speed wear' or 'adhesive wear' [1]. In German literature also, the term 'cold wear' [2] (in contrast to scuffing, which is sometimes called 'hot wear') is used. In this paper, slow-speed wear will be discussed, defined as the following: wear occurring either on lubricated gears at very low pitch line velocity or on dry-running gears.

Wear on gears is not an intensely researched topic, so little literature can be found. When compared with the exhaustive investigations carried out on other phenomena such as macropitting, scuffing, micropitting, or tooth flank breaking, it seems that slow-speed wear has literally been left out! But despite this, there are applications in heavy gear applications where wear is a criterion that cannot be ignored.

Worldwide, until 2014, only one standard existed, AGMA 925 [3], which describes wear and proposes a method to evaluate the risk of wear. As will be discussed further on, the wear described by AGMA 925 is the wear occurring in the mixed-film regime; wear at very slow speed is not covered by AGMA 925.

In a quite different area of application, wear is a very important topic—for dry running plastic gears. Over the past few years, the authors have worked closely with a number of manufacturers of plastic gears and the University of Erlangen (Germany) to investigate the problems of gear wear in detail. A calculation method could be developed that can be used to predict where and when local wear will occur on a tooth flank. Parts of these findings have also just been published in the final version of the German standard VDI 2736 [4].

The basic mechanics of slow-speed wear of metallic gears is the same as for dry-running plastic gears. However, the wear coefficients to be applied in each case are very different, and the influence of the lubricant (in particular, the effect of the lubricant additives) is crucial. In 1980, at the FZG in Munich, Plewe [5] published investigations of the adhesive wear behavior of lubricated metallic gears (pitch line velocities 0.007–1.0 m/s). The wear coefficients were determined for additive-free oil. However, a "factor for the influence of lubrication" is required before Plewe's data can be used for a modern gear lubricant, and up to now, very little is known about these factors.

If the wear coefficient is known, the distribution of wear can be defined over the tooth contact area in the contact analysis. If the step-by-step change in the tooth flank (due to wear) is then also taken into account, a realistic prediction of the progression of wear and its effects on noise and vibrations can be made.

ISBN: 1-55589-039-1 Pages: 15

15FTM28. Application of Advanced Mesh Analysis to Eliminate Pinion Failures

Author: **Terry Klaves**

This paper will walk through a case study involving pinion failures on plastic extruder drives. It will cover failure analysis, gear rating review, application of advanced mesh analysis to define component deflections causing loaded mesh misalignment, and reduced tooth contact/high stress concentration resulting in tooth macropitting. The paper will demonstrate the capability and benefits of advanced mesh analysis, including design of optimized microgeometry and application of said microgeometry through precision tooth form grinding, with recommendations on types of microgeometry which are most effective, easiest to apply, inspect, and document in a production gear manufacturing environment. The summary will review tools which are commercially available to perform advanced mesh analysis, design, manufacture, and inspect optimized microgeometry—which compensates for tooth deflection, shaft bending, torsional windup, and bearing deformation in order to improve gearing mesh alignment and tooth contact under load for quiet running and longer life gearing. This tool can be applied proactively at the design phase to optimize gearing performance or reactively to identify root cause of failures and recommend corrective action.

ISBN: 978-1-55589-042-1 Pages: 10

15FTM29. Tooth Flank Fracture – Influence of Macro and Micro Geometry

Author: **Stefan Beermann**

In this paper, the method to calculate the risk of tooth flank fracture, which is defined in the current draft of ISO DTS 19042-1, is investigated and discussed. Part of this investigation is a sensitivity analysis with respect to the main gear parameters. Therefore, parameters including pressure angle, helix angle, normal module, hardness depth, tip relief, and crowning were systematically varied and the respective safety factor against tooth flank fracture was calculated.

With this method, it can be shown that the risk of tooth flank fracture and the risk of pitting might have opposite trends. It is also shown that a tip relief on spur gears typically has no effect or might even increase the risk of tooth flank fracture. On helical gears, the situation is more complex. For lead modifications, a certain beneficial effect is seen by compensating misalignments of the flanks; however, if the modification chosen is too large, it will increase the risk of tooth flank fracture.

In the first part of the paper, some formulas of the draft are discussed. There, it is shown that the definition of the material factor and the calculation of the course of the hardness into the depth of the material could be improved.

ISBN: 1-55589-043-8 Pages: 11

2014 PAPERS

14FTM01 Molecular Decomposition Process = Electrochemical Assisted Precision Form Grinding

Author: **J.A. DeAngelo**

Molecular decomposition process (MDP) is an anodic dissolution process (electrochemical) whereby the work piece is the anode and the grinding wheel is the cathode. Specific controls of electrical, mechanical and chemical actions are applied to enable the MDP system to remove stock without mechanical or thermal deformation. This process enables stock removal rates in sample materials such as nickel and titanium alloys to occur at rates more aggressively than conventional creep-feed grinding. Migrating the system to employ super-abrasives greatly increases the rate of stock removal. The anodic process implemented permits the perishable wheel geometry to be preserved which equates to longer perishable life and dimensional stability, which enables longer production runs with consistent dimensional results.

MDP has proven to produce gear involute geometries from “as supplied” blanks with minimal stock for finishing. Roughing and finishing of forms in full hardened 4140 tool steel yielding an MDP produced product with surfaces to less than 1 Ra µin while maintaining dimensional stability to achieve a 1.67 CPK. The MDP system removes large or small amounts of stock while providing a safe work environment for operators and the environment.

ISBN: 1-61481-093-3 Pages: 11

14FTM02 Prediction of Surface Zone Changes in Generating Gear Grinding

Authors: **F. Klocke, M. Brumm, J. Reimann, M. Ophey**

One possible process for hard finishing gears is generating gear grinding. Due to high process efficiency generating gear grinding has replaced other grinding processes like profile grinding in batch production of small and middle sized gears.

Despite the wide industrial application of generating gear grinding, the process design is based on experience and time and cost intensive trials. The science-based analysis of generating gear grinding needs a high amount of time and effort and only a few published scientific analyses exist. In addition, the transfer of existing knowledge from other grinding processes onto generating gear grinding is complicated due to the contact conditions between tool and gear flank, which change continuously during the grinding process.

One research objective for generating gear grinding is to increase economic efficiency and productivity of the process. At the same time gear quality must be equal or higher and the external zone must not be damaged. But especially the influence of the grinding process on the external zone in generating gear grinding is unknown. In case of an inappropriate process design in combination with stock deviations an unrequested process result or even a thermal damage of the external zone can occur. In this report a thermo-mechanical process model, which describes influences on the surface zone in generating gear grinding, is introduced.

ISBN: 1-61481-094-0 Pages: 15

14FTM03 Surface Roughness Measurements of Cylindrical Gears and Bevel Gears on Gear Inspection Machines

Author: **G. Mikoleizig**

Alongside the macro test parameters on tooth flanks for profile and tooth traces, surface properties (roughness) play a decisive role in ensuring proper toothed gear function.

The generally increased load stresses on gear teeth can only be implemented by maintaining precisely defined roughness parameters.

Roughness measurements are therefore conducted on the gearing flanks in all highly developed drives, in the automotive industry, aircraft industry, or the area of wind energy drives, for example.

This article addresses roughness measurement systems on tooth flanks. In addition to universal test equipment, modified test equipment based on the profile method for use on gears is addressed in particular. The equipment application here refers to cylindrical gear flanks and bevel gear flanks.

ISBN: 1-61481-095-7 Pages: 13

14FTM04 Reliable Measurements of Large Gears

Authors: **M. Stein, K. Kniel, F. Härtig**

Large gears have become an indispensable part of modern technical applications. The expanding industrial sectors of power generation and transmission, like shipbuilding industry, wind turbine generators and petroleum conveying systems, have led to an increasing demand for large scale gear boxes. Thus, the qualified measurement of large gears has become more and more important as well. Their conformance with specifications according to ISO 14253-1 [1] has to be proved, which is not possible without a qualified statement of the task-specific measurement uncertainty. As a consequence, the manufacturing processes cannot be controlled quantitatively and at a reasonable process capability level, especially if tolerances are small compared to the achievable measurement uncertainty. This specifically applies to large gears.

In this report three current projects are outlined and presented with a comparison for large involute gears. The measurement results are presented. As a second step towards traceable measurements of large gears, a special calibration laboratory shall be established. This is part of a joint research project, within which also a new measurement standard of 2 m in diameter has been developed. Lastly, information about a Joint Research Project within the European Metrology Research Program which will start in September 2014 is provided.

ISBN: 1-61481-096-4 Pages: 10

14FTM05. A Different Way to Look at Profile and Helix Inspection Results
Author: **J.M. Rinaldo**

The traditional inspection of involute gear profile and helix deviations results in plots of deviations from a perfect involute and from a perfect helix. While this is appropriate for gears with an unmodified profile or helix, it is not ideal for gears that have intentional modifications. This paper explores the advantages of looking directly at deviations from the design shape. This type of analysis is implied but not explicitly stated nor is it pictured in the new edition of ISO 1328-1. Also presented is a modification to zone based tolerance evaluation as presented in ISO 1328-1:2013, with limits on the total deviation from design given graphically.

ISBN: 1-61481-097-1 Pages: 7

14FTM06. High Contact Ratio Gearing: A Technology Ready for Implementation?
Author: **C.D. Schultz**

Today's competitive industrial gear marketplace demands products with excellent reliability, high capacity, and low noise. Surface hardened ground tooth gearing predominates but the legacy tooth forms handicap further improvements in capacity and noise generation. Vehicle and aircraft equipment use tooth forms not found in the standard charts to achieve better performance at little or no increase in cost. This paper will propose adopting these high contact ratio forms to industrial use.

ISBN: 1-61481-098-8 Pages: 13

14FTM07. A Case Study in a Practical Application of Smart Gearbox Technology
Author: **A.J. Soder**

The purpose of the paper is to discuss the development of smart gearbox technology using real-world application testing and data analysis, while keeping in mind the needs of the end-user in order to assist them in developing their monitoring system. It will describe the previous maintenance methodologies used and how the ever-changing needs of the industry require them to introduce a proactive maintenance system rather than a typically reactive approach.

It will explain the testing performed at the user's facility which helps gather the data that cannot be duplicated on a test system. It will then explain how after all the data is reviewed and analyzed, it is then relayed back to the user so it can be implemented by their maintenance departments. It will discuss reviewing the data of a failed gearbox during testing and how looking at the data can give a glimpse of how to understand what the data is telling us in regards to the end goal of the project

ISBN: 1-61481-099-5 Pages: 11

14FTM08. The Efficiency of a Simple Spur Gearbox – A Thermally Coupled Lubrication Model
Authors: **A.I. Christodoulias, A.V. Olver, A. Kadiric, A.E. Sworski, F.E. Lockwood**

A thermally coupled efficiency model for a simple dip-lubricated gearbox is presented. The model includes elastohydrodynamic friction losses in gear teeth contacts as well as bearing, seal and churning losses. An iterative numerical scheme is used to fully account for the effects of contact temperature, pressure and shear rates on EHL friction. The model is used to predict gearbox efficiency with selected transmission oils whose properties were first obtained experimentally through rolling-sliding tribometer tests under representative contact conditions.

Although the gearbox was designed using standard methods against a fixed rating, the model was used to study efficiency over a much wider range of conditions. Results are presented to illustrate the relative contribution of different sources of energy loss and the effect of lubricant properties on the overall gearbox efficiency under varying operating conditions.

ISBN: 1-61481-100-8 Pages: 18

14FTM10. Involute Spiral Face Couplings and Gears: Design Approach and Manufacturing Technique
Authors: **A.L. Kapelevich, S.D. Korosec**

Face gears typically have a straight or skewed tooth line and varying tooth profile in normal cross section at different radii from major to minor diameter. These face gears are engaged with spur or helical involute pinions at intersecting or crossed axes.

This paper presents spiral face gears with involute tooth line and identical tooth profile in the normal section at any radius. There are two main applications for such face gears. One of them is an alternative solution with certain advantages in performance and fabrication technology to the straight tooth, Hirth, or Curvic flange couplings. Another application is when a face gear is engaged with an involute helical pinion or worm at intersecting or crossed axes. Such engagement is also used in Helicon® type gears.

The paper describes gear geometry analysis, and design technique of spiral face involute gears with symmetric and asymmetric tooth profiles. It also explains a highly productive hobbing method of these gears and tool design specifics, and illustrates gear and tool design with numerical examples.

ISBN: 1-61481-102-2 Pages: 9

14FTM11. Mathematical Modeling for the Design of Spiroid®, Helical, Spiral Bevel and Worm Gears

Author: **G. Kazkaz**

This paper will present a novel work for spiroid and worm gears that mathematically calculates the gear tooth profile in terms of the geometry of the machining tool (hob) and the machining setup. Because of similarity, the work was also expanded to spiral bevel gear. We have developed software to plot the gear tooth when the parameters of the geometry of the tool and machining setup are entered. The gear tooth shape can then be altered and optimized by manipulating the input parameters until a desired tooth profile is produced. In effect, the result will be designing the hob and machining setup for best gear tooth profile on the computer. Afterward, the generated gear tooth data are entered into CAD software to generate a true 3D model of the gear. The tool path will also be generated from the data for CNC machining instead of hobbing.

ISBN: 1-61481-103-9 Pages: 16

14FTM12. Optimization of Gear Tooth Contact by Helix Angle Modification

Authors: **S. Hipsley, R.J. Davey, R.T. Wheway**

This paper reports the results of a study of the effects of helix angle modification on the load distribution and stresses within teeth of helical gears, and the calculation of appropriate compensation for torsional effects.

Load distribution and peak stress for helical gears under normal torsional forces inherent in helical gear drives are significantly influenced by the flexibility of the gear body, tooth structure and elastic deformation of the contact surfaces. Uncompensated, these factors reduce the gear face contact area and accordingly increase maximum stress and decrease pitting resistance and bending strength power ratings.

This paper transforms the calculation of the compensation required by translating the underlying analysis into a MATLAB based program that can be run on a modest, standard PC computer. Informed practicing engineers – as opposed to esoteric experts in whose domain these calculations currently reside – now have a tool to do the necessary calculations with ease.

The results from the program are confirmed by FEA analysis of compensated and uncompensated examples, together with a practical example with an operating, 3,000 kW gearbox. The results show that the program produces the appropriate adjustment, such that the contact areas are full width across the gear faces. The authors' recommendation is, now that a user-friendly analysis tool is available, that helix angle compensation should be included in rating standards.

ISBN: 1-61481-104-6 Pages: 13

14FTM13. A Practical Approach for Modeling a Bevel Gear

Author: **B. Bijonowski**

The modern bevel gear design engineer is often faced with knowing the basic appearance of the bevel gear tooth that he is designing. The geometry of the bevel gear is quite complicated to describe mathematically, and much of the overall surface topology of the tooth flank is dependent on machine settings and the cutting method employed. AGMA 929-A06, Calculation of Bevel Gear Top Land and Guidance on Cutter Edge Radius, lays out a practical approach for predicting the approximate top land thicknesses at certain points of interest regardless of the exact machine settings that will generate the tooth form. The points of interest that AGMA 929-A06 is concerned with consists of toe, mean, heel, and the point of involute lengthwise curvature.

The following method expands upon the concepts described in AGMA 929-A06 to allow the user to calculate not only the top land thickness, but the more general case, the normal tooth thickness anywhere along the face and profile of the bevel gear tooth. This method does not rely on any additional machine settings; only basic geometry of the cutter, blank, and teeth are required to calculate fairly accurate tooth thicknesses. The tooth thicknesses are then transformed into a point cloud describing both the convex and concave flanks in a global Cartesian coordinate system. These points can be utilized in any modern computer aided design software package to assist in the generation of a 3D solid model. All pertinent macro tooth geometry can be closely simulated using this technique. Furthermore, a case study will be presented evaluating the accuracy of the point cloud data to a physical part.

ISBN: 1-61481-105-3 Pages: 17

14FTM14. Theoretical and Experimental Study of the Frictional Losses of Radial Shaft Seals for Industrial Gearbox

Authors: **M. Organisciak, P. Baart, S. Barbera, A. Paykin M. Schweig**

In this paper SKF presents an engineering model for the prediction of radial lip seal friction based on a physical approach. The friction model includes the generation of friction due to rubber dynamic deformation and lubricant viscous shear between the surfaces of a seal and a shaft. The friction model is coupled with a heat generation and seal thermal model. Indeed, seal friction and seal temperature are closely related: the heat generated in the sealing lip is conducted through the seal and shaft and dissipated into the environment. This changes for instance the lubricant viscosity.

The model is verified step by step in an extensive experimental study. Measurements of seal friction, seal temperature and lubricant film thickness have been performed for various dynamic lip seals. The analyzed parameters are: surface speed, oil viscosity, seal material, seal size, seal lip style and duty cycles. The correlation between model predictions and experimental friction measurements can therefore be verified.

ISBN: 1-61481-106-0 Pages: 12

14FTM15. Application of a Unique Anti-Wear Technology – Ion-Sulfurized Lubricating Gradient Material

Authors: **G. Wang, Y. Zhang, X. Zhang, H. Liu**

This Ion-sulfurization, also called plasma sulfurization, is a state-of-the-art technology conferring excellent anti-friction and wear-resistant characteristics on metallic parts including gears, splines, and bearings. It is characterized by a sulfur-proliferated zone composed of sulfides and sulfur-metal solid solution case with smooth sulfur compositional gradient towards the underlying substrate. Varity of metals and alloys, including steels, cast irons, super-hard alloys, and bronze, are suitable for ion-sulfurization. This treatment is carried out at low temperature, so that geometric integrity, microstructure and mechanical characteristics of the substrate are not impaired. Ion-sulfurized gears and bearings shorten the run-in time span of the machinery/automotive units. Even more, the contact fatigue in gears and splines can be noticeably reduced. Another distinguished engineering advantage is, the tribological property of the sulfide layer on steel can survive a temperature as high as 2000°F, which is rarely surpassed by other lubricants.

In this article, the engineering characteristics of ion-sulfurization are introduced. Exemplary application is provided as reference for those interested in this technology

ISBN: 1-61481-107-7 Pages: 13

14FTM16. The Modified Life Rating of Rolling Bearings – A Criterion for Gearbox Design and Reliability Optimization

Authors: **A. Doyer, A. Gabelli, G. Morales-Espejel**

This The concepts of rolling bearing rating life and basic load rating (load carrying capacity) were introduced by Arvid Palmgren in 1937 [1]. At that time, until the 1950s, most bearing manufacturers listed in their catalogues the load admissible on the bearing for thousands hours of operation at five different speeds. In those days the selection of a bearing size for a given application was a rather simple and approximate matter.

The concept of a single rating factor to characterize the dynamic capacity of the bearing was new and initially used only within the bearing company that developed this new technology. This rating method was backed by the theory of Lundberg & Palmgren (L-P) [2] and by the Weibull statistics [3]. It was found that it could provide a correct interpretation of the many series of endurance tests available at the time, [2], [4], [5]. This calculation method prevailed on all the others methods used at the time and was adopted by ISO in 1962.

ISBN: 1-61481-108-4 Pages: 16

14FTM17. The Impact of Surface Condition and Lubricant on Gear Tooth Friction

Authors: **S. Rao, A. Isaacson, G. Sroka, L. Winkelmann**

Frictional losses in gear boxes are of significant interest to gear box designers as these losses transform into heat. The direct result is a reduction in the fuel efficiency of the vehicle involved. Further, in many instances, this heat has to be absorbed and dissipated so that lubricant properties and gear box performance are not significantly compromised. This effort is to measure and document the comparative friction losses in a gear mesh due to gear tooth surface condition and lubricant. Three distinct surface conditions are considered. They are ground, Isotropic Superfinished (REM ISF®) and tungsten-incorporated diamond-like carbon coating (W-DLC). Two lubricants, MIL-PRF-23699 and Mobil SHC 626 lubricants are considered.

The experimental effort is conducted on a high speed, power re-circulating (PC), gear test rig, which had been specially instrumented with a precision torque transducer to measure input torque to the 4-square loop. The torque required to drive the loop is measured under various speeds and tooth loads within the torque loop, with test gears with different surface conditions and with different lubricants. Two operating torque levels within the 4-square loop at speeds ranging from 4,000 rpm (pitch-line velocity of 19 m/sec) to 10,000 rpm (pitch-line velocity of 47 m/sec) are evaluated.

Based on the collected data a qualitative analysis of the effect of gear tooth surface condition on frictional losses is presented. Further, the surface characteristics of the tooth flanks of the ground, superfinished and coated gears are also described.

ISBN: 1-61481-109-1 Pages: 9

14FTM18. Precision Bevel Gears with Low Tooth Count

Authors: **S.P. Radzevich, V.V. Irigireddy**

The paper deals with the geometry and kinematics of right-angle bevel gears that feature low tooth count. Right-angle bevel gears are a particular case of intersected-axis gearing (further I_a - gearing) with an arbitrary value of shaft angle. In this paper, gears that have 12 teeth and fewer are referred to as the low-tooth-count-gears (or LTC - gears, for simplicity).

When operating, right-angle bevel gears often generate vibration and produce an excessive noise. Dynamic loading of the gear teeth can result in the tooth failure. These problems become more severe in bevel gearings with low tooth count. The performed analysis shows that inequality of base pitches of the gear and mating pinion is the root cause for insufficient performance of LTC - gears.

In most applications, the main purpose of I_a - gearing is to smoothly transmit a rotation and torque between two intersected axes. Gear pairs that are capable of transmitting a uniform rotation from the driving shaft to the driven shaft are referred to as the geometrically accurate intersected-axis gear pairs (or, in other words, the ideal intersected-axis gear pairs).

ISBN: 1-61481-110-7 Pages: 12

14FTM19. Application of ICME to Optimize Metallurgy and Improve Performance of Carburizable Steels

Authors: **J. Grabowski, J. Sebastian, A. Asphahani, C. Houser, K. Taskin, D. Snyder**

QuesTek Innovations LLC has applied its Materials by Design® computational design technology and its Integrated Computational Materials Engineering (ICME)-based methods to successfully design, develop and implement two new high-performance gear steels (Ferrium® C61™ and Ferrium C64® steels) that are being used in demanding gear and bearing applications in ground and aerospace military, commercial aerospace, high-performance racing, oil & gas and other industries. Additionally, QuesTek has successfully designed and developed two new high-performance structural steels (Ferrium S53® and Ferrium M54® steels). All four Ferrium alloys are commercially available from Carpenter Technology and have been awarded SAE AMS numbers for procurement. QuesTek has also designed several other high performance alloys using ICME technologies, including a stainless nitridable bearing and gear steel and alloys for additive manufacturing applications.

ISBN: 1-61481-111-4 Pages: 10

14FTM20. Influence of Central Members Radial Support Stiffness on Load Sharing Characteristics of Compound Planetary Gear Sets

Authors: **Z. Peng, S. Wu**

In this study, a non-linear dynamics model of Ravigneaux compound planetary gear set which adopts the intermediate floating component is set up based on concentration parameter. By considering the position errors and eccentric errors, the dynamic load sharing factors of the gear set are calculated. The relationship between central members radial support stiffness and the dynamic load sharing factors is obtained and the influence of central members radial support stiffness on load sharing characteristic is analyzed. The research results show that central members radial support stiffness effect obvious to the gear pairs which are directly contacted to the central members, while the effect is rather small to the gear pairs which are not directly connected. Reducing the radial support stiffness of the central members helps improve the load sharing performance of the system.

ISBN: 1-61481-112-1 Pages: 12

14FTM21. On the Correlation of Specific Film Thickness and Gear Pitting Life

Author: **T. Krantz**

The effect of the lubrication regime on gear performance has been recognized, qualitatively, for decades. Often the lubrication regime is characterized by the specific film thickness defined as the ratio of lubricant film thickness to the composite surface roughness. It can be difficult to combine results of studies to create a cohesive and comprehensive dataset. In this work gear surface fatigue lives for a wide range of specific film values were studied using tests done with common rigs, speeds, lubricant temperatures, and test procedures. This study includes previously reported data, results of an additional 50 tests, and detailed information from lab notes and tested gears. The dataset comprised 258 tests covering specific film values [0.47 to 5.2]. The experimentally determined surface fatigue lives, quantified as 10-percent life estimates, ranged from 8.7 to 86.8 million cycles. The trend is one of increasing life for increasing specific film. The trend is nonlinear. The observed trends were found to be in good agreement with data and recommended practice for gears and bearings. The results obtained will perhaps allow for the specific film parameter to be used with more confidence and precision to assess gear surface fatigue for purpose of design, rating, and technology development.

ISBN: 1-61481-113-8 Pages: 18

2013 PAPERS

13FTM01. Power Skiving of Cylindrical Gears on Different Machine Platforms

Author: **H.J. Stadtfeld**

Skiving is a cutting process which was first patented in 1910 as an efficient process to manufacture internal ring gears. Like honing, Power Skiving uses the relative sliding motion between two “cylindrical gears" whose axes are inclined. The skiving cutter looks like a shaping cutter with a helix angle for example, 20° different than the helix angle of the cylindrical gear to be machined.

The skiving process is multiple times faster than shaping and more flexible than broaching, due to the continuous chip removal in skiving, but it presents a challenge to machines and tools. While the roll motion between the cutting edge and the gear slots occurs with the spindle RPM, the relative axial cutting motion is only about one third of the circumferential speed of the cutter. The cutting components of rolling and cutting which result in a "spiral peeling" are represented with the process designation skiving.

Because of the relatively low dynamic stiffness in the gear trains of mechanical machines as well as the fast wear of uncoated cutters, skiving of cylindrical gears never achieved a breakthrough against shaping or hobbing until recently. The latest machine tools with direct drive train and stiff electronic gear boxes present an optimal basis for the skiving process. Complex tool geometry and the latest coating technology were required to give the soft skiving of cylindrical gears a breakthrough. Gleason has developed a line of dedicated power skiving machines, which apply solid HSS cutters for small to medium modules.

ISBN: 1-61481-058-2 Pages: 18

13FTM02. Performance and Technological Potential of Gears Ground by Dressable cBN Tools

Authors: **J. Reimann, F. Klocke, M. Brumm, A. Mehr and K. Finkenwirth**

Dressable vitrified bond cBN grinding tools combine the advantages of other common tool systems in generating gear grinding. The cBN grains are a highly productive cutting material due to their high specific stock removal rate. Vitrified bonds are dressable and thereby very flexible: By dressing different profile modifications can be set up and constant gear quality can be guaranteed during the tool life time. Despite those technological advantages there is only a small market distribution of these grinding tools due to high tool costs. Furthermore, only a few published scientific analysis of generating gear grinding with dressable cBN exist. Especially, the influence of the grinding tool system on manufacturing related component properties has not been analyzed yet. The research objective of this report is to determine the advantages of dressable cBN tools in generating gear grinding.

ISBN: 1-61481-059-9 Pages: 12

13FTM03. Analysis of Gear Root Forms: A Review of Designs, Standards and Manufacturing Methods for Root Forms in Cylindrical Gears

Authors: **N. Chaphalkar, G. Hyatt, and N. Bylund**

Gear root is an important but often neglected element of the gear. The stress concentration point typically lies in the tooth to root transition area and it is this point that determines the life or the fatigue life of a gear in many applications. Specific standards are in place on design of the involute part of a gear tooth, the root area however is less standardized. New manufacturing methods enable the designer of gears greater latitude in the design of strong alternative root forms. The standards on design and specification for the root geometry are lax so these root forms fit into current standards.

This paper reviews the designs of various root forms for the gears. It compares the various root forms on basis of their strength, fatigue resistance and other parameters. This analysis will be based on compilation of various research previously conducted on gear root forms.

The paper also discusses current manufacturing methods to produce the roots, and recently introduced alternatives. It will compare the traditional methods with new methods of gear manufacturing it terms of types of roots produced and overall control over the root profile.

ISBN: 1-61481-060-5 Pages: 9

13FTM04. Best Practices for Gearbox Assembly and Disassembly

Author: **J. Bello**

When industry is looking at the best ways to increase efficiency, reduce downtime and increase profitability, gearbox performance and reliability are key factors. In most applications gearbox reliability is critical to the productivity of the overall plant operation. Repair is often required with a swift turn around, as down time is very expensive. Designing for repair, and writing effective repair procedures, can speed the service time, and provide a quality refurbishment. Minimizing down time and extending service life will contribute significantly to achieving the lowest overall operation costs.

The best practices listed below are proven, effective methods used to install and remove bearings, seals, gears, couplings and shafts within a gearbox. These techniques are not new, and are usually obtained by hard won experience. Collecting them in one location is an attempt to document the best practices and provide a reference for design engineers. Engineers write the procedures for assembly and disassembly, they also dictate to the rest of the design team the design intent. Including features to facilitate disassembly, minimizes repair cycle time and helps to prevent damage to components that could radically compromise their design life or performance.

ISBN: 1-61481-061-2 Pages: 11

13FTM05. Cubitron™ II: Precision Shaped Grains (PSG) Turn the Concept of Gear Grinding Upside Down

Author: **W. Graf**

To date, grinding, according to the German DIN Standard 8580, is “machining with geometrically undefined cutting edges" while other machining processes such as turning and milling are classified as processes with “geometrically defined cutting edges". New abrasive grains, called PSG and developed by 3M, stand this definition on its head. For the first time, grinding wheels made with PSG, called Cubitron™ II, can claim to be made up of “geometrically defined cutting edges" as each and every grain is exactly the same engineered shape. Hence, it might be more appropriate to talk about “micro-milling" rather than grinding. This is borne out by looking at the resulting “flowing" chips which are akin to chips seen in milling operations, just finer.

These free-flowing chips no longer clog up the grinding wheel and, therefore, the grinding wheel remains free-cutting and dressing becomes only necessary due to loss of from rather than loss of cutting ability. In repeated tests, this has shown to drastically reduce the risk of burning and to give consistent and predictable results. Furthermore, tests and subsequent long term trials under production conditions have shown that grinding time can be cut in most cases by at least 50% in comparison to grinding wheels made of standard ceramic abrasives.

Based on more than 100 carefully monitored and documented gear grinding trials, this paper will demonstrate how Cubitron™ II grinding wheels work both in continuous generating grinding of car and truck gears, and in form grinding of large diameter gears for wind generators, for example. Furthermore, the paper will discuss chip formation, filmed with high resolution slow motion; and the benefits of the free-flowing chips in terms of resulting consistent surface finish, superior form holding and extended dressing cycles.

ISBN: 1-61481-062-9 Pages: 10

13FTM06. High Gear Ratio Epicyclic Drives Analysis

Author: **A. Kapelevich**

Epicyclic gear stages provide high load capacity and compactness to gear drives. There is a wide variety of different combinations of planetary gear arrangements [1, 2]. For simple epicyclic planetary stages when the ring gear is stationary, the practical gear ratio range varies from 3:1 to 9:1. For similar epicyclic planetary stages with compound planet gears, the practical gear ratio range varies from 8:1 to 30:1.

This paper presents analysis and design of epicyclic gear arrangements that provide extremely high gear ratios. Using differential-planetary gear arrangements it is possible to achieve gear ratios of several hundred to one in one-stage drive with common planet gears and several thousand to one in one-stage drive with compound planet gears. A special two-stage planetary arrangement may utilize a gear ratio of over one hundred thousand to one.

This paper shows an analysis of such uncommon gear drive arrangements, defines their major parameters, limitations, and gear ratio maximization approaches. It also demonstrates numerical examples, existing designs, and potential applications.

ISBN: 1-61481-063-6 Pages: 12

13FTM07. Finite Element Analysis of a Floating Planetary Ring Gear with External Splines

Authors: **V. Kirov and Y. Wang**

This study investigates the stresses and deflections of a floating ring gear with external splines working in a large planetary wheel motor of a mining truck. Such calculations carried out with conventional engineering approaches described in popular standards and textbooks are not comprehensive because of the complexity of the problem. These approaches can give us good stress numbers for non-floating gears and some guidance about the rim thickness factor but they lack the capabilities to effectively calculate the deflections and their influences on the stresses, especially for floating gears. Moreover, they cannot calculate an entire gearing system and the interdependent influences of the different components.

The model studied consists of a floating ring gear driving a torque tube. The ring gear is driven through internal gear meshing by three planets and it transmits the torque to the torque tube through its external splines. The torque tube transmits the motion to the hub and the truck tires. A nonlinear static analysis of the ring gear and torque tube was conducted in ABAQUS. Linear 8-node hex elements and linear tetra elements were used to model the ring gear and torque tube. External torque was resolved into corresponding tangential force, which was then applied directly onto three of the ring gear's internal teeth. Contact pairs were used to capture the load transfer between the ring gear and torque tube through the splines.

The results show that the deflections in the ring gear were so excessive that about one-tenth of the spline teeth were actually transmitting torque against the common engineering understanding that only half of the spline teeth are typically engaged. The crowning of the spline teeth had also effect on the stresses though quite small compared to the deflections. Conclusions and recommendations were made about the effectiveness of the design.

ISBN: 1-61481-064-3 Pages: 11

13FTM08. Application and Improvement of Face Load Factor Determination Based on AGMA 927 (Accurate and Fast Algorithm for Load Distribution Calculation, for Gear Pair and Planetary Systems, Including Duty Cycle Analysis)

Author: **U. Kissling**

The face load factor $K_{H\beta}$, which in rating equations represents the load distribution over the common face width in meshing gears, is one of the most important items for a gear strength calculation. In the international standard for cylindrical gear rating, the ISO 6336-1, using method C, some formulas are proposed to get a value for this factor. But as the formulas are simplified, the result is often not very realistic. Also AGMA 2001 (or AGMA 2101) proposes a formula for $K_{H\beta}$, different from ISO 6336, but again not always appropriate. Therefore, a note in AGMA stipulates, that "it may be desirable to use an analytical approach to determine the load distribution factor".

In the last edition of ISO 6336 (2006), a new annex E was added: "Analytical determination of load distribution". This annex is entirely based on AGMA 927-A01. It is a well-documented procedure to get a direct and precise number for the face load factor. Today an increasing number of gear designers are using tooth contact analysis (TCA) methods to get precise information over the load distribution on the full gear flank. Contact analysis is very time consuming and does not permit to get a value for $K_{H\beta}$, as defined by the ISO or AGMA standard. A contact analysis result combines different factors of ISO 6336 as $K_{H\beta}$, $K_{H\alpha}$, Z_ε, Z_β, Z_B, Z_D and buttressing effects, etc., thus to `extract' $K_{H\beta}$ from a TCA is not possible.

The use of the algorithm, as proposed by AGMA 927, is a good solution to get proper values for $K_{H\beta}$; it is simpler and therefore much quicker than a contact analysis calculation. The paper explains how this algorithm can be applied for classic gear pair rating procedure, for ratings with complex duty cycles and even for planetary systems with interdependent meshings between sun, all planets and ring.

ISBN: 1-61481-065-0 Pages: 19

13FTM09. Investigations on Tooth Root Bending Strength of Case Hardened Gears in the Range of High Cycle Fatigue

Authors: **N. Bretl, S. Schurer, T. Tobie, K. Stahl and B.-R. Höhn**

Tooth root load-carrying capacity is one of the determining factors in gear design. In addition to the strength of the material itself, the existing state of stress significantly influences tooth root load-carrying capacity.

Based on extensive experimental investigations of gears, the beginning of the fatigue strength range is generally set 3×10^6 load cycles, which common calculation methods, like ISO 6336, also take into account. According to this, standard test methods for tooth root bending endurance strength usually assume a load cycle limit of 3-6 10^6.

However, current as well as completed studies on tooth root load carrying capacity show tooth root fractures with relatively high numbers of load cycles in a range of general fatigue strength and above. Analysis of these fracture surfaces shows that these late breakages are often initiated by small inclusions or microstructural defects in the material. These tooth fractures that initiate with cracks under the surface have a negative effect on the tooth root load-carrying capacity in the range of high cycle fatigue. Therefore, experimental investigations regarding high cycle fatigue have been carried out in a pulsator test rig on gears of various sizes, materials and residual stress conditions. As a result, depending on the existing residual stress condition, there are different levels of tooth root load carrying capacity, different failure behaviors in high cycle fatigue and different types of damage. Especially for test variants with high residual stresses, the size of the gear and the cleanness of the material have an impact on the tooth root load-carrying capacity and the damage pattern.

This paper discusses the different fracture modes by means of examples. Furthermore, it presents the influence of residual stresses, size and material cleanness on the tooth root load-carrying capacity and on the type of tooth root fractures with crack initiation on and under the surface. These influences will be additionally confirmed by examples of experimental test results.

ISBN: 1-61481-066-7 Pages: 16

13FTM10. Calculation of the Tooth Root Load Carrying Capacity of Beveloid Gears

Authors: **C. Brecher, M. Brumm and J. Henser**

In this paper, two developed methods of tooth root load carrying capacity calculations for beveloid gears with parallel axes are presented. The first method calculates the tooth root load carrying capacity in an FE-based approach. The initial step of the method is the manufacturing simulation in the WZL software GearGenerator. The manufacturing simulation calculates the 3D geometry of the beveloid gears by simulating the generating grinding process. The next step is an FE-based (finite element) tooth contact analysis with the WZL software ZaKo3D which is able to calculate the tooth root stresses of several gear types during the meshing. From these stresses and further parameters (e.g., local material properties) the tooth root load carrying capacity is calculated in an approach which is based on the weakest link model of Weibull.

The second method uses analytic formulas to calculate the tooth root load carrying capacity of beveloid gears. In this method the tooth root load carrying capacity of beveloid gears is compared to the tooth root load carrying capacity of cylindrical gears. The effects which are observed during this comparison are described and formulas are derived to take these effects into account. Finally, both methods are applied to a test gear. The methods are compared to each other and to tests on beveloids gears with parallel axes in test bench trials.

ISBN: 1-61481-067-4 Pages: 19

13FTM11. Striving for High Load Capacity and Low Noise Excitation in Gear Design

Authors: **K. Stahl, M. Otto and M. Zimmer**

In the design process of gearboxes, common requirements are high load capacity and low noise excitation. Reaching both goals is laborious and normally requires a trade-off. Detailed analyses of contact conditions and deformations are necessary. These should take place in an early design stage to realize a mostly straightforward design approach and prevent late design changes. Focused on cylindrical gears, the paper covers an approach starting at the first draft of a gearbox.

Defining the macrogeometry of the teeth regarding load capacity calculation according to standards leads to a reasonable gear design. On that basis, the micro geometry of the teeth is specified and load distribution as well as noise excitation is calculated. The design parameters are interdependent so provisions have to be made to adjust each step on the remaining ones. Effects resulting from changing profile contact ratio under load and contact patterns not covering the whole flank have to be regarded. The beneficial effect of a modified microgeometry is dependent on the ability to precisely account for contact conditions and meshing clearances.

To find an optimal solution for the competing goals of capacity and excitation, detailed calculation methods are required. To be able to apply latest research results, these are implemented in highly specialized software. The task described above is handled by using the software that was developed at the Gear Research Center (FZG) with funding by the German Research Association for Gears and Transmissions (FVA). The underlying calculation methods and analyzed phenomena are covered.

ISBN: 1-61481-068-1 Pages: 14

13FTM12. Practical Considerations for the Use of Double Flank Testing for the Manufacturing Control of Gearing

Authors: **E. Reiter and F. Eberle**

The gearing industry has developed many unique measuring techniques for the production control of their products. Each technique has inherent advantages and limitations which should be considered by designers and manufacturers when selecting their use. Double flank composite inspection, (DFCI) is one such technique that can functionally provide quality control results of test gears quickly and easily during manufacturing. The successful use of DFCI requires careful planning from product design, through master gear design and gage control methods in order to achieve the desired result in an application.

This document explains the practical considerations in the use of double flank testing for the manufacturing control of spur, helical, and crossed axis helical gearing including:

- a general description of double flank inspection equipment including an explanation of what can be measured;
- recommendations on practical master gear design;
- the calculation of tight mesh center distance and test radius limits;
- the resulting backlash that can be anticipated in gear meshes based on applying double flank tolerances in a design;
- initial and ongoing statistical techniques in double flank testing and how they can be practically used to improve gear quality;
- double flank gage measurement system analysis including case studies of gage repeatability and reproducibility (R&R) and uncertainty analysis.

ISBN: 1-61481-069-8 Pages: 32

13FTM13. Gear Failure Analysis and Lessons Learned in Aircraft High-Lift Actuation

Authors: **A. Wang, S. Gitnes, L. El-Bayoumy and J. Davies**

Several gear failure cases and lessons learned in the development phase of aircraft high lift actuation systems are presented, including leading edge geared rotary actuators, and trailing edge geared rotary actuators, sector gears and pinions, and offset gearboxes. The high lift system of an aircraft, which contains trailing edge flaps and/or leading edge slats, increases lift for takeoff, controls flight during cruise, and reduces speed while increasing lift for shorter landing distance.

Many of these components contain highly loaded gears to increase the power to weight ratio. Because of requirements on weight or envelope and consideration of cost, the gears are always designed to the limit with reasonable margins of safety in a high lift system. The structure which supports the gears is limited in size and simplified, and the gear material and heat treatment are selected for easy manufacturing. Therefore, when misalignment and/or deflection of the gears are large enough to cause reduction in tooth contact area, the stress on gears becomes large enough to cause damage. The failure modes can be classified as spalling or pitting at the location of concentrated loads. Most of the problems can be resolved by providing correct lead modification to alleviate the concentrated loading, while some need increase of the gear diameters, design modifications, or introduction of materials with higher allowable.

ISBN: 1-61481-070-4 Pages: 15

13FTM14. Metallurgical Investigation of "Tiger Stripes" on a Carburized High Speed Pinion

Authors: **M. Li, P. Terry, and R. Eckert**

"Tiger stripes" on a high speed pinion made of carburized SAE 9310 steel were investigated. The stripes were on lines of action on the load side of the teeth coinciding with different angular positions of the gear mesh. Scanning Electron Microscopy (SEM) of the affected areas showed fused metal particles, with a diameter of 1–3 microns, and gas pockets. The morphology of the damage was typical of electric discharge damage shown in ANSI/AGMA 1010-E95. This indicates that the stripes were in fact electric discharge damage. Microhardness surveys on a metallurgical transverse section of a tooth showed a hardness loss due to the discharge, with load side surface hardness even lower than 58 HRC. The cause of the "tiger stripes" and potential damage to the gear tooth were analyzed.

ISBN: 1-61481-071-1 Pages: 7

13FTM15. White Structure Flaking in Rolling Bearings for Wind Turbine Gearboxes

Authors: **H. Uyama and H. Yamada**

Bearing failures in wind turbine gearboxes were investigated and rolling contact fatigue tests to reproduce them using a hydrogen-charge method were conducted. Two main failure modes in wind turbine gearbox bearings were white structure flaking and axial cracking, which were involving a microstructural change. Both failure modes can be reproduced by using specimens charged with hydrogen. Operating conditions, which can induce hydrogen generation from lubricant and penetration of the bearing steel were discussed. Effects of bearing material on white structure flaking life were suggested as one of the countermeasures.

ISBN: 1-61481-072-8 Pages: 13

13FTM16. The Anatomy of a Lubrication Erosion Failure – Causation, Initiation, Progression and Prevention

Authors: **R.J. Drago, R.J. Cunningham, W. Flynn**

Visual examination of a compressor box revealed that the Low Speed (LS) Pinion exhibited pitting type defects on each of its forty-seven (47) helical teeth. Review of the failed component revealed a somewhat repetitive type of damage at one end of the teeth only. Each tooth showed what appeared to be one defect at a similar location 3600 around the Pinion. Each defect was located within ~0.5 inch of the end of the helical tooth. It was noted that each tooth defect was observed on the coast side of the teeth only.

Visual examination of the mating gear revealed no evidence of similar damage. While of and by itself, this pitting may not be cause for alarm, debris from the pitting can adversely affect other components in the gearbox, especially the bearings, and the stress concentration effect of the pitting, even though it is on the coast flank, could lead to partial tooth fracture in the region of the distress.

This paper presents a discussion of the causation, diagnosis and metallurgical failure investigation of this lubrication erosion failure. Our effort was aimed at identifying the nature of the pitting and providing recommendations to avoid repeat instances of this failure in this specific application and in other future designs for similar applications.

The subject is presented by way of the discussion of detailed destructive metallurgical evaluations of this specific lubrication erosion failure which the authors have conducted in order to analyze and characterize the failures. Lubrication erosion is generally limited to helical gears but the authors have also found this type of distress when evaluating damage to carburized, hardened and hard finished spiral bevel gears as well when operated under the "right" circumstances. Lubrication erosion observed on helical gears only, however, will be addressed in this presentation. Although a specific failure "case" is used as the vehicle for presentation, information has been extracted and condensed from several individual actual failure investigations conducted by the authors so that a better understanding of the specific conditions that lead to micropitting and the actual progression from micropitting to fracture can be presented.

ISBN: 1-61481-073-5 Pages: 30

13FTM17. Dynamic Simulations of Radial Lip Seals Followability in an Industrial Gearbox

Authors: **M. Organisciak, R. Iervolino, M. Sansalone, S. Barbera, A. Paykin and M. Schweig**

Industrial gear units are widely used in power transmission systems. They are composed of shafts, gears, rolling elements bearings and dynamic lip seals. The seals performance is critical for a proper functioning of the system. Water or contamination ingress into a mechanical system may lead to a premature failure. Leakage of oil may have the same effect and be harmful for the environment. Depending on the application, seals may need to operate under various dynamic conditions, such as wide range of rotational speed (RPM) and temperatures, shaft–to–bore–misalignment (STBM), shaft dynamic run-out (DRO) or global structure deformations.

The prediction of dynamic seal performance is a complex task. The rotating lip seals are usually made in elastomeric materials which display a hyper-elastic and viscoelastic behavior. Combined with the dynamic operating conditions, the simulation of the seal performance requires time dependent approaches which are very often time consuming. Innovative modeling methods need to be developed in order to be usable by the development engineering community.

This paper presents a novel approach to predict seal dynamic performance under dynamic conditions. A formulation of viscoelastic super-elements is developed to predict the deformations of the seal lips. It is combined with a contact solver to assess contact force and its distribution around the shaft and other lip contersurfaces (such as other radial or axial locations). In order to demonstrate functionalities and advantages of the developed method, please consider an example of radial lip shaft seal. The problem addresses prediction of seal performance at cold temperature, large shaft-to-bore misalignment and dynamic run-out conditions. Different material and spring options are assessed in order to improve the performance.

This unique modeling capability will allow selecting or developing the shaft seals which would meet and exceed modern gearbox demanding application. It will also enable gearbox manufacturers to bring to the market more performing and reliable gearboxes.

ISBN: 1-61481-074-2 Pages: 10

13FTM18. Gear Lubrication – Long Term Protection for Wind Turbines

Authors: **S. Mazzola, M. Hochmann and J. Wald**

The chemical and physical properties of gear oils in use may change more or less depending on its formulation and the operating conditions. For this reason, a gear oil was investigated after three years of use in a wind turbine to find out if changes are evident and if the protection of the gears and rolling bearings still meet the requirements as with fresh oil. Beside chemical and physical analyses, the used gear oil was examined on a FZG back-to-back gear test rig and on a FE8 test rig. The test results could show that the used gear oil as well as its ability to protect the gears and rolling bearings has changed very little compared to fresh oil.

ISBN: 1-61481-075-9 Pages: 17

13FTM19. Gear Resonance Analysis and Experimental Verification Using Rapid Prototyped Gears

Authors: **S.R. Davidson and J.D. Hayes**

Determination of gear resonance frequencies is necessary in the design of light weight aerospace gears. Resonant frequencies and mode shapes calculated are then identified as damaging or non-damaging and compared to the gear's mesh frequencies to determine if gear tooth bending stresses will be amplified in a particular operating speed range. Finite Element Analysis (FEA) is well suited to determining gear resonant frequencies and modes. In order to verify the analysis quickly, rough gear geometry is fabricated and tested using accelerometers and a calibrated hammer in a modal excitation test. In past efforts, rough geometry fabricated was a simplified version of the final part minus gear teeth or other features. To reduce the time of fabrication and to increase the accuracy of the prototype part, modern rapid prototyping manufacturing techniques may hold promise in approaching the realism of the actual part with material properties that are similar to material properties of gear steels.

This paper studies gear resonance modal excitation testing of two stage idler spur gear rapid prototyped parts, using two different rapid prototyping techniques and compares results to the final production part and FEA model. Damaging and non-damaging modes and nomenclature will be reviewed as well as the testing method.

ISBN: 1-61481-076-6 Pages: 11

13FTM20. Influence of Gear Loads on Spline Couplings

Authors: **C.H. Wink and M. Nakandakari**

Involute splines are commonly used in gearboxes to connect gears and shafts, especially when high torque is transmitted through the coupling. The load is shared among multiple teeth around the coupling circumference resulting in higher load capacity than a conventional single key. However, the total load is not equally shared among all spline teeth, mainly because of pitch deviations resulting from the manufacturing process. The load distribution along the spline engagement length is also non-uniform because of tooth misalignments and shaft torsional effects. A typical modeling assumption is that pure torsion load is applied to the spline coupling. In gearbox applications, when splines are used to connect a gear to a shaft, the torque is transmitted from the gear teeth in mesh to the shaft, or vice-versa, through the coupling. The gear loads, such as tangential and radial loads, can affect the load distribution of spline teeth. This paper presents an investigation on the influence of spur gear loads on load distribution of spline teeth. A generalized analytical model was developed to include external gear loads on spline couplings. The method divides the spline teeth into stations in the tooth axial direction, and calculates the load applied to each station based on separation between the mating points. A constant for tooth stiffness was used to calculate tooth deflections. The load distribution problem was solved using a simple approach from industry gear standards. The method was implemented into a spreadsheet for numerical example analyses. The results showed significant effect of side clearance, which is the difference between the space width of internal spline grooves and external spline tooth thickness, on the maximum load applied to the spline teeth. The greater the side clearance, the greater is the maximum load applied to the spline teeth. The proposed method may be helpful to quickly assess load distribution of spline teeth in gear applications, to determine tooth stresses, and to define lead modifications as needed.

ISBN: 1-61481-077-3 Pages: 14

13FTM21. How to Spec a Mill Gear

Author: **F.C. Uherek**

For optimal torque delivery as a function of cost, there are critical parameters that need to be communicated to the gear designer from the mill builder when designing gear drive systems for ore grinding applications. Apart from loads and speeds, interface dimensions and site specific conditions are also needed. Deciding up front which gear rating practice to select can affect the torque capacity of the drive train by ~15%. How to deliver the torque to the mill pinion, either by a gear reducer or low speed motor, influences the distribution of cost between the prime mover and the gear train. This paper will outline the design considerations that go into construction of the drive system in order to explain why specific data is required and where design freedom is necessary. A clear specification up front that allows for matching interface dimensions while allowing for the most cost efficient up front design achieves this goal.

ISBN: 1-61481-078-0 Pages: 14

13FTM22. Heat Treatment of Large Components

Author: **G.L. Reese**

Large gear components can be offered in many applications such as in marine, wind power, steel rolling mills, power plants, transportation, railroad, aircraft, cement crushers, mining and oil industry applications. There are three important surface hardening methods used to improve and expand the technical use of gear components. Design and material engineers must decide which hardening method to use. Case hardening is normally the first choice because of the highest load capacity. But, case hardening also poses challenges that must be acknowledged. Therefore, it is good to know that there are three options for very large components.

ISBN: 1-61481-079-7 Pages: 21

13FTM23. Ductile Iron for Open Gearing – A Current Perspective

Authors: **F. Wavelet and M. Pasquier**

For over three decades, open gearing for many applications has been successfully designed and manufactured from ductile iron. Examples spanning a full range of size and transmitted power are in service in various process industries throughout the world, proving the soundness of this material selection in technical as well as economical terms.

The latest metallurgical and manufacturing developments have re-established the practical limits for this material, well beyond what was considered possible as recently as a few short years ago. A ductile iron gear of 16 m diameter, 340 BHN (min.) hardness, module 42, with a face width of 1200 mm and having AGMA Q10 teeth quality, capable of transmitting 2x10 000+ kW was previously a concept. Today, such a gear can be manufactured. Despite its long and successful service history, ductile iron remains a somewhat lesser known commodity as an open gearing material.

The goal of this paper is to present the current “state-of-the-art" with respect to ductile iron as a gear material, including its mechanical properties as applicable to gear design, structural characteristics, typical manufacturing and inspection plans, and in-service behavior. For each of these aspects, ductile iron will be compared to other available materials for open gearing design and manufacture, such as cast

ISBN: 1-61481-080-3 Pages: 20

13FTM24. Innovative Induction Hardening Process with Preheating for Improved Fatigue Performance of Gear Component

Author: **Z. Li**

Contact fatigue and bending fatigue are two main failure modes of steel gears. Surface pitting and spalling are two common contact fatigue failures, which are due to the alternating subsurface shear stresses from the contact load between two gear mates. When a gear is in service under cyclic load, concentrated bending stresses exist at the root fillet, which is the main driver of bending fatigue failures. Heat treatment is required to increase the hardness and strength of gears to meet the required contact and bending fatigue performance. Induction hardening is becoming more popular due to its process consistency, reduced energy consumption, clean environment, and improved product quality. It is well known that an induction hardening process of steel gears can generate compressive residual stresses in the hardened case. Compressive residual stresses in the hardened case of tooth flank benefit the contact fatigue performance, and residual compression in the root fillet benefits the bending fatigue. Due to the complex gear geometry, the residual stress distribution in the hardened case is not uniform, and different induction hardening process can lead to different residual stress pattern and significant variation of fatigue performance. In this paper, an innovative approach is proposed to flexibly control the magnitude of residual stress in the regions of root fillet and tooth flank by using the concept of preheating prior to induction hardening. Using an external spur gear made of AISI 4340 as an example, this concept of innovative process is demonstrated with finite element modeling, using commercial software DANTE.

ISBN: 1-61481-081-0 Pages: 13

13FTM25. Press Quenching and the Effects of Prior Thermal History on Distortion during Heat Treatment

Author: **A.C. Reardon**

Precision components such as industrial bearing races and automotive gears often distort unpredictably during heat treatment due to the deleterious effects of free or unconstrained oil quenching. Press quenching is a method that can be utilized to minimize the distortion of these complex components during heat treatment. This is accomplished in a quenching machine by utilizing specialized tooling for generating concentrated forces to constrain the movement of the component during oil quenching. When performed correctly, this method of quenching can often achieve the relatively stringent geometrical requirements stipulated by industrial manufacturing specifications. It can be performed on a wide variety of steel alloys. These include high carbon through-hardening grades such as AISI 52100 and A2 tool steel, as well as low carbon carburizing grades such as AISI 3310, 8620, and 9310. The relevant aspects of this specialized quenching technique will be presented together with a case study of the effects of prior thermal history on the distortion that is generated during press quenching.

ISBN: 1-61481-082-7 Pages: 9

13FTM26. Vacuum Carburizing Large Gears

Author: **N. Plough**

Vacuum carburizing of gears has typically been limited to parts with relatively small cross-sections. Most alloys currently in use require oil quenching to achieve adequate surface hardness and core properties in large gear applications. Pit or large batch IQ furnaces with endothermic atmospheres are often used to process this type of gear. The majority of vacuum carburizing equipment is designed for processing smaller parts with a high pressure gas quench. Recent equipment and process developments allow vacuum carburizing and oil quenching of very large gears and pinions – up to 70" diameter and 7,000 lbs. Fixture design and careful process control help minimize distortion, while providing the case uniformity and surface integrity that is unique to vacuum carburizing. This paper will discuss specific case studies involving large gears and pinions. Distortion, case hardness profiles and microstructures from conventional gas carburizing and vacuum carburizing will be examined and compared.

ISBN: 1-61481-0 Pages: 7

2012 PAPERS

12FTM01. Balancing – No Longer Smoke and Mirrors

Author: **R. Mifsud Hines**

In the late 1970's a balancing machine salesman visited a customer's plant who had just received a new balancer from the salesman's competitor. The plant manager said they were very happy with their automatic balancing machine and offered to show it to the salesman. The manager walked the salesman out on the floor and the two of them watched the operator and balancer in action.

The operator placed a part on the balancer and closed the door. The balancer spun up the part, welded on a weight, spun up again, and displayed “good part.” The operator removed the balanced part, put in a new part, and closed the door. The balancer spun up the part, welded on a weight, spun up again, and displayed “good part.” This scenario was repeated several more times as the salesman and the manager watched.

The manager commented, “We just love our new machine. All day long it balances parts by welding on weights and puts out good parts.” The salesman suggested having the operator place a “balanced part” back in the balancer again just to see what would happen. So the operator placed the previously balanced part back in the balancer again and closed the door. The balancer spun up the part, welded on a second weight, spun up again, and displayed “good part.” The manager had the operator take another balanced part and put it into the balancer again. Again, the balancer spun up the part, welded on another weight, spun up again, and displayed “good part.” Suddenly the manager was not so happy with his balancing machine. It seems this machine was not balancing the parts at all. They had purchased an expensive welding machine to weld weights on their parts.

ISBN: 1-978-61481-032-2 Pages: 10

12FTM02. Power Loss and Axial Load Carrying Capacity of Radial Cylindrical Roller Bearings

Authors: **S. Söndgen, W. Predki**

The application of cylindrical roller bearings (CRB) is widely spread in mechanical engineering. CRB can carry comparatively high loads and are usable in high speed ranges. These bearings have been proven to be variously applicable and economic. With lipped inner and outer rings CRB permit the transmission of axial loads in addition to radial loads. The axial load is induced on the lip of the inner or the outer ring and transferred by the roller end face contacts to the opposing lip. In comparison to an only radially loaded bearing there are additional friction losses in the contact between the lip and the roller ends as a result of sliding.

The limiting factors for the permissible axial load are high temperatures which can cause smearing and seizing, lip fracture, fatigue failure and wear. In consequence of the axial loading the stresses in the contact between the roller and the raceway rise and the fatigue durability of the bearing is reduced.

At high speeds the permissible thrust load is dominantly limited by high temperatures. At low speeds the limiting factors are lip fracture and wear.

Within the examination an extensive test program with different bearing geometries is carried out. Thereby the decisive measure is the friction torque of the bearings.

The friction torque of a thrust loaded radial cylindrical roller bearing is mainly dependent on the parameters speed, load, size and design of the bearing.

An analytical simulation model which has been developed at the institute allows calculating the lubrication conditions, the stresses within the lip-roller contact and the axial load dependent friction torque.

The intention of the study is to enlarge the application range of radial cylindrical roller bearings by means of a more precise determination of the thrust load capacity and to allow more economic designs.

ISBN: 1-978-61481-033-9 Pages: 11

12FTM03. Gear Lubrication – Gear Protection also at Low Oil Temperatures

Author: **M. Hochmann**

To find out if the high-performance gear oils of today are able to reliably protect gears and rolling bearings in gearboxes against damage also at a reduced oil temperature of 40°C, different high-performance gear oils were examined on an FZG back-to-back gear test rig as well as on an FE8 bearing test rig by modifying the standardized test methods. It has been shown that the advanced additive technologies used in today's high-performance gear oils are capable of inducing the required reactions on the surfaces of gears and bearings also at 40°C, thus providing reliable damage protection even under these operating conditions.

ISBN: 1-978-61481-034-6 Pages: 15

12FTM04. Energy Efficient Industrial Gear Lubricants

Authors: **D. Blain, A. Galiano-Roth, R. Russo, K. Harrington**

Global energy demand is predicted to be about 30 percent higher in 2040 compared to 2010. Energy demand growth will slow as economies mature, population growth moderates and efficiency gains accelerate. This paper will focus on the third factor: energy efficiency. The industrial sector consumes almost 48% of global energy, with the remainder being used for residential/commercial and transportation. Clearly, improvements in energy efficiency in the industrial setting can have a major impact on overall global energy use and resultant CO_2 emissions.

There are multiple sources of lubricant-related energy loss in industrial equipment in general, and gearboxes in particular. These include frictional losses due to metal-to-metal contact, frictional traction losses under elasto-hydrodynamic lubrication conditions and windage/churning loses in the bulk oil. All three of these factors can be improved by using a properly formulated lubricant, with carefully selected base oils and additives to improve efficiency.

ExxonMobil has developed a series of industrial lubricants that can reduce energy usage by up to 4% relative to conventional lubricants. These savings have been documented in both carefully controlled laboratory testing and in extensive evaluations in actual industrial equipment in the field. Experiments to measure lubricant-related energy efficiency benefits are inherently challenging. Valid determinations of these benefits require precise measurements and controls, meticulous attention to detail and appropriate statistical analysis. In addition to the energy efficiency benefits, these oils can reduce equipment operating temperatures, resulting in increased component and lubricant life. This leads to longer oil drain intervals, and less used oil disposal.

ExxonMobil defines sustainability as having three components: social development, economic growth and environmental protection. In addition to discussing all of the points above, this paper will also describe how the new energy efficient lubricants contribute to each of these sustainability attributes.

ISBN: 1-978-61481-035-3 Pages: 16

12FTM05. Combined Effects of Gravity, Bending Moment, Bearing Clearance, and Input Torque on Wind Turbine Planetary Gear Load Sharing

Authors: **Y. Guo, J. Keller, W. LaCava**

This computational work investigates planetary gear load sharing of three-mount suspension wind turbine gearboxes. A three dimensional multi-body dynamic model is established, including gravity, bending moments, fluctuating mesh stiffness, nonlinear tooth contact, and bearing clearance. A flexible main shaft, planetary carrier, housing, and gear shafts are modeled using reduced degrees-of-freedom through modal compensation. This drive train model is validated against the experimental data of Gearbox Reliability Collaborative for gearbox internal loads. Planet load sharing is a combined effect of gravity, bending moment, bearing clearance, and input torque. Influences of each of these parameters and their combined effects on the resulting planet load sharing are investigated. Bending moments and gravity induce fundamental excitations in the rotating carrier frame, which can increase gearbox internal loads and disturb load sharing. Clearance in carrier bearings reduces the bearing load carrying capacity and thus the bending moment from the rotor can be transmitted into gear meshes. With bearing clearance, the bending moment can cause tooth micropitting and can induce planet bearing fatigue, leading to reduced gearbox life. Planet bearings are susceptible to skidding at low input torque.

ISBN: 1-978-61481-036-0 Pages: 16

12FTM06. Virtual Optimization of Epicyclic Gearbox Planet Bearings in Wind Turbines

Authors: **S. Vasconi, D. Raju**

Demand for higher reliability, robustness and performance in epicyclical gearboxes have led SKF to develop Design for Six Sigma (DfSS) based simulation tools and methods.

This paper will illustrate the advantages of using simulation driven design in the development of planetary gearboxes for multi megawatt wind turbines. The simulation example will show the influence of the housing flexibility and of the non-linear bearing and gear stiffness on the gearbox performance under transient load. In particular, the load distribution and deformation of the planetary gears and bearings will be analyzed.

The flexibility and accurate stiffness description led to non-intuitive results. The gear deformation and load distribution led to significantly different results compared to results obtained by using traditional calculation tools and methods. A comparison between advanced and standard calculation methods is given as evidence that advanced analyses should be used to design reliable, robust and high performing gearboxes.

A virtual design of experiments was used to determine the most influential parameters affecting the gearbox performance. This paper will highlight the results of this DfSS study.

ISBN: 1-978-61481-037-7 Pages: 16

12FTM07. Validation of a Model of the NREL Gearbox Reliability Collaborative Wind Turbine Gearbox

Authors: **C.K. Halse, Z.H. Wright, A.R. Crowther**

Gearboxes in the wind industry have been suffering from a poor reputation due to major issues with reliability. There has been a long list of issues; e.g. grind temper, material inclusions, axial cracking in bearings, poor load sharing on shaft-bearing arrangements, significant gear misalignment, bearing ring creep, gear scuffing, gear and bearing micropitting; all of which are common and often serial problems. There has been improvement in the last few years for some of the products, yet it is not uncommon for wind sites built as recently as 2008 to have 20–40% of gearboxes requiring a component replacement (such as a high speed pinion or intermediate shaft bearing) already (by 2012) and 5–10% complete gearbox failures. An important program for the industry, "*The Gearbox Reliability Collaborative*" (GRC), has been funded by the US Department of Energy and run by the National Renewable Energy Laboratory for several years to aid the industry in improving the reliability of this key component. The collaborative has brought together manufacturers, academia, national laboratories, engineering consultants and gear and bearing software providers as part of a program to model, build, simulate and test gearboxes with a goal to improve reliability and reduce the cost of energy.

The team at NREL have instrumented two gearboxes with over 125 channels, for measurements such as planetary tooth load distributions, annulus gear hoop strains, planet bearing load distribution, sun orbit and carrier deflection. They were then subjected to a rigorous testing regime, both up-tower and on the NREL 2.5MW dynamometer. Romax Technology have been a collaborator in the GRC Analysis Group and have developed detailed computer simulation models of the gearbox including gear macro and micro-geometry, bearing macro and micro-geometry, structural stiffness of gearbox housing, carrier and annulus gear, system clearances and preloads, and surrounding boundary conditions (such as main shaft, rotor hub and bedplate). The model is used for accurate simulation of the whole system deflections and the prediction of the resulting gear and bearing contact conditions under various loading conditions.

The focus of this paper is a comparison between measurement and simulation for key parameters including gear load distributions, annulus deflection and sun motion. The simulation results that are robust and those that are sensitive to hard-to-predict parameters that include significant effects from manufacturing and assembly variations will be outlined. Lessons learned in how best to apply computer-aided-engineering tools to improve wind turbine gearbox reliability will be described.

ISBN: 1-978-61481-038-4 Pages: 12

12FTM08. Combined Marine Propulsion Systems: Optimization and Validation by Simulation

Authors: **B. Pinnekamp and F. Hoppe**

Modern Navy and Coast Guard Vessels usually have combined propulsion systems using gas turbines, diesel engines and electric motors as main propulsors. Desired operating profiles demand for individual optimization of the gear propulsion system with respect to efficiency, noise, operational flexibility and capital cost.

Combined systems are complex and therefore sensitive to dynamic excitation and resonance. To avoid unfavorable dynamic effects, it is necessary to validate candidate arrangements using modern tools like multi body simulation.

The paper describes the evaluation process for optimized combined marine propulsion systems and system validation by dynamic simulation.

ISBN: 1-978-61481-039-1 Pages: 20

12FTM09. Systematic Approach for the Psychoacoustic Analysis of Dynamic Gear Noise Excitation

Authors: **C. Brecher, M. Brumm, C. Carl**

The sound quality of technical products is an increasingly important quality criterion and has a significant influence on the product acceptance. But sound quality does not only depend on the physical attributes of the sound signal. It is defined to a large extent by human sound and noise perception. This perception is based on a physiological and psychological signal processing. These aspects depend on complex properties of the physical signal like the spectral distribution and a relative comparison. However, today the sound design of gearboxes is mainly based on the physical reduction of the noise level that is detected by absolute and objectivized parameters. The noise oriented gear design is based on a fundament of physical key parameters like the reduction of transmission error in compliance with achievable manufacturing tolerances. Nevertheless, these design rules may lead to a minimal sound pressure level but cannot solely be applied for an optimal sound quality in every case. Under economic and technical aspects there is no excitation free gear set. Furthermore, modern tendencies such as lightweight design and masking noise reduction (engine downsizing and electrification) lead more and more to scenarios where the sound of a gear set, which is only designated to have low transmission error, can be perceived as annoying. This requires design guidelines which take also the human related aspects of gear noise into account. Nowadays the gear design does not yet consider human noise perception sufficiently.

Thus, a research project at the WZL has been established that investigates the correlation between gear mesh excitation and the evaluation of gear noise. The objective of this project is to deduce a method for the consideration of perception-based noise evaluation already in the stage of gear design. Therefore, psychoacoustics metrics are used to analyze the gear noise of different gear sets in the dimensions of airborne noise, structural vibration and the excitation due to meshing. The aim of this paper is to discuss the correlation between the signal properties of the excitation and the radiated noise in order to investigate the possibilities to transfer the perception related evaluation from sound pressure to the gear mesh excitation. The paper firstly shows central psychoacoustic parameters that are most relevant for the properties of gear noise. Furthermore, a new test fixture will be introduced that allows a dynamic measurement of gear mesh excitation directly adjacent to the meshing. Regarding these aspects two different gear sets are discussed concerning the calculated transmission error and the experimentally determined excitation, surface vibration and noise radiation. These aspects are accordingly examined with respect to human noise perception, which is described by psychoacoustics. It is shown that operating conditions, order distributions as well as the gear geometry are the main influences on the signal evaluation. The influence of dynamic aspects and especially the influence of resonance effects on the noise characteristics are additionally considered.

ISBN: 1-978-61481-040-7 Pages: 22

12FTM10. Development of Novel CBN Grade for Electroplated Finish Grinding of Hardened Steel Gears

Authors: **U. Sridharan, S. Kompella, S. Ji, J. Fiecoat**

The unique requirements of an electroplatable superabrasive CBN grit used in profile grinding of hardened steel gears as well as the attributes and grinding behavior of a new CBN developed specifically for this application are discussed. Profile gear grinding parameters were simulated in through-hardened AISI 4140 steel (56 HRC) and the grinding performance of the new CBN was compared against a competitive CBN grade widely used in the application. Consistent with field criteria, grinding performance was characterized based on occurrence of 'burn' or 'form' failure. The 'burn' or metallurgical phase transformation failure was detected by Barkhausen Noise Analysis (BNA) and corroborated by microstructural and microhardness evaluations. The 'form' failure was simulated by tracking average radial wheel wear to a threshold value where form loss was expected to occur. Grinding tests indicate that the new CBN grit can grind 35% more parts compared to the competitive CBN grade before burn failure. In addition, the new CBN displayed a lower wear rate. The new CBN grade also exhibited a unique ability to grind with lower grinding power, resulting in a near constant BNA response on the ground surface throughout the test. This implied minimal microstructural change on the ground part from start to end of the test compared to the progressive softening of ground surface noticed with the competitive CBN.

ISBN: 1-978-61481-041-4 Pages: 13

12FTM11. Contemporary Gear Pre-Machining Solutions

Author: **C. Kobialka**

Depending on production volumes, batch sizes and work piece geometry, several gear manufacturing technologies are used for industrial gear production. Most frequently applied is the hobbing process, followed by broaching, shaping, sintering and rolling processes. Upcoming gear manufacturing processes are power skiving, forging, precision blanking and cold forging. Due to improvements to the numerical control of direct drive technology, the power skiving process has become a competitive gear manufacturing process in comparison to shaping, blanking and broaching. The potential of the reinvented power skiving process will be explained by production volume analyses, achievable gear quality and gear geometry modifications. Also the economical and environmentally friendly aspect of the power skiving process will be explained.

ISBN: 1-978-61481-042-1 Pages: 10

12FTM12. Manufacturing Method of Pinion Member of Large-Sized Skew Bevel Gears Using Multi-Axis Control and Multi-Tasking Machine Tool

Authors: **I. Tsuji, K. Kawasaki, H. Gunbara, H. Houjyou, S. Matsumura**

In this paper, a manufacturing method of the pinion member of large-sized skew bevel gears using multi-axis control and multi-tasking machine tool considering that the gear member is provided is proposed. First, the tooth surface forms of skew bevel gears are modeled. Next, the real tooth surfaces of the gear member are measured using a coordinate measuring machine and the deviations between the real and theoretical tooth surface forms are formalized using the measured coordinates. It is possible to analyze the tooth contact pattern of the skew bevel gears with consideration of the deviations of the real and theoretical tooth surface forms expressing the deviations as polynomial equations. Moreover, the deviations of the tooth surface form of the gear member are fed back to the analysis of the tooth contact pattern and transmission errors, and the tooth surface form of the pinion member that has a good performance mating with the gear member. Finally, the pinion member is manufactured by swarf cutting using multi-axis control and multi-tasking machine tool. Afterward, the real tooth surfaces of the manufactured pinion member were measured using a coordinate measuring machine and the tooth surface form errors were detected. As a result, although the tooth surface form errors were large relatively on the heel side, those were small on the other side. In addition, the tooth contact pattern of the manufactured pinion member and provided gear member was compared with those of tooth contact analysis. As a result, there was good agreement.

ISBN: 1-978-61481-043-8 Pages: 15

12FTM13. Gear Material Selection and Construction for Large Gears

Author: **F.C. Uherek**

For gears larger than 3 m (10 feet), construction of gear blanks tend to divide into cast steel, ductile iron, and forged rim welded web structures for use in cylindrical grinding mills and kilns. This paper will review the application, various options for material selection, and the impact of selection on tooth geometry. A group of sample gears are developed to compare each of the materials and method of blank construction. Each sample is discussed in light of structural stress, deflection, expected life, handling weight, material origin, fabrication method, inspection requirements during construction, and impact of selection on field performance. Based on the above, a roadmap is developed listing critical considerations and optimal use of each material and method of construction in this application.

ISBN: 1-978-61481-044-5 Pages: 14

12FTM14. Large Pinions for Open Gears: The Increase of Single Mesh Load – A New Challenge for Manufacturing and Quality Inspection

Author: **M. Pasquier, and F. Wavelet**

Most of the large open gear sets for mining industry are designed according to AGMA 6014-A06 and AGMA 2001-D04. and rating according to AGMA standard (service factor) involve the final design of the pinion such as: material and heat treatment (through hardening or case carburized pinion), and the finishing process of the teeth (to achieve the design geometry).

Basically, customer specification and rating according to AGMA standard (service factor) involve the final design of the pinion such as: material and heat treatment (through hardening or case carburized pinion), and the finishing process of the teeth (to achieve the design geometry).

Moreover, the increase of applied load for a single meshing becomes a new challenge.

In addition to the mechanical properties for the material used and its associated heat treatment requirements given in standards, elastic and thermal behavior and resulting accuracy, as well, have to be taken into account at design stage, even for large open gears.

Beside design consideration, such increase of single meshing load cannot be achieved by using conventional manufacturing and quality control methods.

Therefore, improvements in manufacturing process and in quality inspections for such heavily loaded single large parts, as already performed for smaller parts in batch are now mandatory to achieve these new design requirements.

Based on examples, in this paper, it is presented such manufacturing and the associated quality controls improvements from steel fabrication to final machining for heavy parts, to ensure the customer that the result meets the specification requirements.

ISBN: 1-978-61481-045-2 Pages: 20

12FTM15. New Methods for the Calculation of the Load Capacity of Bevel and Hypoid Gears

Authors: **C. Wirth, B.-R. Höhn, C. Braykoff**

A failure mode called “flank breakage" is increasingly observed in different applications of cylindrical and bevel gears. These breakages typically start from the active flank approximately in the middle of the active tooth height and propagate to the tooth root of the unloaded flank side. Crack initiation can be localized below the surface in the region between case and core of surface hardened gears. This failure mode can neither be explained by the known mechanism of tooth root breakage nor by the mechanism of pitting. Even bevel gears in truck and bus applications are at the risk to suffer from subsurface fatigue, if the optimum utilization of the material should be achieved. In this case a balance between the flank breakage and pitting risk has to be found. The purpose of this paper is to describe a new material physically based calculation method to evaluate the risk of flank breakage versus the risk of pitting. The verification of this new method by experimental tests is exemplarily shown.

In cooperation with “ZG-Zahnräer und Getriebe GmbH” (ZG) “MAN truck and bus AG" (MTB) developed a new method for the calculation of the risks of flank failure by flank breakage and pitting. The calculation method has been adjusted and approved by experimental tests on powertrain test rigs of MAN. The ten different test gear variants had an outer diameter of d_{e2} = 390 mm to 465 mm, a ratio i = 4,5 to 5,7 and a normal module of m_{mn} = 6 mm to 8 mm. Also variants with the same main geometry but different Ease-Off designs were examined. All gear sets were tested under a defined load spectrum. Based on the research work at the FZG (Gear Research Center at the Technical University of Munich in Germany) of Oster, Hertter and Wirth a calculation method for bevel gears was established. The principle of the calculation model is the local comparison of the occurring stresses and the available strength values over the whole tooth volume. Therefore, it is possible to evaluate the risk of initial cracks beyond the surface of the flank. Close to the surface cracks may grow and cause pitting— especially in the flank area with negative specific sliding. Cracks in the transient area between case and core lead to a high flank breakage risk.

First the local stresses and forces on the flank are determined by a loaded tooth contact analysis followed by the calculation of the maximum exposure (regarding yielding) and dynamic exposure (regarding fatigue) of the material inside the tooth. Thereby the stress components from the Hertzian contact, bending, thermal effects (flash temperature) and friction are considered. Furthermore, the positive effect of residual compressive stresses and accordingly the disadvantageous effect of the residual tensile stresses can be implicated. Finite elements method investigations have been carried out in order to achieve a sufficient approximation of the residual stress distribution in the transverse tooth section. The strength values are locally considered, depending on the material depth and the position on the flank.

The recalculation of the test gears showed a good correlation between the occurred type of damage and the determined material exposure inside the tooth. The variants failed with flank breakage could be reliably distinguished from the variants failed by pitting by the new material-physical method. With this knowledge it is now possible to optimize the main geometry parameters of the gear set (e.g. number of teeth, spiral angle, pressure angle) as well as the micro geometry (Ease-Off) that influences the load distribution on the flank. Altogether this new method leads to an insured increase of the permissible material utilization and hence to smaller gear sizes while keeping the load capacity on a constant level.

ISBN: 1-978-61481-046-9 Pages: 21

12FTM16. Gear Design Optimization for Low Contact Temperature of a High-Speed, Non-Lubricated Spur Gear Pair

Authors: **C.H. Wink, N.S. Mantri**

This paper presents a gear design optimization approach that was applied to reduce both tooth contact temperature and noise excitation of a high-speed spur gear pair running without lubricant. The optimum gear design search was done using the RMC (Run Many Cases) program from The Ohio State University. Over 480 thousand possible gear designs were considered, which were narrowed down to the 31 best candidates based on low contact temperature and low transmission error. The best gear design was selected considering, also, its manufacturability. The selected optimum gear design was compared to an existing gear set using LDP (Load Distribution Program) from The Ohio State University. Tooth contact temperature was calculated for both designs using dry a steel-on-steel coefficient of friction. Predicted contact temperature correlated well with results observed on dynamometer tests with the existing gear set. Predictions with the optimized design showed a 48% contact temperature reduction and a 79% noise excitation reduction. The low contact temperature of the optimized design will significantly contribute to preventing tooth surface damage under no lubricant operating conditions.

ISBN: 1-978-61481-047-6 Pages: 9

12FTM17. Dynamic Analysis of a Cycloidal Gearbox Using Finite Element Method

Authors: **S. Thube, T. Bobak**

Speed reducers incorporating cycloidal technology as their primary reduction mechanism have always been active topics of research given their unique trochoidal tooth profile. A cycloidal reducer is recognized for its strength and mainly studied for rotational performance improvement. Nowadays, this study can be performed by digital prototyping, which has become a valuable tool for simulating exact scenarios without experimenting on actual model.

This paper discusses the stress distribution, modeled in a dynamic simulation environment, on the rotating parts of Cycloidal reducer. A three dimensional finite element model is developed using Algor FEA commercial code to simulate the combined effect of external loading and dynamic as well as inertial forces on one-cycloid disc system. This model utilizes surface-to-surface contact to define interaction between rotating parts of the reducer assembly. The results are analyzed for the variation in stress and deformation with respect to time for a certain simulation period. This study gives an insight of internal load sharing of rotating parts and their capability of carrying shock loads.

ISBN: 1-978-61481-048-3 Pages: 13

12FTM18. Analysis of Ripple on Noisy Gears

Author: **G. Gravel**

A low noise level is an important quality feature in modern gearboxes for passenger cars. But a troublesome noise can have many causes. The noise origination and transmission is amongst others affected by the design layout, by the actual deviations of the components, by the assembly of the components and also by the mounting situation of the complete gearbox.

Damages, form errors and displacement errors or ripples are often present on the flanks of a gear, if it is found to be the cause of problems in a noise check. Especially ripples or 'ghost frequencies' of a gear are problematic, because up to now they rarely can be detected on a gear measuring device but only in a relative complex single-flank roll checking procedure.

A new evaluation method now allows to identify and to describe ripples on the flanks of gears based on the results of a normal gear measurement. The deviation curves were approximated by sine functions, the results are displayed graphical and by characteristic values. A combination of the deviation of each measured point with its rotation angle allows an evaluation equal to a rolling with the mating gear. The results show a very good correlation to a noise check and to a single-flank roll check.

The application of the software is demonstrated by practical examples of the manufacturing methods generating grinding, honing, broaching and shaving. Vibrations of machine tool and ripple generating influences in the manufacturing process can be verified down to a level of a few tenth micrometers. At the same time this method is well suited to describe long-wave form deviations like an ovality or a 3- or 4-fold ripple caused by the clamping or by a square blank.

With this new evaluation method gears can be tested in an early state of production for known, critical ripples and conclusions can be drawn on the state of machine tool, cutting tool and clamping device.

ISBN: 1-978-61481-049-0 Pages: 11

12FTM19. A Field Case Study of "Whining" Gear Noise in Diesel Engines

Author: **Y. Kotlyar, G.A. Acosta, S. Mleczko, M. Guerra**

The proposed paper is a field case study of diesel engine whining gear noise. The paper will describe the development work performed to reduce the gear whining noise. It will include the problem definition, inspection of BOB & WOW engines, design of experiment, development and review of gear geometry modifications, inspection charts, sample size for a statistically significant analysis, and correlation of noise measurement results and tooth profiles.

ISBN: 1-978-61481-050-6 Pages: 13

12FTM20. The Effect of the Surface Profile on Micropitting

Authors: **M. Bell, G. Sroka, R. Benson**

A wide choice of surface roughness parameters is available to characterize components, such as gears or bearings, with the goal of predicting the performance of such metal-to-metal contacting parts. Commonly in industry, the Roughness Average (R_a) or the Mean Peak-to Valley Height ($R_{z\,(DIN)}$) is chosen to calculate the Specific Film Thickness Ratio for both superfinished and honed surfaces. However, these two surface roughness parameters fail to adequately predict the performance properties of surfaces that are superfinished or surfaces that are honed. In this paper, a superfinished surface is defined as a planarized surface having a ≤0.25 μm R_a. A honed surface is not considered to be planarized, even with a finish of ≤0.25 μm R_a. Thus, one is falsely led to predict that a planarized surface or a honed surface, having an equivalent R_a or R_z, will perform similarly. Nothing is further from the truth. Experimentally, an isotropic planarized surface delivers superior performance. The following discussion utilizes another roughness parameter, 3_{S50}, to further explain this phenomenon.

ISBN: 1-978-61481-051-3 Pages: 15

12FTM21. Typical Heat Treatment Defects of Gears and Solutions Using FEA Modeling

Authors: Z. Li, B.L. Ferguson

Steel gears are heat treated to obtain enhanced properties and improved service performance. Quench hardening is one of the most important heat treatment processes used to increase the strength and hardness of steel parts. Defects seen in quenched parts are often due to high thermal and phase transformation stresses. Typical defects include excessive distortion, surface decarburization, quench cracks, large grain growth, and unfavorable residual stresses. Gear geometries with large section differences may suffer high stress concentrations and crack during quenching. Surface decarburization before quenching may lead to high surface residual tension and possible post heat treatment cracking. In this paper, the commercial heat treatment software DANTE is used to investigate three examples of heat treatment defects. Improved processes are suggested with the help of modeling. The first example is an oil quench process for a large gear. Peeling cracks were observed on the gear surface during grinding of the quench hardened gears. Computer modeling showed that surface decarburization was the cause. The second example is a press quench of a large face gear. Unexpected large axial bow distortion was observed in quenched gears, and computer modeling indicated that an incorrect press load and die setup were the reasons. The third example is an in-process quenching crack caused by high concentrated tensile stress from unbalanced temperature and phase transformations in a spiral bevel pinion gear. The quenching process was modified to solve the problem. This example also emphasizes the need for heat treatment modeling in gear design to reduce the possibility of heat treatment defects. The three examples illustrate how to effectively use heat treatment modeling to improve the quality of the gear products.

ISBN: 1-978-61481-052-0 Pages: 14

12FTM22. Crack Testing and Heat Treat Verification of Gears Using Eddy Current Technology

Authors: **D. DeVries**

While eddy current technology has long been used in the testing of bar, tube, and wire stock, advances in electronics, automation, and coil design have paved the way for a new generation of testers specifically designed for component testing applications. This includes the testing of gears and bearings which go into automotive and industrial applications. These testing systems easily integrate into production processes allowing for in-line testing at production line speeds. In addition to enabling 100% of production components to be inspected, it can help monitor upstream processes notifying operators that something is not functioning correctly. This greatly reduces scrap and warranty costs for gear and bearing manufacturers.

Eddy current crack testing is performed by passing a small pair of coil windings over a section of the component to be tested. These coil windings are small enough to test between gear teeth, and with multi-coil probes can test very complex shapes. Most crack test applications require only one test frequency since most tests require the detection of only surface flaws. Simultaneous testing with multiple frequencies allows for testing of both surface and sub-surface defects when inspecting nonferromagnetic parts.

While not an absolute hardness test like a Rockwell test, eddy current heat treat verification can achieve sorting results on par with Rockwell testing. This has been demonstrated with both forged and powder metal gears. Eddy current heat treat inspection coils come in both standard encircling coil configurations and multi-coil custom configurations. The custom configurations allow for precise location testing verifying that induction heating parameters were correctly applied. Defects to be tested include misplaced case, shallow case, short quench, delayed quench, air cooled, non-heat-treat, and ground out conditions. When performing heat-treat inspection, multiple test frequencies are used to reliably detect these various heat-treat anomalies.

Eddy current testing offers fast, repeatable testing of gears and bearings. Testing data on each component can be stored electronically and re-analyzed off-line at a later date. Eddy current test instruments are designed to integrate with PLC's in material handling stations to set up real-time rejection capabilities. These are all features that complement modern QC requirements.

ISBN: 1-978-61481-053-7 Pages: 9

12FTM23. Enhancing Control of Distortion Through "One-Piece Flow – Heat Treatment"

Authors: **V. Heuer, D. Bolton, K. Löser, T. Leist**

Proper control of distortion has become even more important on new powertrain designs. To answer the demand for fuel-efficient vehicles, modern transmissions are built much lighter, therefore the components of the transmission exhibit less wall thickness which makes them more sensitive to distortion. Distorted gear components can create noise in the transmission, require post heat treat machining processes and may even create problems during transmission assembly.

By applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ), the distortion caused by heat treatment can be significantly reduced. This technology has been successfully established in serial production for many different gear applications.

With the introduction of *One Piece Flow – Heat Treatment*, the distortion control can be further enhanced. This 'One-piece Flow – heat treatment' allows for a rapid case hardening where the components are low pressure carburized at high temperatures (1050°C) followed by gas quenching. The components are not treated in conventional big batches with multiple layers, but they are treated in small batches consisting of one layer only. The quench intensity is controlled more precisely to allow for processes which are customized individually for each gear-component. The single-layer treatment provides

- homogenous and rapid heating of the components;
- homogenous and rapid carburizing of the components;
- homogenous and precisely controlled gas quenching.

All the variations from layer to layer are eliminated, which leads to reductions in distortion-variation within the load.

In addition, this new technology allows strong costs-savings for logistics. The manufacturing-line can be completely automated since the parts are 1st taken one by one from the soft machining unit, then 2nd heat treated in time with the cycle-time of soft machining ("Synchronized heat treatment") and then 3rd passed down one by one to the hard machining unit. The paper presents applications for enhanced distortion control when using *One Piece Flow – Heat Treatment*."

ISBN: 1-978-61481-054-4 Pages: 14

12FTM24. Recent Inventions and Innovations in Induction Hardening of Gears and Gear-like Components

Author: **V. Rudnev**

Presentation focuses on recent inventions and innovations (last 4–6 years) in induction hardening of gears and gear-like components, including but not limited to:

- "Know-how" in controlling distortion of induction hardened gears.
- Simultaneous dual-frequency induction hardening.
- Advanced induction hardening process recipes when hardening small and medium size gears.
- Novel inductor designs to minimize a distortion when induction hardening of hypoid and spiral bevel gears.
- IFP technology for induction gear hardening.
- Induction tempering and stress relieving of gear-like components with improved temperature uniformity.

Presentation also provides a review of basic principles and applications devoted to induction hardening small, medium and large size gears using tooth-by-tooth techniques and encircling method.

ISBN: 1-978-61481-055-1 Pages: 9

2011 PAPERS

11FTM01. A New Way of Face Gear Manufacturing

Author: **H.J. Stadtfeld**

There are two major intentions to apply face gears in power transmissions: the advantage to be able to use a cylindrical gear as a pinion member; and particular design solutions which require a plurality of cylindrical driving members as in a propulsion system.

While the automotive and truck industry conducted substantial research in the application of face gear systems in their drive trains, the results did not favor face gears versus bevel and hypoid gears. In many cases, the face gear system was found to be the less economical solution, as the manufacturing of the face gear itself was expensive. Machine tools require a special design, are not readily available, and the cutting tools have to be designed specifically for the particular face gear design.

The obstacles which prevented manufacturers in the past to apply face gears were removed entirely, when a new way of forming the profile of face gear teeth, using standard bevel gear cutting and grinding machines as well as standard cutter heads was designed. The idea is based on the tools used in straight bevel gear cutting and grinding according to the CONIFLEX method, however, using a generating gear which is not flat like it is for straight bevel gears but cylindrical, resembling the mating cylindrical pinion for the particular face gear design.

The complexity of modified cylindrical hobbing and shaping machines and job dependent custom tooling disappears completely with the new CONIFACE cutting and grinding process.

ISBN: 1-61481-000-1 Pages: 14

11FTM02. Generating Gear Grinding – New Possibilities in Process Design and Analysis

Authors: **J. Reimann, F. Klocke, and C. Gorgels**

To improve load carrying capacity and noise behavior, case hardened gears usually are hard finished. One possible process for the hard finishing of gears is the continuous generating gear grinding, which has replaced other grinding processes in batch production of small to medium sized gears due to its high process efficiency. Despite the wide industrial application of this process only a few published scientific analyses exist. The science-based analysis of generating gear grinding needs a high amount of time and effort. This is due to the complex contact conditions between tool and gear flank, which change continuously during the grinding process. These complicate the application of the existing knowledge of other grinding processes onto the generating gear grinding.

The complex contact conditions lead to high process dynamics which pose challenges in the design of machine tools, the control engineering and the process design. Furthermore, unfavorable contact conditions can lead to process related profile form deviation. So the knowledge of the cutting forces and their time dependent behavior is necessary to describe and optimize the process dynamics and results.

The aim of this report is to determine the existing cutting forces for a sample gear in trials for the first time and to analyze their connection to the process parameters and the appearance of profile form deviations. Simultaneously for the sample gear the same process design will be analyzed using a manufacturing simulation. The results of the trials and the simulation will be compared. The report will present new possibilities in process analysis and will give the process user ideas for future process improvements.

ISBN: 1-61481-001-8 Pages: 15

11FTM03. Towards an Improved AGMA Accuracy Classification System on Double Flank Composite Measurements

Author: **E. Reiter**

AGMA introduced ANSI/AGMA 2015-2-A06 – Accuracy Classification System – Radial System for Cylindrical Gears – in 2006 as the first major rewrite of the double flank accuracy standard in over twelve years. Although this document is not yet in wide use, many practical problems exist in the standard which affects its intended benefit.

This document explains the issues related to the use of ANSI/AGMA 2015-2-A06 as an Accuracy Classification System and recommends a revised system which can be of more service to the gearing industry.

ISBN: 1-61481-002-5 Pages: 14

11FTM04. First International Involute Gear Comparison

Authors: **F. Härtig, W. Adeyemi, and K. Knielm**

Seven national metrology institutes have carried out the first international intercomparison in the field of gear metrology organized from the EURAMET (European Association of National Metrology Institutes) with non-European involvement. As leader the Physikalisch-Technische Bundesanstalt (PTB) provided three of their involute gear artifacts and sent them to the participants from China, Japan, Thailand, United Kingdom, Ukraine and USA. Each of the institutes measured the profile, helix and the pitch artifact and evaluated the specified measurands. The results collected and evaluated by the PTB were compared and analyzed by evaluating the normalized error En. At the end of this comparison the large distribution of the results which lay in the range of today's required tolerances in industry pose a lot of questions. The presentation explains details of the measurement setup and evaluation parameter, damages of some artifacts due to unqualified handling, and finally the interesting results.

ISBN: 1-61481-003-2 Pages: 11

11FTM05. Epicyclic Load Sharing Map – Application as a Design Tool

Author: **A. Singh**

One of the main advantages of planetary transmissions is that the input torque is split into a number of parallel paths. However, equal load sharing between the planets is possible only in the ideal case due to the presence of positional type manufacturing errors, equal load sharing is not realized, and the degree of inequality in load sharing has major implications for gear system sizing, tolerancing schemes, and torque ratings.

The sensitivity of load sharing to torque, tolerance level, directionality of error, system flexibility, number of planets, and amount of float in the system have all been studied. However, a physical understanding of the true mechanism that leads to the load sharing phenomenon was lacking.

In a recent paper, the author has proposed a physical mechanism that explains all known load sharing behavior. The physical explanation leads to simple expressions that seem to completely describe the complex load sharing behavior. Comparisons to computational models and experimental results have shown excellent correlation.

The proposed physical explanation leads to the concept of an epicyclic load sharing map (ELSM). The ELSM is a plot of the load ratio (or % of input torque) versus a non-dimensional parameter Xe. The non-dimensional parameter is a function of combined system stiffness, tolerance level, and operating torque. The ELSM contains curves for 3, 4, 5, 6 and 7 (and more) planet systems. Once a gear set is located on the ELSM, its behavior under any load and error condition can be quickly predicted. Also, the advantages of adding extra planets can be accurately estimated.

The use of the ELSM as a design tool for the general case when there are errors on the position of every carrier pin-hole are illustrated. Statistical simulations are performed for a given manufacturing error distribution for 3 to 7 planet systems

ISBN: 1-61481-004-9 Pages: 25

11FTM06. Reversed Gear Tooth Bending Stress and Life Evaluation

Author: **J. Chen**

There is a wealth of literature and test results regarding the subject on single directional gear tooth bending stress and life relationships (S-N curves), they have been published on various journals and handbooks over the past decades, and several of them had been widely accepted and adapted as industry standards by different gear societies around the world. However, very limited information regarding the bi-directional tooth bending life has been revealed.

To fill in the above mentioned gap for practical usages, the authors first intended to apply the traditional fatigue theories such as modified Goodman, Gerber, Morrow or similar theories with minor modifications to derive a series of S-N equations for different loading conditions, but the correlation with the actual test results was not satisfied. Nevertheless, from the observation on these test results, the slopes and endurance limits on the fitted S-N curves from all the test points were reasonable closer to each other, as long as the test gears were produced by the same material and similar manufacturing process. Based on the above observation, the author proposes a new approach that uses the common (or averaged) slope and endurance limit, and a series of S-N curve equations on any loading conditions can be derived, once the single directional S-N curve has been obtained.

ISBN: 1-61481-005-6 Pages: 19

11FTM07. The Effects of Helix Angle on Root Stresses of Helical Gears

Authors: **D.R. Houser and A.P. Thaler**

The ISO and AGMA Gear Rating Committees have for several years been comparing the results of different rating methods for several sets of gear pairs that have similar normal sections but different helix angles. The analysis presented here uses a finite element code that was developed specifically for gear and bearing contacts to analyze the example gear sets. Analyses are also performed using a more conventional load distribution analysis program. The results for the original gear sets show that the narrow face width gear teeth twist significantly, thus moving the load to one edge of the face width and essentially showing that the example gear sets are highly unrealistic. Yet when analyzed by the ISO and AGMA rating methods, the results do not reflect this twisting action. In an effort to come up with a valid comparison of stresses for different helix angles, three adjustments using wider face widths were attempted. The first uses a narrow load patch in the middle of the tooth pair and results in the stresses increasing with helix angle. The second scheme again uses a wider face width, but with perfect involutes. Edge effects result in the peak stresses being near the ends of the face width. The third method, which uses the wide face width with teeth that have some lead crown and tip relief, gives the most reasonable results, with the root stresses being at a maximum in the center region of the tooth face widths. The paper compares each of the results to earlier analyses performed by others using both the AGMA and ISO calculations.

ISBN: 1-61481-006-3 Pages: 14

11FTM08. A Comprehensive System for Predicting Assembly Variation with Potential Application to Transmission Design

Authors: **K.W. Chase and C.D. Sorensen**

Recent advances in tolerance analysis of assemblies allow designers to: predict tolerance stack-up due to process variations; examine variation in clearances and fits critical to performance; use actual production variation data or estimates from prior experience; and use engineering design limits to predict the percent rejects in production runs.

A comprehensive system has been developed for modeling 1D, 2D, and 3D assemblies, which includes three sources of variation: dimensional (lengths and angles), geometric (GD&T), and kinematic (small internal adjustments due to dimensional variations).

Once the assembly has been described, an algebraic model is created, in which each dimension is represented by a vector, with a nominal +/- tolerance. The vectors are linked into chains or loops, describing each critical clearance or assembly feature in terms of the contributing dimensions. The chains form vector loops describing the interaction and accumulation of the three sources of variation in the assembly.

Small variations are applied to each source and analyzed statistically to predict the resulting variation in the critical assembly features. Solutions for the mean and standard deviations are obtained by matrix algebra. Only two assemblies are analyzed: one for the mean and another for the variance of the assembly features. The same modeling elements may be used to model complex assemblies.

Benefits of tolerance analysis include reduced reject rates, fewer problems on the assembly floor, reduced costs, and shorter time to market. Critical requirements of shaft alignment, gear meshing and controls in transmissions and gear trains are ideally suited for this efficient, comprehensive system.

ISBN: 1-978-61481-007-0 Pages: 18

11FTM09. Standardization of Load Distribution Evaluation: Uniform Definition of $K_{H\beta}$ for Helical Gears

Author: **K. Nazifi**

The load distribution measurement of gear teeth and the determination of the face load factor for contact stress $K_{H\beta}$ are of fundamental importance to the gear manufacturing industry. The factor is a measure for the uniformity of the load along the face width. The closer this factor is to one the more uniform is the load distributed along the face width. In the design phase this factor is determined with the help of approximation equations and finite element analysis and is used to dimension the flank modifications. In addition, $K_{H\beta}$ is used in the lifetime calculations according to DIN 3990 and ISO 6336 required by the certification societies. In the testing phase this factor is experimentally determined by strain measurements of the tooth fillets in order to verify the load distribution calculations and the suitability of the used modifications.

For spur gears with no helix angle the interpretation of the measurements to a face load factor is intuitively easy. For helical gears, used more frequently in large gearboxes, the determination of the factor gets more difficult. The line of contact of these gears runs inclined over the face width of the teeth flank. In this context the question arises whether the face load factor is evaluated along the face width or along the path of contact.

Evaluation of the measured values and the interpretation to a face load factor is a complex challenge and is not standardized. The standardization of load distribution evaluation and a uniform definition of $K_{H\beta}$ especially for helical gears enable a safer design for the manufacturers and an easier comparability of the results for the customers.

The paper will compare the different suggestions to the $K_{H\beta}$ definition and will derive a new definition suitable for the calculation methods in DIN 3990 and ISO 6336.

ISBN: 1-978-61481-008-7 Pages: 18

11FTM10. New Methods for the Calculation of the Load Capacity of Bevel and Hypoid Gears

Authors: **B.-R. Höhn**, **K. Stahl, and C. Wirth**

Pitting and tooth root breakage are still the two most frequent failure types occurring in practical applications of bevel gears. There are several national and international standards for the calculation of the load carrying capacity of these gears such as DIN 3991, AGMA 2003 and ISO 10300. But up to now these standards do not cover bevel gears with offset (hypoid gears). For that reason, a research project was carried out at FZG (Gear Research Centre, Munich, Germany) to analyze the influence of the hypoid offset on the load capacity of bevel gears by systematic theoretical and experimental investigations.

The results of the tooth root tests showed, as expected, an increasing load capacity with higher offsets. In contrast, the pitting tests showed an increasing, but after reaching a maximum, a decreasing load capacity with higher offsets. This can be explained by two interfering phenomena: On the one side higher offsets lead to decreasing pinion loads and thus decreasing contact stresses; on the other side the permissible stresses are decreasing due to the higher sliding velocities.

Regarding these test results a new standard capable calculation method was developed on the basis of ISO 10300. First the bevel gear geometry is transformed into a virtual cylindrical gear. Systematic theoretical investigations and comparisons with tooth contact analysis methods have shown that the new virtual cylindrical gears have representative mesh conditions compared to the bevel gears. This includes the size and shape of the contact area as well as the load distribution between the mating teeth. Particularly with regard to hypoids it is necessary to consider the unbalanced mesh conditions between drive and coast side flank, what can be described by the limit pressure angle. Several influence factors were adjusted considering geometry, material properties and operating conditions of the gear set. For the tooth root safety factor, the influence factors were adapted to the specific conditions of hypoid gears. For the calculation of the pitting safety factor two new influence factors were introduced to consider the hypoid specific sliding conditions on the gear flanks. The recalculation of the pitting and tooth root tests showed a very good correlation of calculated with real load capacity of the test gears.

Meanwhile the newly developed calculation method is widely-used in the gear manufacturing industry. For that reason, it is currently introduced into the revision of ISO 10300 as method B1 beside method B2 based on the AGMA calculation method for bevel and hypoid gears.

ISBN: 1-978-61481-009-4 Pages: 20

11FTM11. Marine Reversing Main Gear Rating Factor Versus Number of Loading Reversals and Shrink Fit Stress

Authors: **E.W. Jones, S. Ismonov and S.R. Daniewicz**

The marine vessel reversing main gear tooth is subjected to three different loading cycles: ahead travel with load pulsing from zero to 100% of full power; astern travel with load pulsing from zero to about minus 66% of full power; and reversal of direction with load changing from 100% of full power to about minus 66% of full power.

The number of repetitions of these three different loading cycles varies with the vessel duty cycle and life. The published values of allowable design stress for teeth are based on pulsing loads, which must be modified for this third loading cycle. The tooth may also be subjected to mean stress due to shrink fitting of the gear onto a hub.

Publications which address these conditions include:

- Guide values for mean stress influence factor, Y_m, of ISO 6336-3 gives a factor, which de-rates the pulsing, i.e. unidirectional, allowable stress value for non-pulsing load.
- The American Bureau of Shipping Rules, derate the allowable unidirectional bending strength by 10% for the reversing main gear tooth. (Idler gear teeth, which are under bidirectional loading at full power, are de-rated by 30%).
- Det Norske Veritas DNV Classification Notes No. 41.2 addresses gears: with other working conditions than pure pulsations; with periodical changes of rotational direction; and with shrink fitting stresses. For gears with occasional full load in reversed direction such as the main wheel in a reversing gearbox, the derating factor of 10% is recommended.

This paper evaluates the derating factor for marine reversing main gear tooth allowable bending stress using the Goodman fatigue line and Miners equation as a function of the average number of changes in vessel direction per hour, shrink fitting stress values, and different materials based on the AGMA values for allowable stress and life factor.

ISBN: 1-978-61481-010-0 Pages: 18

11FTM12. The Application of the First International Calculation Method for Micropitting

Authors: **U. Kissling**

The international calculation method for micropitting, ISO/TR 15144, was recently published. It is the first official international calculation method to check for the risk of micropitting ever published. Years ago AGMA published a method for the calculation of the specific oil film thickness containing some comments about micropitting, and the German FVA published a calculation method based on intensive research results. The FVA and the AGMA are close to the ISO/TR. New is the calculation of the micropitting safety factors.

The technical report presents two calculation rules, method A and B. Method A needs as input the Hertzian pressure on every point of the tooth flank, based on an accurate calculation of the meshing of the gear pair, considering tooth and shaft deflections to get the load distribution over the flank line in every meshing position. Method B is much simpler; the load distribution is defined for different cases as spur or helical gears, with and without profile modifications.

The risk of micropitting is highly influenced by profile and flank line modifications. A new software tool can evaluate the risk of micropitting for gears by automatically varying different combinations of tip reliefs, other profile modifications and flank line modifications, in combination with different torque levels, using method A. The user can define the number of steps for variation of the amount of modification. Then all possible combinations are checked combined with different (user defined) torque levels. Any modifications including flank twist, arc-like profile modifications, etc. can be combined. The result is presented in a table, showing the safety factor against micropitting for different subsets of profile/flank modifications, depending on the torque level.

Some applications from wind turbine and industrial gearboxes, known to the author, will be discussed.

ISBN: 1-978-61481-011-7 Pages: 15

11FTM13. Investigations on the Flank Load Carrying Capacity in the Newly Developed FZG Back-to-Back Test Rig for Internal Gears

Authors: **B.-R. Höhn, K. Stahl, J. Schudy, T. Tobie, and B. Zornek**

Micropitting, pitting and wear are typical gear failure modes, which can occur on the flanks of slowly operated and highly stressed internal gears. However, the calculation methods for the flank load carrying capacity have mainly been established on the basis of experimental investigations on external gears.

The target of a research project was to verify the application of these calculation models to internal gears. Therefore, two identical back-to-back test rigs for internal gears have been designed, constructed and successfully used for gear running tests. These gear test rigs are especially designed for low and medium circumferential speeds and allow the testing of the flank load carrying capacity of spur and helical internal gears for different pairings of materials at realistic stresses. The three planet gears of the test rig are arranged uniformly around the circumference. Experimental and theoretical investigations regarding the load distribution across the face width, the contact pattern and the load sharing between the three planet gears have been carried out.

Furthermore, substantial theoretical investigations on the characteristics of internal gears were performed. Internal and external spur gears were compared regarding their geometrical and kinematical differences as well as their impact on the flank load. Based on the results of these theoretical investigations an extensive test program of load stage tests and speed stage tests on internal gears of different material, different finishing of the flanks and different operating conditions has been carried out. The main focus of this test program was on the fatigue failures of micropitting and wear at low circumferential speeds.

The paper describes the design and functionality of the new developed test rigs for internal gears and shows basic results of the theoretical studies. Furthermore, it presents basic examples of experimental test results.

ISBN: 1-978-61481-012-4 Pages: 16

11FTM14. AGMA 925-A03 Predicted Scuffing Risk to Spur and Helical Gears in Commercial Vehicle Transmissions

Author: **C.H. Wink**

The risk of gear tooth scuffing in commercial vehicle transmissions has gained more attention because of increasing demand for fuel-efficient powertrain systems in which diesel engines run at lower speeds, power density is higher, and lubricants are modified to improve efficiency and compatibility with components of new technologies, such as dual clutch transmissions. Thus, predicting scuffing risk during the design phase is vital for the development of commercial vehicle transmissions. AGMA 925-A03 is a comprehensive method to predict the probability of gear scuffing. Therefore, this paper presents the AGMA 925-A03 scuffing risk predictions for a series of spur and helical gear sets in transmissions that are used in commercial vehicles ranging from SAE class 3 through class 8. Limiting scuffing temperatures of mineral and synthetic lubricants were determined from FZG scuffing tests, dynamometer tests and field data. The agreement between prediction, test results and actual usage can provide confidence in the predictor of scuffing risk of gears in commercial vehicle transmissions.

ISBN: 1-978-61481-013-1 Pages: 11

11FTM15. Micropitting – A Serious Damage? Testing, Standards and Practical Experience

Authors: **B. Pinnekamp, T. Weiss and G. Steinberger**

Micropitting is a surface fatigue phenomenon on highly loaded case hardened gear flanks. Main contributors are local stress, surface roughness, sliding speed and lube oil properties. To determine the lube oil performance with respect to micropitting, different test methods have been established in the past. Actual proposals are evaluated for adopting suitable calculation methods for micropitting resistance to the ISO 6336 gear rating standards. But is micropitting necessarily a damage in any case? Practical experience shows, that a certain level of micropitting is actually acceptable, leading to even more favorable load distribution and can end up in a stable flank condition performing without problems for the designed service live.

The paper describes testing, calculation approaches and application to practical cases with respect to micropitting on wind turbine and high speed gears and perennial observations and experience.

ISBN: 1-978-61481-014-8 Pages: 15

11FTM16. Gear Lubrication – Stopping Micropitting by Using the Right Lubricant

Authors: **M. Hochmann and H. Siebert**

Micropitting is a type of fatigue failure occurring on hardened tooth flanks of highly loaded gears. This failure consists of very small cracks and pores on the surface of tooth flanks. Micropitting looks greyish and causes material loss and a change in the profile form of the tooth flanks, which can lead to pitting and breakdown of the gears.

The formation of micropitting depends on different influences. Besides material, surface roughness, and geometry of the tooth flanks, the lubricant and the operating conditions show a main influence on micropitting formation.

The micropitting load-carrying capacity of gears can be calculated according to ISO/TR 15144-1, where the influence of lubricant, operating conditions, and surface roughness is considered with the specific lubricant film thickness. For this purpose, the specific lubricant film thickness of a practical gear is compared with a minimum required specific lubricant film thickness. The latter is the specific film thickness where no micropitting risk is given for a lubricant and can be determined by performing a micropitting test according to FVA 54/7. This test procedure consists of a load stage test and an endurance test. Lubricants with a high micropitting load-carrying capacity reach the failure criterion of a profile form deviation of 7.5 µm due to micropitting in load stage greater than or equal to LS 10 of the load stage test. In the endurance test, a stagnation of micropitting formation compared with the micropitting area at the end of the load stage test is preferred but not required.

In field applications, micropitting formation is often reported even though industrial gear oils with a high micropitting load-carrying capacity are used. Such oils offer a good micropitting protection determined in the load stage test, but with a low micropitting performance in the endurance test.

The aim of research is therefore the investigation whether a change from an oil with low micropitting performance in the endurance test to an oil with high micropitting performance in the endurance test can stop the micropitting formation.

ISBN: 1-978-61481-015-5 Pages: 11

11FTM17. Morphology of Micropitting

Author: **R.L. Errichello**

Micropitting occurs in gears and rolling-element bearings that operate in the mixed or micro EHL lubrication regime. It manifests in many different ways depending on the loads, speeds, rolling and sliding velocities, macrogeometry, surface topography, edge effects, metallurgy, and lubricant properties. The failure analyst must discern whether the micropitting is a primary failure mode or a secondary failure that occurs because of prior damage. Understanding the morphology of micropitting is the key to determining the primary failure mode and root cause of failure.

Several examples of micropitting in gears and rolling-element bearings are presented to illustrate the morphological variation that can occur in practice.

ISBN: 1-978-61481-016-2 Pages: 19

11FTM18. Longitudinal Tooth Contact Pattern Shift

Authors: **J.B. Amendola, J.B. Amendola III, and D. Yatzook**

After a period of operation turbo gears may exhibit a change in the tooth contact pattern, reducing full face width contact, and thereby increasing the risk of tooth distress due to the decreased loaded area of the teeth.

The phenomena may or may not occur. In some units the shift is more severe than others and has been observed in cases where there is as little as 50,000 hours of operation. In other cases, there is no evidence of any change for units in operation for more than 100,000 hours. This condition has been observed primarily in single helical gears with low helix angles (10–13°). All recorded observations have been with case carburized hardened and ground gear sets.

This paper describes the phenomena observed among some of many installed high speed gear units in field operation that have been inspected. The authors have not found any written material describing this behavior and upon further investigation suggest a possible cause. Left unchecked and without corrective action, this occurrence may result in tooth breakage.

ISBN: 1-978-61481-017-9 Pages: 11

11FTM19. Convoloid® Gearing Technology – The Shape of the Future

Authors: **B.E. Berlinger, Jr. and J. Colbourne**

Since the invention of the involute curve and the application thereof to gearing, the world has embraced and developed this type of gear tooth form to a very high degree of engineering and manufacturing excellence. Improvements in recent years have been relatively modest, since this form has been so rigorously studied and applied. The long term adoption of the involute is rooted in large part to the simplicity of its tools and field operation. Straight sided tools and conjugacy, even with limited changes in center distance, were consistent with the industrial revolution of the 18th, 19th, and 20th centuries, and the mechanically based machine tools of these ages. The recent ubiquitous nature of computers and CNC machinery exacerbates the cost effective freedom to optimize many parameters affecting gear tooth forms.

Convoloid is a new gear tooth form capable of increasing torques 20% to 35% over those of conventionally designed involute pairs. The form is computer optimized, is compatible with the world's existing capital asset infrastructure, and mirrors the manufacturing sequences, processes and basic production costs of involute gears. The result is a major enhancement in gear drive system power density and cost reduction for a given power requirement. Convoloid gearing is totally scalable and is used in parallel axis helical, planetary, and other configurations.

The design, rating (surface durability and bending), flash temperature analysis and other important performance criteria for this technology along with the manufacturing and inspection protocols in keeping with AGMA and ISO specifications will be discussed. Test results confirming many of the superior load carrying characteristics of this tooth form will be presented. Side by side comparisons of involute versus Convoloid designs and test performance results will be presented confirming the validity of the theory.

ISBN: 1-978-61481-018-6 Pages: 18

11FTM20. Case Study Involving Surface Durability and Improved Surface Finish

Authors: **G. Blake and J. Reynolds**

Gear tooth wear and micro-pitting is a very difficult phenomenon to predict analytically. The failure mode of micro-pitting is closely correlated to the lambda ratio. Micropitting can be the limiting design parameter for long-term durability. Also, the failure mode of micropitting can progress to wear or macropitting, and then manifest into more severe failure modes such as bending. The results of a gearbox test and manufacturing process development program will be presented to evaluate super finishing and its impact on micropitting.

Testing was designed using an existing aerospace two stage gearbox with a low lambda ratio. All gears were carburized, ground and shot peened. Two populations were then created and tested. One population was finish honed and the second was shot peened and isotropic super finished.

A standard qualification test was conducted for 150hrs at maximum continuous load. The honed gears experienced micro and macro pitting during the test. The Isotropic Super Finishing (ISF) gears were also tested for 150hr under the same loading. The ISF gears were absent of any surface distress. The ISF gears were further subjected to a 2000hr endurance test. The ISF gears had less surface distress after 2000hr than the baseline honed gears after 150hrs.

ISBN: 1-978-61481-019-3 Pages: 18

11FTM21. Gearbox Bearing Service Life – A Matter of Mastering Many Design Parameters

Author: **H. Wendeberg**

The service life of a gearbox is determined by many factors. The bearings in the gearbox play a major role since they themselves deliver an important function, and in addition interact with the shafts, the casing and the oil. Without a doubt, the sizing of the bearings is of great importance for the gearbox reliability. Since more than 50 years the bearing dynamic carrying capacity has been used to determine a suitable size needed to deliver a sufficient fatigue life – but despite the advanced calculation methods developed, the methods do not fully predict service life. Producers of high quality bearings have introduced high performance class bearings and, lacking better ways to express the improved performance, this is only represented by increased dynamic carrying capacity.

The availability of high-strength shaft materials in combination with bearings with high carrying capacity allows slimmer shafts to be used. The modulus of elasticity remains the same, so seat design for bearings and gears must be given close attention.

This paper covers the following: sizing of bearings based on dynamic carrying capacity and how this relates to service life; how the design of the interface between bearing and shafts should be adapted to modern shaft materials; how the design of the interface between bearing and gearbox casing influences service life of the gearbox; and influence of modern electric motor speed controls in bearing type selection.

ISBN: 1-978-61481-020-9 Pages: 17

11FTM22. Bearing Contribution to Gearbox Efficiency and Thermal Rating: How Bearing Design Can Improve the Performance of a Gearbox

Author: **A. Doyer**

Gearbox efficiency is a topic of rising interest amongst both OEM and end-users due to an increased sensitivity to gearbox performance, reliability, total cost of ownership (energy cost), overall impact on the environment, and also anticipating future regulations.

In a gearbox there are difference sources of losses: gear, lubrication, seal and bearing loss. The use of modern simulation tools makes easier the evaluation of losses in various load case conditions. It has been demonstrated that the contribution of bearing loss on the system efficiency is dependent on the load cases. Even if the bearing is by far not the primary source of losses, the optimization of the bearing set can significantly improve gearbox performance. Simulation of a single stage gearbox using tapered roller bearings shows that the running temperature of the gearbox can be reduced up to 10C, by using latest bearing generation. Such a saving could improve the thermal rating of the gearbox by up to 30%. Experiments also demonstrated that different design of tapered roller bearing shows significant variation in friction performance.

Having proper bearing design can significantly improve the performance of a gear unit: by a lower running temperature, by improving lubricant life, potentially simplified lubrication system, and consequently reduced running cost.

ISBN: 1-978-61481-022-3 Pages: 12

11FTM23. Integration of Case Hardening into the Manufacturing-Line: "One Piece Flow"

Authors: **V. Heuer, K. Löser, G. Schmitt and K. Ritter**

For decades the gear industry has addressed the challenge to produce high performance components in a cost-efficient manner. To meet quality specifications, the components need to be heat treated, which traditionally takes place in a central hardening shop. However, this separation between machining and heat treatment results in high costs for transportation and logistics within the production plant. Therefore, for many years it has been being discussed how to integrate heat treatment into the manufacturing line.

For about 10 years it has been possible to integrate heat treatment into the machining facility by applying the technology of Low Pressure Carburizing (LPC) and High Pressure Gas Quenching (HPGQ). The components are collected after soft-machining into big batches and treated with LPC- and HPGQ-technology. This means however that the heat treatment is not synchronized with soft- and hard-machining since the components must be collected in buffers before heat treatment and must be singularized again after heat treatment.

In order to totally integrate heat treatment into the manufacturing line and in order to synchronize heat-treatment with machining, a new heat treatment cell has been developed. Following the philosophy of "One Piece Flow" the parts are: taken one by one from the soft machining unit; then heat treated in time with the cycle-time of soft machining ("synchronized heat treatment") and then passed down one-by-one to the hard machining unit. To allow for rapid case hardening, the components are low pressure carburized at high temperatures (1050°C) followed by gas quenching.

In addition to the cost-savings for logistics, the new concept in equipment offers the following advantages: individual processes customized for each gear-component; homogenous and quick heating of the components and therefore low spread of distortion; homogenous and controllable gas quenching and therefore low spread of distortion; environmentally friendly carburizing and quenching; and compact and space-saving heat treat unit.

The paper shows first results achieved with the new process technology applied in the new heat treatment cell.

ISBN: 1-978-61481-023-0 Pages: 12

11FTM24. Induction Hardening of Gears with Superior Quality and Flexibility Using Simultaneous Dual Frequency (SDF®)

Authors: **C. Krause, F. Biasutti, and M. Davis**

Induction hardening of gear teeth is well known for its challenges, but also for its potential for improved quality and process control. For complex geometric parts like gears, the power density and induction frequency need to be adjusted very precisely to achieve the required hardening pattern. Since 1940s it is known that working with two simultaneous frequencies (1–15 kHz and 200–20 000 kHz) is the optimal way to heat a geared part to hardening temperature. The key point in this process is that the medium frequency (about 10 kHz) affects primarily the tooth root and the high frequency affects first of all the tip of the tooth and the flanks. The right combination of the power densities of medium- and high-frequency energy values and the heating time are the crucial factors to reach a contour true heating pattern and, thereby, a contour true hardening pattern.

The authors will describe the state of the art of induction hardening of gears with simultaneous dual frequency using some examples of use and present the possibilities to manipulate the hardening pattern in a positive way for different gear geometries.

ISBN: 1-978-61481-024-7 Pages: 8

11FTM25. Controlling Gear Distortion and Residual Stresses During Induction Hardening

Authors: **Z. Li and B.L. Ferguson**

Induction hardening is widely used in both automotive and aerospace gear industries to reduce distortion and obtain favorable residual stresses. The heating process during induction hardening has a significant effect on the quality of the heat-treated parts, but the importance of the quench portion of the process often receives less attention. However, experiences have shown that the cooling rate, cooling fixture design and cooling duration can significantly affect the quality of the hardened parts in terms of distortion, residual stresses, as well as the possibility of cracking. DANTE is commercial heat treatment software based on finite element method. In this paper, DANTE is used to study an induction hardening process for a helical ring gear made of AISI 5130 steel. Prior to induction hardening, the helical gear is gas carburized and cooled at a controlled cooling rate. In this study, two induction frequencies in sequential order are used to heat the gear tooth. After induction heating, the gear is spray quenched using a polymer/water solution. By designing the spray nozzle configuration to quench the gear surfaces with different cooling rates, the distortion and residual stresses of the gear can be controlled. The crown and unwind distortions of the gear tooth are predicted and compared for different quenching process designs. The study also demonstrates the importance of the spray duration on the distortion and residual stresses of the quenched gear.

ISBN: 1-978-61481-025-4 Pages: 12

11FTM26. Atmosphere Furnace Heating Systems

Author: **J.W. Gottschalk**

A detailed evaluation of furnace heating systems is presented. Topics of discussion include application guidelines for both gas fired and electrically heated furnaces. Heating system selection considers operating temperature, processing atmosphere and heating method (radiant or convective heating) along with heating system orientation within the furnace chamber.

The evaluation consists of a comparison of operating costs, environmental considerations and lifetime maintenance costs of the various systems. Systems to be evaluated consist of alloy radiant tubes (single ended, U-tube, etc.), ceramic radiant tubes (single ended and U-tubes) and a variety of electrical element designs. Actual case studies of the various heating systems are presented with respect to maintenance and operating costs.

ISBN: 1-978-61481-026-1 Pages: 8

11FTM27. Manufacturing and Processing of a New Class of Vacuum-Carburized Gear Steels with Very High Hardenability

Authors: **C.P. Kern, J.A. Wright, J.T. Sebastian, J.L. Grabowski, D.F. Jordan and T.M. Jones**

Ferrium C61 and C64 are new secondary-hardening steels that provide superior mechanical properties versus 9310, 8620, Pyrowear Alloy 53 and other steels typically used for power transmission, such as significantly higher core tensile strength, fracture toughness, fatigue strength and thermal stability (i.e. tempering temperature). One recent example of their application is the application of C61 to the forward rotor shaft of CH-47 Chinook helicopter, in order to reduce the weight of the shaft by 15–25% and provide other benefits.

This paper reviews the significant manufacturing and processing benefits that arise from this new class of secondary-hardening steels, and analyze the potential implications and opportunities. C61 and C64 were computationally designed to take advantage of high-temperature, low-pressure (i.e. vacuum) carburization technology, in part by combining carburizing and austenizing steps as well as being designed to have very high hardenability. The very high hardenability of these steels permits a mild gas quench subsequent to low-pressure vacuum carburizing and reduces part distortion, thus reducing grind stock removal, simplifying final machining and heat treat operations. A framework analysis is used to compare total manufacturing/production costs and impacts (including environmental) of these new steels versus traditional gear steels. Conclusions and recommendations are drawn regarding best manufacturing practices and appropriate use of these new steels for product applications.

ISBN: 1-978-61481-027-8 Pages: 14

11FTM28. Simulation of Wear for High Contact Ratio Gear – A Mixed FE and Analytical Approach

Authors: **G. Venkatesan, M. Rameshkumar and P. Sivakumar**

High contact ratio gears offer high load carrying capacity and increased life with less volume and weight. Gear tooth wear of high contact ratio gears is of great importance as excessive wear is characterized by loss of tooth profile and thickness, which might result in higher dynamic gear mesh and tooth forces. Surface wear changes not only the contact pattern and load distribution, but also the vibration and noise characteristics of the gear system. This paper deals with the simulation of wear for high contact ratio (HCR) and normal contact ratio (NCR) gears using a Mixed Finite Element (FE) and analytical approach. A numerical model for wear prediction of gear pair is developed. The methodology employs single point, observation-based gear contact mechanics in conjunction with the Archard's wear formulation to predict the tooth wear in spur gears. The contact pressure and loads are determined using a FE approach in which a two dimensional deformable body contact model of HCR and NCR gears is analyzed in ANSYS software, and ANSYS Parametric Design language (APDL) is used for capturing the load sharing ratio and contact stress variation on the complete mesh cycle of the gear pair. A MATLAB code program is developed to determine the sliding velocities, equivalent contact radius and contact width along the path of contact for both HCR and NCR gears. The contact loads and pressures obtained using FEM are used for predicting the wear depth for NCR and HCR gear pair.

ISBN: 1-978-61481-021-6 Pages: 12

2010 PAPERS

10FTM01. Complete Machining of Gear Blank and Gear Teeth

Author: **C. Kobialka**

Demands for increased throughput, with smaller lot sizes at lower cost have led to the development of an innovative approach to machining both: the gear bland and gear teeth on a single machine.

This paper will concentrate on the potentials and risks of combined process machines what are capable of turning, hobbing, drilling, milling, chamfering and deburring of cylindrical gears. The same machine concept can be used for singular operations of each manufacturing technology on the same design concept. This leads to reduced amounts of different spare parts, increases achievable work piece quality and harmonizes on common user friendliness. In the end the economic potential of combined process technology and a vision for integrated heat treatment is shown.

ISBN: 1-55589-976-9 Pages: 8

10FTM02. Improving Heat Treating Flexibility for Wind Turbine Gear Systems through Carburizing, Quenching and Material Handling Alternatives

Author: **W. Titus**

Part handling and processes for heat treating large gears have created challenges for decades. Growth in wind energy technology has focused more attention on this issue in recent years. The vast majority of installations processing such large parts utilize conventional methods via pit furnace systems. Such equipment has inherent limitations with respect to quench flow and part handling, making true improvements in areas such as distortion control difficult due to physical limitations of this processing approach. This presentation will explain alternative methods for heat treating large components that allow part distortion to be minimized. Benefits will be quantified regarding cost savings to produce such gearing and quality.

ISBN: 1-55589-977-6 Pages: 19

10FTM03. A Novel Approach to the Refurbishment of Wind Turbine Gears

Authors: **M. Michaud, G.J. Sroka and R.E. Benson**

Multi-megawatt wind turbine gearboxes operate under demanding environmental conditions including considerable variation in temperature, wind speed, and air quality. It is not uncommon for gearboxes rated for a maintenance free 20-year lifespan to fail after only a few years. These gearboxes experience several types of repairable damage including micropitting or “gray staining", abrasive wear, foreign object debris (FOD) damage, surface corrosion and fretting corrosion. Wear is greatest on the input stage, especially on the sun pinion gear. Historically, grinding is utilized to refurbish these damaged gears. However, there are numerous drawbacks including but not limited to high capital investment and the extraordinary amount of time and skill involved in the grinding process. Moreover, nitrided gears cannot be ground and must be scrapped. However, chemically accelerated vibratory finishing, or isotropic superfinishing (ISF), represents a value adding, low-cost option for refurbishing both case carburized and nitrided gears. Isotropic superfinishing removes light to moderate gear flank surface damage. The result is a surface with a non-directional pattern with a roughness of approximately 0.08 mm or less. Moreover, evidence suggests that isotropic superfinishing imparts a finish that increases gear durability and service life in the field. A case study on a sun pinion gear is presented.

ISBN: 1-55589-978-3 Pages: 10

10FTM04. Low Distortion Heat Treatment of Transmission Components

Authors: **V. Heuer, K. Löser, D.R. Faron and D. Bolton**

In many applications the high demands regarding service life of transmission components can be reached only by the application of a customized case hardening. This case hardening process results in a wear resistant surface-layer in combination with a tough core of the component. However, as a side-effect the components get distorted during heat treatment. This distortion has a significant cost-impact, because distorted components often need to be hard-machined after heat treatment. Therefore, the proper control of distortion is an important measure to minimize production costs.

By applying the technology of low pressure carburizing (LPC) and high pressure gas quenching (HPGQ) heat treat distortion can be significantly reduced. HPGQ provides a very uniform heat transfer coefficient. The predictability of movement during quenching is more certain and uniform throughout the load. Further improvements can be achieved by “Dynamic Quenching" processes where the quenching severity is varied during the quench sequence by step control of the gas velocity. Proper fixturing is another factor for distortion control. Modern CFC-materials (carbon reinforced carbon) are well suited as fixture-material for gas quenching.

The paper presents how LPC and HPGQ processes are successfully applied on internal ring gears for a 6 speed automatic transmission. The specific challenge in the heat treat process was to reduce distortion in such a way that subsequent machining operations are entirely eliminated. As a result of extensive development in the quenching process and the use of specialized CFC-fixtures it was possible to meet the design metrological requirements.

The Internal ring gears addressed in this report have been in continuous production since 2006. Subsequent testing and monitoring over a two-year period progressively demonstrated that consistent metrology was achieved and quality inspection was reduced accordingly.

ISBN: 1-55589-979-0 Pages: 16

10FTM05. Comparison of the AGMA and FEA Calculations of Gears and Gearbox Components Applied in the Environment of Small Gear Company

Author: **V. Kirov**

The current AGMA standards provide a lot of information about the calculations of loose gears and gearbox components – shafts, splines, keys, etc. These recommendations are based mostly on the "traditional" methods of mechanical engineering, found in many classical textbooks and research papers. Their accuracy and reliability have been proven in many years of gearbox design and field tests. They are clear, concise, in most cases easy to program and apply even by a small gear company with limited resources. However new methods for calculations of mechanical engineering components like FEA (finite element analysis) are becoming wide spread. Once these techniques were used only by big companies because of their complexity and price but with the development of the computer technology they become more and more accessible to small gear companies which are the majority of participants in the market.

Nowadays, in the gear business, even a small gear company is usually in possession of a modern CAD system which always includes a basic or advanced FEA package. Such CAD systems are most often run by one gear engineer who makes 3D models, engineering calculations and production drawings. The level of the FEA packages is such that it allows the gear engineer to be able to do components calculations without deep knowledge in the FEA itself.

So the question about the effectiveness of the traditional AGMA calculations and the new FEA methods becomes of vital importance particularly for small firms.

ISBN: 1-55589-980-6 Pages: 9

10FTM06. Finite Element Analysis of High Contact Ratio Gear

Authors: **M. Rameshkumar, G. Venkatesan and P. Sivakumar**

Modern day vehicles demand higher load carrying capacity with less installed volume and weight. The gears used in the vehicles should also have lesser noise and vibration. Even though helical gears will meet the requirement, they are prone for additional axial thrust problem. High contact ratio (HCR) is one such gearing concept used for achieving high load carrying capacity with less volume and weight. Contact ratio greater than 2.0 in HCR gearing results in lower bending and contact stresses. Previously published literature deal with studies on various parameters affecting performance of HCR gears but a comparison of HCR and normal contact ratio (NCR) gears with same module and center distance has not been carried out so for. This paper deals with finite element analysis of HCR, NCR gears with same module, center distance and the comparison of bending, contact stress for both HCR, NCR gears. A two dimensional deformable body contact model of HCR and NCR gears is analyzed in ANSYS software. ANSYS Parametric Design language (APDL) is used for studying the bending and contact stress variation on complete mesh cycle of the gear pair for identical load conditions. The study involves design, modeling, meshing and post processing of HCR and NCR gears using single window modeling concept to avoid contact convergence and related numerical problems.

ISBN: 1-55589-981-3 Pages: 12

10FTM07. A New Statistical Model for Predicting Tooth Engagement and Load Sharing in Involute Splines

Authors: **J. Silvers, C.D. Sorensen and K.W. Chase**

Load-sharing among the teeth of involute splines is little understood. Designers typically assume only a fraction of the teeth are engaged and distribute the load uniformly over the assumed number of engaged teeth. This procedure can widely over- or underestimate tooth loads.

A new statistical model for involute spline tooth engagement has been developed and presented earlier, which takes into account the random variation of gear manufacturing processes. It predicts the number of teeth engaged and percent of load carried by each tooth pair. Tooth-to-tooth variations cause the clearance between each pair of mating teeth to vary randomly, resulting in a sequential, rather than simultaneous tooth engagement. The sequence begins with the tooth pair with the smallest clearance and proceeds to pick up additional teeth as the load is increased to the maximum applied load. The new model can predict the number of teeth in contact and the load share for each at any load increment.

This report presents an extension of the new sequential engagement model, which more completely predicts the variations in the engagement sequence for a set of spline assemblies. A statistical distribution is derived for each tooth in the sequence, along with its mean, standard deviation and skewness. Innovative techniques for determining the resulting statistical distributions are described. The results of an in-depth study are also presented, which verify the new statistical model. Monte Carlo Simulation of spline assemblies with random errors was performed and the results compared to the closed-form solution. Extremely close agreement was found. The new approach shows promise for providing keener insights into the performance of spline couplings and will serve as an effective tool in the design of power transmission systems.

ISBN: 1-55589-982-0 Pages: 17

10FTM08. Calculation of Load Distribution in Planetary Gears for an Effective Gear Design Process

Authors: **T. Schulze, C. Hartmann-Gerlach, B. Schlecht**

The design of gears—especially planetary gears—can just be carried out by the consideration of influences of the whole drive train and the analysis of all relevant machine elements. In this case the gear is more than the sum of its machine elements. Relevant interactions need to be considered under real conditions. The standardized calculations are decisive for the safe dimensioning of the machine elements with the consideration of realistic load assumptions. But they need to be completed by extended analysis of load distribution, flank pressure, root stress, transmission error and contact temperature.

ISBN: 1-55589-983-7 Pages: 11

10FTM09. Reverse Engineering

Author: **C.D. Schultz**

As America's manufacturing base has contracted the need for reverse engineering has grown. Well established suppliers have disappeared, often leaving customers with no source of spare parts or technical support. Over time certain pieces of equipment require changes to output speeds or power levels and new parts have to be designed, built, and installed. And unfortunately, some pieces of equipment don't measure up to the demands they are subjected to and need redesign or improvement. In many ways, reverse engineering is just as demanding a discipline as original product development with many of the same challenges but plus the additional restrictions of fitting inside of an existing envelope.

The typical reverse engineering project begins with very limited information on the existing piece of equipment. This paper will describe a methodology for the reliable measurement, evaluation, re-design, and manufacture of replacement parts for gearboxes and industrial machinery. A step-by-step example will be provided.

ISBN: 1-55589-984-4 Pages: 9

10FTM10. Evaluation of Methods for Calculating Effects of Tip Relief on Transmission Error, Noise and Stress in Loaded Spur Gears

Author: **D. Palmer and M. Fish**

The connection between transmission error and noise and vibration during operation has long been established. Calculation methods have developed to describe the influence such that it is possible to evaluate the relative effect of applying a specific modification at the design stage. The calculations can allow the designer to minimize the excitation from the gear pair engagement at a specific load. This paper explains the theory behind transmission error and the reasoning behind the method of applying the modifications through mapping the surface profiles and deducing the load sharing. It can be used to explain the results of later experimental validation on various types of tip relief in low contact ratio (LCR) gears, from very long to very short. The paper will also demonstrate that though the effects of modification in any specific case can be modeled with some certainty, the same modifying strategy cannot be applied universally but must consider the required operating conditions. It illustrates that the effect of tip relief on transmission error and load sharing is not a black art but can be fully explained by applying existing theory.

A study of high contact ratio (HCR) gears will be presented to demonstrate why it is often necessary to apply different amounts and extents of tip relief in such designs, and how these modifications affect load sharing and highest point of tooth loading. Specific attention will be paid to the phenomenon of extended contact, where if no modification or insufficient tip relief is applied, contact does not stop at the end of active profile but continues beyond this point as the gear rotates resulting in contact on the tip. This effectively increases contact ratio and has implications for the tooth load and in particular how this may affect the loading position, highest point of single tooth contact (HPSTC), which is relevant to both ISO and AGMA standard rating. The paper will consider 3 methods commonly employed in the industry; a simple 2D mapping procedure carried out on graph paper, a 3D linear tooth stiffness computation method, and a 3D finite element analysis (FEA) calculation. The paper will demonstrate that though in some cases these methods can produce similar results, albeit with varying degrees of accuracy, further examples will be presented which demonstrate behavior which can only be detected using some of the more complex analysis methods. The commercial viability of implementing a better quality models against the time constraints in the development process will be discussed and conclusions drawn.

ISBN: 1-55589-985-1 Pages: 15

10FTM11. Point-Surface-Origin, PSO, Macropitting Caused by Geometric Stress Concentration, GSC

Authors: **R.L. Errichello, C. Hewette, and R. Eckert**

Point-Surface-Origin, PSO, macropitting occurs at sites of Geometric Stress Concentration, GSC, such as discontinuities in the gear tooth profile caused by micropitting, cusps at the intersection of the involute profile and the trochoidal root fillet, and at edges of prior tooth damage such as tip-to-root interference. When the profile modifications in the form of tip relief, root relief, or both are inadequate to compensate for deflection of the gear mesh, tip-to-root interference occurs. The interference can occur at either end of the path of contact, but the damage is usually more severe near the start-of-active-profile, SAP, of the driving gear.

An FZG-C gearset (with no profile modifications) was tested at load stage 9 and three pinion teeth failed by PSO macropitting. It is shown that the root cause of the PSO macropitting was GSC created by tip-to-root interference.

ISBN: 1-55589-986-8 Pages: 11

10FTM12. Flank Load Carrying Capacity and Power Loss Reduction by Minimized Lubrication

Authors: **B.-R. Höhn, K. Michaelis and H.-P. Otto**

The lubrication of gears has two major functions: Reducing friction and wear as well as dissipating heat. The power losses, especially the no-load losses, decrease with decreasing immersion depth using dip lubrication. The load-dependent gear power losses are nearly unaffected by minimized lubrication. However, the gear bulk temperatures rise dramatically by using minimized lubrication due to a lack of heat dissipation.

With minimized lubrication the scuffing load carrying capacity decreased by up to more than60%compared to rich lubrication conditions. The dominating influence of the bulk temperature is therefore very clear. Starved lubrication leads to more frequent metal-to-metal contact and the generation of high local flash temperatures must be considered. An additional factor for the scuffing load carrying capacity calculation in case of minimized lubrication conditions is proposed.

Concerning pitting damage test runs showed that by lowering the oil level the load cycles without pitting damage decreased by approximately 50% up to 75% for minimized lubrication compared to the results with rich lubrication conditions. The allowable contact stress is clearly reduced (up to 30%) by minimized lubrication. A reduced oil film thickness as a consequence of increased bulk temperatures results in more frequent metal-to-metal contacts causing a higher surface shear stress. In combination with a decreased material strength due to a possible tempering effect at high bulk temperatures the failure risk of pitting damage is clearly increased. The common pitting load carrying capacity calculation algorithms according to DIN/ISO are only valid for moderate oil temperatures and rich lubrication conditions. For increased thermal conditions, the reduction of the pitting endurance level at increased gear bulk temperatures can be approximated with the method of Knauer (FZG TU München, 1988). An advanced calculation algorithm for pitting load carrying capacity calculation at high gear bulk temperatures (valid for high oil temperatures as well as for minimized lubrication) is proposed.

The micropitting risk was increased by low oil levels, especially at high loads and during the endurance test. The micropitting damage is caused by poor lubrication conditions which are characterized by a too low relative oil film thickness due to high bulk temperatures. Again, the actual bulk temperatures are of major significance for calculation of the micropitting load carrying capacity.

The wear rate of the gears is almost unaffected by the oil level. Only a slight increase of wear could be observed with minimized lubrication. This increase can be explained by the higher bulk temperature of the gears running under minimized lubrication conditions. The investigations showed that there exists a natural limitation for lowering the oil quantity in transmissions without detrimental influence on the load carrying capacity. Knowing these limitations enables the user to determine the possible potential benefits of reduced oil lubrication. The correct prediction of the actual gear bulk temperatures is of major importance in this context. A method for the estimation of the gear bulk temperature at reduced immersion depth respectively poor lubrication conditions is proposed.

ISBN: 1-55589-987-5 Pages: 15

10FTM13. Gear Design for Wind Turbine Gearboxes to Avoid Tonal Noise According to ISO/IEC 61400-11

Author: **J. Litzba**

Present wind turbine gearbox design usually includes one or two planetary gear stages and at least one high speed helical gear stage, which play an important role regarding noise and vibration behavior. Next to the overall noise of the gearbox and the structure-born noise on the gearbox housing also tonal noise is becoming a much more important issue in recent years. Since tonal noise is problematic due to the human perception as “uncomfortable", avoidance is important. Conventional theories regarding low noise gear design are not developed in view of tonal noise. This leads to the question: How to deal with tonal noise in the design stage and which gear parameters can be used for an optimization regarding good tonal noise behavior?

Within a research project measurements have been performed on different gearboxes using different gear designs. These measurements have been evaluated according to ISO/IEC 61400-11 and the results have been analyzed in view of the influence of different gear parameters. It was also investigated if it is possible to rank gearboxes in wind turbines according to their tonal noise behavior as observed on the test rig.

The paper will give an introduction into the definition of tonal noise according to ISO/IEC 61400-11 and give insight in measurement results from test rigs and from gearboxes in the field, where noise behavior is also evaluated according to ISO/IEC 61400-11. Furthermore, the paper will show and discuss the link between measurement results and different gear parameters, which are affecting tonal noise behavior. In addition, simulation results will be presented, showing how tonal noise can be estimated within the design stage using state-of-the–art calculation software.

The paper will give recommendations regarding a gear design process that is considering tonal noise in the design stage and will compare an, regarding tonal noise, improved gear set with an older one.

ISBN: 1-55589-988-2 Pages: 19

10FTM14. Analysis and Testing of Gears with Asymmetric Involute Tooth Form and Optimized Fillet Form for Potential Application in Helicopter Main Drives

Authors: **F.W. Brown, S.R. Davidson, D.B. Hanes, D.J. Weires and A. Kapelevich**

Gears with an asymmetric involute gear tooth form were analyzed to determine their bending and contact stresses relative to symmetric involute gear tooth designs which are representative of helicopter main drive gears. Asymmetric and baseline (symmetric) toothed gear test specimens were designed, fabricated and tested to experimentally determine their single-tooth bending fatigue strength and scuffing resistance. Also, gears with an analytically optimized root fillet form were tested to determine their single-tooth bending fatigue characteristics relative to baseline specimens with a circular root fillet form. Test results demonstrated higher bending fatigue strength for both the asymmetric tooth form and optimized fillet form compared to baseline designs. Scuffing resistance was significantly increased for the asymmetric tooth form compared to a conventional symmetric involute tooth design.

ISBN: 1-55589-989-9 Pages: 15

10FTM15. Drive Line Analysis for Tooth Contact Optimization of High Power Spiral Bevel Gears

Authors: **J. Rontu, G. Szanti and E. Mäsä**

It is a common practice in high power gear design to apply relieves to tooth flanks. They are meant to prevent stress concentration near the tooth edges. Gears with crownings have point contact without load. When load is applied, instantaneous contact turns from point into a Hertzian contact ellipse. The contact area grows and changes location as load increases. To prevent edge contact, gear designer has to choose suitable relieves considering contact indentations as well as relative displacements of gear members. In the majority of spiral bevel gears spherical crownings are used. The contact pattern is set to the center of active tooth flank and the extent of crownings is determined by experience. Feedback from service, as well as from full torque bench tests of complete gear drives have shown that this conventional design practice leads to loaded contact patterns, which are rarely optimal in location and extent. Too large relieves lead to small contact area and increased stresses and noise; whereas too small relieves result in a too sensitive tooth contact.

Today it is possible to use calculative methods to predict the relative displacements of gears under operating load and conditions. Displacements and deformations originating from shafts, bearings and housing are considered. Shafts are modeled based on beam theory. Bearings are modeled as 5-DOF supports with non-linear stiffness in all directions. Housing deformations are determined by FEM-analysis and taken into account as translations and rotations of bearing outer rings. The effect of temperature differences, bearing preload and clearances are also incorporated.

With the help of loaded tooth contact analysis (LTCA), it is possible to compensate for these displacements and determine a special initial contact position that will lead to well centered full torque contact utilizing a reasonably large portion of the available tooth flank area. At the same time, crownings can be scaled to the minimum necessary amount. This systematic approach leads to minimum tooth stressing, lower noise excitation as well as increased reliability and/or power density as compared to conventional contact design method.

During recent years ATA Gears Ltd. has gained comprehensive know-how and experience in such analyses and advanced contact pattern optimization. The methodology and calculation models have been verified in numerous customer projects and case studies.

ISBN: 1-55589-990-5 Pages: 14

10FTM16. Analysis of Load Distribution in Planet-Gear Bearings

Authors: **L. Mignot, L. Bonnard and V. Abousleiman**

In epicyclic gear sets aimed at aeronautical applications, planet-gears are generally supported by spherical roller bearings with bearing outer race being integral to the gear hub. This paper presents a new method to compute roller load distribution in such bearings where the outer ring can't be considered rigid. Based on well-known Harris method, a modified formulation enables to account for centrifugal effects due to planet-carrier rotation and to assess roller loads at any position throughout the rotation cycle. New model load distribution predictions show discrepancies with results presented by Harris, but are well correlated with 1D and 3D Finite Element Models. Several results validate the use of simplified analytical models to assess the roller load distribution instead of more time consuming Finite Element Models. The effects of centrifugal effects due to planet-carrier rotation on roller loads are also analyzed. Finally, the impact of the positions of rollers relative to the gear mesh forces on the load distribution is shown.

ISBN: 1-55589-991-2 Pages: 11

10FTM17. Self-Locking Gears: Design and Potential Applications

Authors: **A.L. Kapelevich and E. Taye**

In most of the gear drives, when the driving torque is suddenly reduced as a result of power off, torsional vibration, power outage or any mechanical failure at the transmission input side, then gears will be rotating either in the same direction driven by the system inertia, or in the opposite direction driven by the resistant output load due to gravity, spring load, etc. The latter condition is known as backdriving. During inertial motion or backdriving, the driven output shaft (load) becomes the driving one and the driving input shaft (load) becomes the driven one. There are many gear drive applications where the output shaft driving is less desirable. In order to prevent it, different types of brake or clutch devices are used. However, there are also solutions in gear transmission that prevent inertial motion or backdriving using self-locking gears without any additional devices. The most common one is a worm gear with a low lead angle. In self-locking worm gears, torque applied from the load side (worm gear) is blocked, i.e. cannot drive the worm. However, their application comes with some limitations: the crossed axis shafts' arrangement, relatively high gear ratio, low speed, low gear mesh efficiency, increased heat generation, etc.

The paper describes the design approach as well as potential applications of the parallel axis self-locking gears. These gears, unlike the worm gears don't have such application limitations. They can utilize any gear ratio from 1:1 and higher. They can be external, internal, or incorporated into the planetary gear stage or multistage gear system. Their gear mesh efficiency is significantly higher than the worm gears and closer to conventional gears. As a result, they generate less heat. The self-locking can be designed to prevent either the inertia driving, or backdriving, or both. The paper explains the principle of the self-locking process for gears with symmetric and asymmetric teeth profile, and shows their suitability for different applications. It defines the main parameters of gear geometry and operating conditions. It also describes potential self-locking gear applications and references to related publications.

ISBN: 1-55589-992-9 Pages: 8

2009 PAPERS

09FTM01. Influence of the Residual Stresses Induced by Hard Finishing Processes on the Running Behavior of Gears

Authors: **V. Vasiliou, C. Gorgels and F. Klocke**

Low noise and high load carrying capacity are two important characteristics of competitive power transmissions. The challenge in the development, design and manufacturing of these power transmissions is to meet these requirements economically. One of the ways to meet both of these requirements is through a process known as hard finishing. There are various types of hard finishing and it is important to know which process produces which requirement.

The aim of this research project is to induce residual stresses in the edge of the work pieces by different hard finishing processes and to analyze their influence on the durability of the gears. The tested gears are manufactured by profile grinding, gear honing and generating grinding. The gear deviations and the finish quality have to be comparable. Through this the influence of the residual stresses on the durability can be analyzed independent from the geometrical conditions. The presentation will show the results of the load carrying capacity tests depending on the values of the residual stresses.

ISBN: 1-55589-954-7 Pages: 11

09FTM02. Implementing ISO 18653, Evaluation of Instruments for the Measurement of Gears

Authors: **R.C. Frazer and S.J. Wilson**

A trial test of the calibration procedures outlined in ISO 18653, *Gears – Evaluation of instruments for the measurement of individual gears*, showed that the results are reasonable, but a minor change to the uncertainty formula is recommended.

Gear measuring machine calibration methods are reviewed. The benefits from using work-piece like artifacts are discussed and a procedure for implementing the standard in the work place is presented.

Problems with applying the standard to large gear measuring machines are considered and some recommendations are offered.

ISBN: 1-55589-955-2 Pages: 15

09FTM03. Producing Profile and Lead Modifications in Threaded Wheel and Profile Grinding

Author: **A. Türich**

Modern gear boxes are characterized by high torque load demands, low running noise, and compact design. In order to fulfill these demands, profile and lead modifications are being applied more and more. The main reason for the application of profile and or lead modification is to compensate for the deformation of the teeth due to load, thus ensuring proper meshing of the teeth which will result in optimized tooth contact pattern.

This paper will focus on how to produce profile and lead modifications by using the two most common grinding processes, threaded wheel and profile grinding. In addition, more difficult modifications, such as defined flank twist or topological flank corrections, will also be described in this paper.

ISBN: 1-55589-956-1 Pages: 16

09FTM04. New Developments in Gear Hobbing

Author: **O. Winkel**

Several innovations have been introduced to the gear manufacturing industry in the past few years. In the case of gear hobbing, dry cutting technology and the ability to do it with powder-metallurgical HSS-materials might be two of the most impressive ones. But the technology is still moving forward. The aim of this paper is to present recent developments in the field of gear hobbing, focusing on innovations regarding tool materials, process technology and process integration.

ISBN: 1-55589-957-8 Pages: 18

09FTM05. HYPOLOID™ Gears with Small Shaft Angles and Zero to Large Offsets

Author: **H. Stadtfeld**

Beveloid gears are used to accommodate a small shaft angle. The manufacturing technology used for beveloid gearing is a special set up of cylindrical gear cutting and grinding machines.

A new development, called Hypoloid gearing, addresses the desire of gear manufacturers for more freedom in shaft angles. Hypoloid gear sets can realize shaft angles between zero and 20° and at the same time allow a second shaft angle (or an offset) in space which provides the freedom to connect two points in space.

In all wheel-driven vehicles that traditionally use a transfer case with a pinion/idler/gear arrangement or a chain, the exit of the transfer case needs to be connected with the front axle. This connection necessitates the use of two CV joints, because the front axle input point has a vertical offset and is shifted sideways with respect to the transfer case exit. Compared to a single CV joint, the two CV connections are more costly and less efficient.

However, the newly developed Hypoloids can remedy the situation by offering more freedom in shaft angle and additional offset which eliminates the need for an additional CV joint. Moreover, the Hypoloid technology offers enhanced performance compared to beveloids with straight teeth. In addition to the automotive drive trains, Hypoloid technology can be applied to aircraft as well as general gearbox manufacturing.

ISBN: 1-55589-958-5 Pages: 15

09FTM06. Dependency of the Peak-to-Peak Transmission Error on the Type of Profile Correction and Transverse Contact Ratio of the Gear Pair

Author: **U. Kissling**

Profile corrections on gears are a commonly used method to reduce transmission error, contact shock, and scoring risk. There are different types of profile corrections. It is a known fact, that the type of profile correction used will have a strong influence on the resulting transmission error. The degree of this influence may be determined by calculating tooth loading during mesh. The current method for this calculation is very complicated and time consuming; however, a new approach has been developed which could reduce the calculation time.

This approach uses an algorithm which includes the conventional method for calculating tooth stiffness in regards to bending and shearing deformation, flattening due to Hertzian pressure, and tilting of the tooth in the gear body. The new method was tested by comparing its results with FEM and LVR.

This paper illustrates and discusses the results of this study. Furthermore, the maximum local power losses are compared with the scoring safety calculated following the flash temperature criteria of AGMA 925 and DIN 3990.

ISBN: 1-55589-959-2 Pages: 19

09FTM07. Optimizing Gear Geometry for Minimum Transmission Error, Mesh Friction Losses and Scuffing Risk

Authors: **R.C. Frazer, B.A. Shaw, D. Palmer and M. Fish**

Minimizing gear mesh friction losses is important if plant operating costs and environmental impact are to be minimized. This paper describes how a validated 3D FEA and TCA can be used to optimize cylindrical gears for low friction losses without compromising noise and power density. Some case studies are presented and generic procedures for minimizing losses are proposed. Future development and further validation work is discussed.

ISBN: 1-55589-960-8 Pages: 20

09FTM08. Load Sharing Analysis of High Contact Ratio Spur Gears in Military Tracked Vehicle Application

Authors: **M. Rameshkumar, P. Sivakumar, K. Gopinath and S. Sundaresh**

Military tracked vehicles demand a very compact transmission to meet mobility requirements. Some of the desirable characteristics of these transmissions include: increased rating, improved power to weight ratio, low operating noise and vibration, and reduced weight. To achieve all or some of these characteristics, it is has been decided to apply a High Contact Ratio (HCR) spur gearing concept which will improve load carrying capacity, lower vibration, and reduce noise. Similar to helical gears, the load in HCR gearing is shared by minimum two pair of teeth. Therefore, load sharing analysis was conducted on Normal Contact Ratio (NCR) gearing used in sun-planet gears of an existing drive.

This paper deals with analysis of load sharing of individual teeth in mesh for different load conditions throughout the profile for both sun and planet gears of NCR/HCR gearing using Finite Element Analysis. Also, the paper reveals the variation of bending stress and deflection along the profile of both gearing designs.

ISBN: 1-55589-961-5 Pages: 12

09FTM09. Designing for Static and Dynamic Loading of a Gear Reducer Housing with FEA

Authors: **M. Davis, Y. S. Mohammed, A.A. Elmustafa, P.F. Martin and C. Ritinski**

A recent trend has been toward more user friendly products in the mechanical power transmission industry. One of these products is a high horsepower, right angle, shaft mounted drive designed to minimize installation efforts. Commonly referred to as “alignment-free” type, this drive assembly offers quick installation with minimum level of expertise required. It is also more cost effective. These characteristics make this type of drive ideal for use in applications such as underground mining where there is little room to maneuver parts.

An alignment free drive is direct coupled to the driven shaft only; it is not firmly attached to a foundation or rigid structure. A connecting link or torque arm connects the drive to a fixed structure, which limits the drive's rotational movement about the driven shaft. The electric motor is supported by the reducer housing through a fabricated steel motor adapter; the coupling connecting the motor shaft and reducer shaft is enclosed by this motor adapter.

FEA was used to test the cast iron housing to determine any potential problem areas before production began. Once analyses were completed, the motor adaptor was redesigned to lower stresses using the information from the FEA and comparing it to the infield test data.

ISBN: 1-55589-962-2 Pages: 9

09FTM10. The Effect of Flexible Components on the Durability, Whine, Rattle and Efficiency of a Transmission Geartrain System

Author: **A. Korde and B.K. Wilson**

Gear Engineers have long recognized the importance of considering system factors when analyzing a single pair of gears in mesh. These factors include: load sharing in multi-mesh gear trains, bearing clearances, and effects of flexible components such as housings, gear blanks, shafts, and carriers for planetary gears. Quality requirements and expectations in terms of durability, lower operating noise and vibration, and efficiency have increased. With increased complexity and quality requirements, a gear engineer must use advanced system design tools to ensure a robust gear train is delivered on time, meeting all quality, cost, and weight requirements.

As a standard practice, finite element models have traditionally been used for analyzing transmission system deflections, but this modeling environment does not always include provisions for analysis of vibration, efficiency, or any considerations for attribute variation. And that often requires many runs of the test to ensure all variations have been included and tested.

An advanced software tool is available for the analysis of transmission system durability, noise, vibration, and efficiency, all within a single programming environment, including the effects of flexible components such as housings, gear blanks, and shafting, while also allowing manufacturing variation studies to be performed. This paper includes the results of a case study of this program.

ISBN: 1-55589-963-9 Pages: 13

09FTM11. Unique Design Constraints for Molded Plastic Transmissions

Authors: **R. Kleiss and E. Wiita**

Molded plastic gears and transmissions must work effectively in extremely variable conditions just as their counterparts in steel. Plastics have the added variables of large thermal expansion and contraction, moisture absorption, greater tolerance variation, lower strength, and form deviations due to the molding process. The design of a molded transmission must consider these effects and characteristics. This paper will offer an example of the development of a molded plastic gear pump intended for the very steady delivery of 50 psi water pressure for a medical application. It will present our approach in design, tolerancing, material selection, molding procedure, and testing to achieve and verify an effective as-molded transmission.

ISBN: 1-55589-964-6 Pages: 7

09FTM12. The Anatomy of a Micropitting Induced Tooth Fracture Failure – Causation, Initiation, Progression and Prevention

Authors: **R.J. Drago, R.J. Cunningham, and S. Cymbala**

Micropitting has become a major concern in certain classes of industrial gear applications, especially wind power and other relatively highly loaded somewhat slow speed applications, where carburized gears are used to facilitate maximum load capacity in a compact package. While by itself the appearance of micropitting does not generally cause much perturbation in the overall operation of a gear system, the ultimate consequences of a micropitting failure can, and frequently are, much more catastrophic.

Micropitting is most often associated with parallel axis gears (spur and helical) however, the authors have also found this type of distress when evaluating damage to carburized, hardened and hard finished spiral bevel gears.

This paper presents a discussion of the initiation, propagation and ultimate tooth fracture failure mechanism associated with a micropitting failure. The subject is presented by way of the discussion of detailed destructive metallurgical evaluations of several example micropitting failures that the authors have analyzed on both parallel axis and bevel gears.

ISBN: 1-55589-965-3 Pages: 12

09FTM13. Bending Fatigue, Impact Strength and Pitting Resistance of Ausformed Powder Metal Gears

Authors: **N. Sonti, S. Rao and G. Anderson**

Powder metal (P/M) process is making inroads in automotive transmission applications because of substantially lower cost of P/M steel components for high volume production as compared to wrought or forged steel parts. Although P/M gears are increasingly used in powered hand tools, gear pumps, and as accessory components in automotive transmissions, P/M steel gears are currently in limited use in vehicle transmission applications.

The primary objective of this project was to develop high strength P/M steel gears with bending fatigue, impact, and pitting fatigue performance equivalent to current wrought steel gears. Ausform finishing tools and process were developed and applied to powder forged (P/F) steel gears in order to enhance the strength and durability characteristics of P/M gears, while maintaining the substantive cost advantage for vehicle transmission applications.

This paper presents the processing techniques used to produce Ausform finished P/F steel gears, and comparative bending fatigue, impact and surface durability performance characteristics of Ausform finished P/F steel gears, as well as conventional wrought steel gears.

ISBN: 1-55589-966-0 Pages: 14

09FTM14. Design Development and Application of New High-Performance Gear Steels

Authors: **J.A. Wright, J.T. Sebastian, C.P. Kern, and R.J. Kooy,**

A new class of high strength, secondary hardening gear steels that are optimized for high-temperature, low-pressure (i.e., vacuum) carburization is being developed. These alloys were computationally designed as secondary-hardening steels at three different levels of case hardness. The exceptional case hardness, in combination with high core-strength and toughness properties, offer the potential to reduce drive train weight or increase power density relative to incumbent alloys such as AISI 9310 or Pyrowear® X53.

This new class of alloys utilizes an efficient nano-scale M2C carbide strengthening dispersion, and their key benefits include: high fatigue resistance (contact, bending, scoring); high hardenability achieved via low-pressure carburization (thus reducing quench distortion and associated manufacturing steps); a tempering temperature of >900°F to provide up to a 500°F increase in thermal stability relative to incumbent alloys; and core tensile strengths in excess of 200 ksi. Ferrium C69™ is one alloy in this family that can achieve a carburized surface hardness of HRC 67 (with a microstructure substantially free of primary carbides), has exceptionally high contact fatigue resistance which make it an excellent candidate for applications such as camshafts and bearings as well as gear sets.

ISBN: 1-55589-967-7 Pages: 14

09FTM15. High Performance Industrial Gear Lubricants for Optimal Reliability

Authors: **K.G. McKenna, J. Carey, N.Y. Leon, and A.S. Galiano-Roth**

In recent years, gearbox technology has advanced and Original Equipment Manufacturers have required gear oils to meet the lubrication requirements of these new designs. Modern gearboxes operate under severe conditions and maintain their reliability to ensure end-user productivity. The latest generation of industrial gear lubricants can provide enhanced performance even under extreme operating conditions for optimal reliability and reduced cost of operation.

This paper describes how gear lubricants function in gearboxes and discusses the facts vs. myths of industrial gear lubricants. The paper will show how advanced gear lubricant technology can optimize the life of the gears, bearings and seals, resulting in reduced cost of operation. Opportunities to use advanced synthetic gear lubricants to achieve operational benefits in the areas of improved energy efficiency, wider operating temperature ranges, extended oil drain intervals and equipment life will be discussed.

ISBN: 1-55589-968-4 Pages: 16

09FTM16. Allowable Contact Stresses of Jacking Gear Units Used in the Offshore Industry

Author: **A. Montestruc**

An offshore jack-up drilling rig is a barge upon which a drilling platform is placed. The barge has legs which can be lowered to the sea floor to support the rig. Then the barge can be “jacked-up” out of the water providing a stable work platform from which to drill for oil and gas. The rack and pinion systems used to raise and lower the rig are enormous in terms of gear pitch or module by gear industry standards. Quarter pitch (101.6 module) pinions are common. Lifetime number of cycles for these units are—again, by gear industry standards—small, as rack teeth typically have 25-year lifetime cycles measured in the low hundreds. That is off the charts for AGMA (and ISO or DIN) design rules which draw a straight line to zero cycles for contact stress cycles less than 10,000. Use of any standards was abandoned from the start in the offshore industry for jacking applications. The author presents methods, and experience of that industry and suggested allowable contact stresses in such applications.

ISBN: 1-55589-969-1 Pages: 8

09FTM17. Variation Analysis of Tooth Engagement and Load-Sharing in Involute Splines

Authors: **K. Chase, C. Sorenson and B. DeCaires**

Involute spline couplings are used to transmit torque from a shaft to a gear hub or other rotating component. External gear teeth on the shaft engage an equal number of internal teeth in the hub. Because multiple teeth engage simultaneously, they can transmit much larger torques than a simple key and keyway assembly. However, due to manufacturing variations, the clearance between each pair of mating teeth varies, resulting in only partial engagement.

A new model for tooth engagement, based on statistics, predicts that the teeth engage in a sequence, determined by the individual clearances. As the shaft load is applied, the tooth pair with the smallest clearance engages first then deflects as the load increases, until the second pair engages. Thus, only a subset of teeth carry the load. In addition, the load is non-uniformly distributed, with the first tooth carrying the biggest share. As a consequence, the load capacity of spline couplings is greatly reduced, though still greater than a single keyway.

This paper discusses the results of a statistical model which predicts the average number of teeth which will engage for a specified load, plus or minus the expected variation. The model quantitatively predicts the load and stress in each engaged pair. Critical factors in the model are the stiffness and deflection of a single tooth pair and the characterization of the clearance. Detailed finite element analyses were conducted to verify the tooth deflections and engagement sequence. The closed form statistical results were verified with intensive Monte Carlo simulations.

ISBN: 1-55589-970-7 Pages: 14

09FTM18. Does the Type of Gear Action Affect the Appearance of Micro-Pitting and Gear Life?

Authors: **A. Williston**

Early results from testing conducted have raised questions concerning the role of gear action with the appearance of micropitting as well as surface fatigue (macropitting). Comparisons between similar gear sets with the same loads, speeds, and lubrication but operated either as speed increasers or as speed reducers have yielded strikingly different propensities for wear. Further, these observations are not limited to lubrication based failures such as micropitting, but, so far, have applied to traditional surface fatigue failures (macropitting) as well.

Findings point to an increase in the presence of micropitting on gearing operated as speed reducers. All components are operating at the same speed and load, yet wear is greatly reduced for the driven components.

Perhaps more intriguing is that to date all macropitting failures have occurred to the driving pinions of gear sets operated as speed reducers. While the number of samples is decidedly small, the length of life for these components is much less than would be anticipated under smooth load circumstances. The other gear sets (operated as speed increasers) do not show any fatigue wear.

In addition to how gear action affects micropitting in gearing is the question of how the gear action affects fatigue life. Current gear rating standards are based upon statistical analysis of real-world experience and mathematical stress-versus-cycle calculations. If gear action affects how gearing fails in fatigue, there may be significant ramifications in the industry. However, before any such conclusion may be made, additional testing is necessary.

ISBN: 1-55589-971-4 Pages: 30

09FTM19. The Effect of Gearbox Architecture on Wind Turbine Enclosure Size

Author: **C.D. Schultz**

Gearbox architecture—the type of gearing used, the overall gear ratio, the number of increaser stages, the number of meshes, the ratio combinations, and the gear proportions—can have a profound effect on the "package" size of a wind turbine. In this paper the author applies a common set of requirements to a variety of potential gearbox designs for a 2.0 MW wind turbine and compares the resulting "geared component" weights, gearbox envelope sizes, generator sizes, and generator weights. Each design option is also evaluated for manufacturing difficulty via a relative cost estimate.

ISBN: 1-55589-972-1 Pages: 19

2008 PAPERS

08FTM01. Parametric Study of the Failure of Plastic Gears

Authors: **M. Cassata and Dr. M. Morris**

This paper presents the results of collaboration to develop tools for the prediction of plastic gear tooth failure for any given set of operating conditions and to classify failure modes of these gears. The goal of the project is to characterize and predict the failure of plastic gears over a range of given parameters.

A test plan was developed to explore the effect of rotational speed, root stress, and flank temperature on the life of plastic gears. The dependent variable for the experiments was the number of cycles (or rotations) until failure.

ISBN: 1-55589-931-8 Pages: 7

08FTM02. A Methodology for Identifying Defective Cycloidal Reduction Components Using Vibration Analysis and Techniques

Authors: **V. Cochran and T. Bobak**

For several years, predictive maintenance has been gaining popularity as method for preventing costly and time consuming machine breakdowns. Vibration analysis is the cornerstone of predictive maintenance programs, and the equations for calculating expected vibration frequencies for bearings and toothed gear sets are widely available. Cycloidal reducers present a special case due to the nature of their reduction mechanism. This paper will describe a method for utilizing vibration analysis in order to identify a defective Cycloidal ring gear housing, disc, and eccentric bearing.

ISBN: 1-55589-932-5 Pages: 25

08FTM03. Effects of Gear Surface Parameters on Flank Wear

Authors: **J.C. Wang, J. Chakraborty, and H. Xu**

Non-uniform gear wear changes gear topology and affects the noise performance of a hypoid gear set. This paper presents the effects of gear surface parameters on gear wear and the measurement/testing methods used to quantify the flank wear in laboratory tests. Gear tooth profile, transmission error, gear tooth surface finish determined by cutting, and gear tooth surface finish determined by other processes are the factors considered in this paper. The measurements include transmission error, pattern rating, and surface roughness before and after test. The effects and interaction between controlled factors provided the information for product improvement. The action resulted from this study is anticipated to significantly improve product reliability and customer satisfaction.

ISBN: 1-55589-933-2 Pages: 15

08FTM04. The Effect of Manufacturing Microgeometry Variations on the Load Distribution Factor and on Gear Contact and Root Stresses

Authors: **D. Houser**

Traditionally, gear rating procedures directly consider manufacturing accuracy in the application of the dynamic factor, but only indirectly through the load distribution consider such errors in the calculation of stresses used in the durability and gear strength equations. This paper discusses how accuracy affects the calculation of stresses and then uses both statistical designs of experiments and Monte Carlo simulation techniques to quantify the effects of different manufacturing and assembly errors on root and contact stresses. Manufacturing deviations to be considered include profile and lead slopes and curvatures, as well as misalignment. The effects of spacing errors, runout and center distance variation will also be discussed.

ISBN: 1-55589-934-9 Pages: 15

08FTM05. Gear Failure Analysis Involving Grinding Burn

Authors: **G. Blake, M. Margetts, and W. Silverthorne**

Aerospace gears require post case-hardening grinding of the gear teeth to achieve their necessary accuracy. Tempering of the case hardened surface, commonly known as grinding burn, occurs in the manufacturing process when control of the heat generation at the surface is lost.

A gearbox with minimal service time was removed in service from an aircraft, disassembled, and visual inspection performed. Linear cracks along the dedendum of the working gear tooth face were found in three adjacent teeth. A detailed inspection of the gearbox found no other components with distress.

AGMA 2007-C00 provides details of the temper etch process and exclusively uses a Nitric acid etch process, which is typically used in production quality inspections. The incident gear was processed for grinding burn using an Ammonium Persulfate etch solution. Quality records documented variation in chemical concentration levels during the time the failed gear was manufactured. A design of experiments was conducted to understand the effects of the factors and interactions that impact the capability of the Ammonium Persulfate process used in production to detect grinding burn.

Presented are the metallurgical findings, load distribution analysis of actual geometry, crack propagation analysis, and design of experiment results of the Ammonium Persulfate etch process.

ISBN: 1-55589-935-6 Pages: 10

08FTM06. Tooth Fillet Profile Optimization for Gears with Symmetric and Asymmetric Teeth

Authors: **A. Kapelevich and Y. Shekhtman**

Involute flanks are nominally well described and classified by different standard accuracy grades, depending on gear application and defining their tolerance limits for such parameters as runout, profile, lead, pitch variation, and others.

The gear tooth fillet is an area of maximum bending stress concentration. However, its profile is typically marginally described as a cutting tool tip trajectory. Its accuracy is defined by a usually generous root diameter tolerance. The most common way to reduce bending stress concentration is application of the basic (or generating) rack with full radius.

This paper presents a fillet profile optimization technique based on the FEA and random search method, which allows for a substantial bending stress reduction, by 15 to 30% compared to traditionally designed gears. This reduction results in higher load capacity, longer lifetime, and lower cost. It includes numerical examples confirming the benefits of fillet optimization.

ISBN: 1-55589-936-3 Pages: 11

08FTM07. Planetary Gearset Lubrication Requirement Estimation Based on Heat Generation

Authors: **H. Kim, D. Zini, J. Chen and N. Anderson**

A planetary gearset is composed of sun gear, planet gears, ring gear, carrier and bearings. As the gearset is in motion under torque, heat is generated at all sliding and rolling contacts for gear meshes and bearing surfaces as lubricant is supplied. Without lubrication the gearset cannot operate properly because all contact surfaces are influenced by heat and subsequent damages. On the other hand, excessive lubrication could cause a significant heat generation as churning or dragging losses increase. It is very important to predict a right amount of lubrication required for each component and to supply a necessary amount of lubricant in an effective way.

Empirical data of temperature increase inside a planetary gearset at different inlet lubrication temperature, torque and speed are presented with physical explanation. It has been attempted to utilize heat generation data as an indicator for required lubrication measure and also for gearset efficiency measure. Heat generation sources are classified to examine largest and smallest contributors and then project a better way to effective lubrication for the planetary gearset. Some published gear efficiency equations are examined with power loss calculations based on gearset heat generations which are empirically measured in the present study.

ISBN: 1-55589-937-0 Pages: 17

08FTM08. PM Materials for Gear Applications

Authors: **S. Dizdar, A. Flodin, U. Engström, I. Howe and D. Milligan**

The latest material and process developments in powder metal (PM) gears have increased their load capacity. These new developments allow PM to fully compete with hardened machined wrought gears in a variety of power transmission applications. New grades of PM materials that can be case hardened using the same conditions as wrought materials improve their load capacity. Increased load capacity is also achieved by surface densifying gear teeth deeper than case hardened depth requirements. Since tooth Hertzian and bending stress gradients are within the fully dense layer, PM gears are virtually equivalent to wrought gears. The performance is demonstrated by gear tooth bending and RCF data on prototype gears.

ISBN: 1-55589-938-7 Pages: 9

08FTM09. Concept for a Multi Megawatt Wind Turbine Gear and Field Experience

Authors: **T. Weiss and B. Pinnekamp**

The increasing call for the use of renewable energy in all industrial countries demands for the extension of wind power generation capacity. In central Europe, as in parts of the Americas and Asia, such further expansion is only possible by re-powering— replacement of existing turbines by higher rated ones—or by developing locations in the open sea—offshore. To this end, the gear industry worldwide is challenged to develop and supply the required number of reliable 5 MW class wind turbine gears.

This paper summarizes the concept evaluation and design of the 5 MW Multibrid® wind turbine transmission arrangement, test bed measurements with the prototype, as well as field experience over a test period of 3 years.

ISBN: 1-55589-939-4 Pages 11

08FTM10. The Effect of Superfinishing on FZG Gear Micropitting – Part II

Authors: **L. Winkelmann and M. Bell**

The most common failure mechanism of highly stressed case carburized gears is micropitting (grey staining). The standard FZG gear test (FVA Work Sheet 54) is generally used to determine the micropitting load capacity of gear lubricants. In recent years, FZG gear testing has also demonstrated its usefulness for evaluating the effect of superfinishing on increasing the micropitting load capacity of gears. Results from the Technical University of Munich were previously presented in Part 1 of this paper. Part II will present the results of Ruhr University Bochum. Both research groups concluded that superfinishing is one of the most powerful technologies for significantly increasing the load carrying capacity of gear flanks.

ISBN: 1-55589-940-0 Pages: 10

08FTM11. Bending Fatigue Tests of Helicopter Case Carburized Gears: Influence of Material, Design and Manufacturing Parameters

Authors: **G. Gasparini, U. Mariani, C. Gorla, M. Filippini, and F. Rosa**

For helicopter gears many aspects of design and manufacturing must be analyzed, such as material cleanliness, case depth and hardness, tooth root shape and roughness, and compressive residual stresses. Moreover, these gears are designed to withstand loads in the gigacycle field, but are also subjected to short duration overloads. Therefore, a precise knowledge of the shape of the S-N curve is of great importance for assessing their in-service life.

A single tooth bending (STB) test procedure has been developed to optimally map gear design parameters and a test program on case carburized, aerospace standard gears has been conceived and performed in order to appreciate the influence of various technological parameters on fatigue resistance, and to draw the curve shape up to the gigacycles region.

The program has been completed by failure analysis on specimens and by static tests. Some accessory investigations, like roughness and micro-hardness measurements, have also been performed. Gigacycle tests confirm the estimations done on the basis of the shorter tests, both in term of fatigue limit and of curve shapes.

ISBN: 1-55589-941-7 Pages: 12

08FTM12. In-situ Measurement of Stresses in Carburized Gears via Neutron Diffraction

Authors: **R. LeMaster, B. Boggs, J. Bunn, J. Kolwyck, C. Hubbard, and W. Bailey**

The total stresses in a mating gear pair arise from two sources: 1) externally induced stresses associated with the transmission of power, and 2) residual stresses associated with the heat treatment and machining of the tooth profiles. The stresses due to power transmission are the result of complex normal and shearing forces that develop during the meshing sequence. The total stress from these two sources contributes to the life of a gear.

This paper, funded by the AGMA Foundation, presents the results of research directed at measuring the total stress in a pair of statically loaded and carburized spur gears. Measurements were made using neutron diffraction methods to examine the change in total stress as a function of externally applied load and depth below the surface. The paper includes a summary of the various test methods that were used and a discussion of their applicability to carburized gears.

ISBN: 1-55589-942-4 Pages: 10

08FTM13. Hydrogen & Internal Residual Stress Gear Failures – Some Failure Analyses and Case Studies

Author: **R. Drago**

Hydrogen and internal stress failures are relatively rare; however, when they occur they are often very costly and sometimes quite catastrophic. While hydrogen and internal stress issues are generally recognized as significant in the design and manufacture of larger gears, they are also important for smaller gears as well.

This paper presents, via illustrated actual case studies, the mechanisms by which these failures occur, the manner in which they progress, and methods for testing finished gears for the possibility of internal problems. In addition, precautionary steps that can be taken during design, manufacture, heat treatment and quality control to minimize the possibility of these problems occurring in a finished part along with similar steps required to prevent any flawed gears from entering service are also presented and discussed.

ISBN: 1-55589-943-1 Pages: 11

08FTM14. Effects of Axle Deflection and Tooth Flank Modification on Hypoid Gear Stress Distribution and Contact Fatigue Life

Authors: **H. Xu, J. Chakraborty, and J.C. Wang**

Flank modifications are often made to overcome the influences of errors coming from manufacturing and assembly processes, as well as deflections of the system. This paper presents a semi-analytical approach on estimating the axle system deflections by combining computer simulations and actual loaded contact patterns obtained from lab tests. By using an example hypoid gear design, influences of axle deflections and typical flank modifications (lengthwise crowning, profile crowning and twist) on stress distribution of the hypoid gear drive are simulated. Finally, several experimental gear samples are made and tested. Tooth surface topography is examined by using a Coordinate Measuring Machine. Test results are reported to illustrate the effect of tooth flank modifications on contact fatigue life cycles.

ISBN: 1-55589-944-8 Pages: 11

08FTM15. Extending the Benefits of Elemental Gear Inspection

Author: **I. Laskin**

It may not be widely recognized that most of the inspection data supplied by inspection equipment following the practices of AGMA Standard 2015 and similar standards are not of elemental accuracy, deviations but of some form of composite deviations. This paper demonstrates the validity of this “composite” label by first defining the nature of a true elemental deviation, and then, by referring to earlier literature, demonstrating how the common inspection practices for involute, lead (on helical gears), pitch, and in some cases, total accumulated pitch, constitute composite measurements. The paper further explains how such measurements often obscure the true nature of the individual deviations. It also contains suggestions as to some likely source of the deviation in various gear manufacturing processes, and how that deviation may affect gear performance. It further raises the question of the likely inconsistencies of some of these inspection results and of inappropriate judgments of gear quality, even to the point of the rejection of otherwise satisfactory gears. Finally, there are proposals for modifications to inspection software, possibly to some inspection routines, all to extending the benefits of the basic elemental inspection process.

ISBN: 1-55589-945-5 Pages: 12

08FTM16. Hob Tool Life Technology Update

Author: **T. Maiuri**

The method of cutting teeth on a cylindrical gear by the hobbing process has been in existence since the late 1800's. Advances have been made over the years in both the machines and the cutting tools used. This paper will examine hob tool life and the many variables that affect it. It will cover the state of the art cutting tool materials and coatings, hob tool design characteristics, process speeds and feeds, hob shifting strategies, wear characteristics, etc. The paper will also discuss the use of a common denominator method for evaluating hob tool life in terms of meters [or inches] per hob tooth as an alternative to tool life expressed in parts per sharpening.

ISBN: 1-55589-946-2 Pages: 15

08FTM17. Innovative Concepts for Grinding Wind Power Energy Gears

Author: **C. Kobialka**

Over the past years, wind power energy has gained greater importance to reduce CO2 emissions and thus antagonize global warming. The development of wind power is driven by increased performance, which requires larger wind turbines and gear boxes. The quality demands of those gears are increasing while the production cost must decrease. This requires new production methods to grind the gears. Profile grinding is known as a process to achieve highest possible quality, even for complex flank modifications, while threaded wheel grinding is known for high productivity. New machine concepts make it now possible to use both advantages at the same time.

This paper will show the newest developments for cycle time reduction and increased work piece quality using tool change systems to be able to use different grinding wheels for rough and finishing operation, work piece clamping systems, and concepts of process integration for one work piece flow.

ISBN: 1-55589-947-9 Pages: 12

08FTM18. Gear Corrosion During the Manufacturing Process

Authors: **G. Blake and G. Sroka**

No matter how well gears are designed and manufactured, gear corrosion can occur that may easily result in catastrophic failure. Since corrosion is often difficult to observe in the root fillet region or in fine pitched gears with normal visual inspection, it may well go undetected. This paper presents the results of an incident that occurred in a gear manufacturing facility several years ago that resulted in pitting corrosion and intergranular attack (IGA). It shows that superfinishing can mitigate the damaging effects of IGA and pitting corrosion, and suggests that the superfinishing process is a superior repair method for corrosion pitting versus the current practice of glass beading.

ISBN: 1-55589-948-6 Pages: 13

08FTM19. How Are You Dealing with the Bias Error in Your Helical Gears?

Author: **J. Lange**

Using illustrations this paper explains that bias error ("the twisted tooth phoneme") is a by-product of applying conventional radial crowning methods to produced crowned leads on helical gears. The methods considered are gears that are finished, shaped, shaved, form and generated ground. The paper explains why bias error occurs in these methods, and then addresses what techniques are used to limit/eliminate bias error. Profile and lead inspection charts will be used to detail bias error and the ability to eliminate it.

The paper details the simultaneous interpolation of multiple axes in the gear manufacturing machine to achieve the elimination of bias error. It also explains that CNC machine software can be used to predict bias error, and equally important that it could be used to create an "engineered bias correction" to increase the load carrying capacity of an existing gear set.

ISBN: 1-55589-949-3 Pages: 14

2007 PAPERS

07FTM01. Estimation of Lifetime of Plastic Gears

Author: **S. Beermann**

This paper gives an overview on the state of art in plastic gear resistance calculation. The main problem with plastics is the dependency of the stress cycle curve (Woehler line) with temperature. Today, more plastic gears (as in automobile headlights) are used in a high temperature range. Furthermore, flank resistance depends strongly on lubrication (lifetime may vary by a factor of ten and more, if oil, grease lubricated or dry running).

As no secure data for plastic gears is available, how can nevertheless plastic gear design and life time prediction be improved? The best strategy is to use the feedback of existing reducers. Plastic gearboxes, before starting production in big series, are normally submitted to endurance tests. If these tests are used to check also the real lifetime limits — or by increasing test length, or by increasing applied torque — these results can be used to define the required safety factors for future gear design. This procedure has been very successful, and will be described with some examples.

ISBN: 1-55589-905-9 Pages: 14

07FTM02. Study of the Correlation Between Theoretical and Actual Gear Fatigue Test Data on a Polyamide

Author: **S. Wasson**

Fatigue tests have been run on actual molded gears in order to provide design data, using fully lubricated, plastic on plastic spur gears in a temperature controlled experiment. The purpose of the testing is to see if there is a good correlation between fatigue data, generated in a lab on test bars, versus the actual fatigue performance in a gear.

In order to do this, the theories of gear calculations to get root stresses also had to be examined. Advanced FEA showed that there are corrections needed to account for high loading or high temperatures in plastic gears. The chemistry of various nylons used in gears is explained. A high crystalline nylon has been found which is an excellent material for gears in demanding applications and can withstand high torques and operating temperatures. The material has very good wear properties and excellent retention of mechanical properties (strength, stiffness, and fatigue) especially at elevated temperatures. Several commercial gear applications are currently utilizing these properties. These will be shown to demonstrate the benefits and manufacturability of this material.

ISBN: 1-55589-906-6 Pages: 6

07FTM03. Material Integrity in Molded Plastic Gears and Its Dependence on Molding Practices

Author: **T. Vale**

The quality of molded plastic gears is typically judged by dimensional feature measurements only. This practice overlooks potential deficiencies in the plastic injection molding process and its effect on the integrity of the plastic material. These deeper issues are often not given proper consideration until a related gear failure demands its study and evaluation. This paper identifies some of these oversights in the molding process, the resultant effect on the plastic material, and discusses their likely effect on short and long term gear performance.

ISBN: 1-55589-907-3 Pages: 11

07FTM04. Applying Elemental Gear Measurement to Processing of Molded Plastic Gears

Author: **G. Ellis**

Although elemental gear inspection is rarely specified for molded plastic gears, the measurement equipment and practices can be valuable in advancing the molding processes and improving quality. After a brief description of plastic gear tooling and molding, this paper gives examples of specific elemental measurements and relates them to process changes and quality improvements. Such examples for spur and helical gears include: profile measurements, leading to gear mesh noise reduction; lead measurement, leading to increased face width load distribution and, continuing from that, even to the molding of crowned gears; and index measurement, leading to improved roundness of gears molded from fiber reinforced plastic materials.

ISBN: 1-55589-908-0 Pages: 10

07FTM05. Vacuum Carburizing Technology for Powder Metal Gears and Parts

Authors: **J. Kowalewski and K. Kucharski,**

Carburizing is one of the leading surface hardening processes applied to the sintered, low-alloyed steel gears in the automotive industry. While diffusion of carbon in wrought steel is well documented, this is not the case for PM steel subject to carburizing in vacuum furnaces. This paper presents results that show that the density of the powder metal is the main factor for the final carbon content and distribution. Also important is the state of the surface of the part; either sintered with open porosity or machined with closed porosity. The way the carburizing gas moves through the furnace might be of some influence as well.

ISBN: 1-55589-909-7 Pages: 5

07FTM06. Using Barkhausen Noise Analysis for Process and Quality Control in the Production of Gears

Authors: **S. Kendrish, T. Rickert and R. Fix**

The use of magnetic Barkhausen Noise Analysis (BNA) has been proven to be an effective tool for the non-destructive detection of microstructural anomalies in ferrous materials. Used as an in-process tool for the detection of grinding burn, heat treat defects and stresses, BNA is a quick comparative and quantitative alternative to traditional destructive methods.

This paper presents examples that demonstrate how BNA is used to evaluate changes in microstructural properties. Quantitative results correlate BNA test values to x-ray diffraction values for the detection of changes in residual stress. Qualitative results correlate BNA test values to acid etch patterns/colors for the detection of grinding burn defects.

ISBN: 1-55589-910-3 Pages: 5

07FTM07. Grinding Induced Changes in Residual Stresses of Carburized Gears

Authors: **R. LeMaster, B. Boggs, J. Bunn, C. Hubbard, and T. Watkins**

This paper presents the results of a study performed to measure the change in residual stress that results from the finish grinding of carburized gears. Residual stresses were measured in five gears using the x-ray diffraction equipment in the Large Specimen Residual Stress Facility at Oak Ridge National Laboratory. Two of the gears were hobbed, carburized, quenched and tempered, but not finished. The remaining three gears were processed similarly, but were finish ground. The residual stresses were measured at 64 different locations on a tooth from each gear. Residual stresses were also measured at fewer points on other teeth to determine the tooth-to-tooth variation. Tooth profile measurements were made of the finished and unfinished gear samples.

The results show a fairly uniform and constant compressive residual field in the non-finished gears. There was a significant reduction in the average residual stress measured in the finished gears. Additionally, there was a significant increase in the variability of the residual stress that was introduced by the grinding process. Analysis of the data suggests a linear relationship between the change in average residual stress and the amount of material removed by the grinding process.

ISBN: 1-55589-911-0 Pages: 14

07FTM08. Manufacturing Net Shaped Cold Formed Gears

Author: **D. Engelmann**

An innovative metal forming process has been developed for manufacturing quality, durable and cost efficient gears for high volume production. In this paper, the development of net shaped Cold Formed Gears (CFG) is presented along with their suitable applications. The manufacturing technique and equipment is introduced, as well as the advantages and limitations. Applicable materials and heat treatment practices are also discussed. Gear tooth inspection charts are presented and compared to conventional manufacturing methodologies.

ISBN: 1-55589-912-7 Pages: 7

07FTM09. The Ikona Clutch and Differential

Authors: **J. Colbourne, V. Scekic, and S. Tesic**

This paper describes two devices, a clutch and a differential, which are based on the Ikona CVT. This CVT is essentially an internal gear pair, in which the pinion is mounted on an eccentric that can drive or be driven by an electric motor/generator, thus providing a variable ratio. Since this arrangement allows for “branching” of energy flow(s), it can be classified as summation-type CVT.

When the CVT is used as a clutch, it would replace the friction-plate clutch in vehicles with standard transmissions, and the fluid torque converter in automatic transmissions. The new clutch will be referred to as the electric torque converter. Any excess energy is converted into electrical energy, and either stored in the battery, or reintroduced into the system through the motor/generator. Modulation of the clutch can be very smooth which is particularly advantageous when the vehicle starts from rest on uphill slopes. Since no friction element is involved, and only a fraction of torque is being manipulated, the modulation can be repeatable regardless of conditions. Finally, in a hybrid-vehicle arrangement, the clutch can be used to maintain the engine at its optimum speed (within limits), regardless of the road speed and the gearbox ratio.

Similar principals apply to the Ikona differential. Unlike today's limited slip differentials, the Ikona differential allows full torque to be transmitted through one drive wheel, even though the other drive wheel may have completely lost traction. Unlike traditional differentials that allow wheels to rotate at different speeds, the Ikona differential forces the wheels to do so. Accordingly, when the vehicle is changing direction, the differential can be used to control the speed of each drive wheel, thus providing active torque steering.

ISBN: 1-55589-913-4 Pages: 6

07FTM10. The Gear Dynamic Factor, Historical and Modern Perspective

Authors: **D. Houser and D. Talbot**

The dynamic factor has been included in gear design and rating formulas since the 1930's. Its original formulation was based on an assessment of entering tooth impacts, but in modern gear design procedures, where tip relief and lead modifications are common, these impacts may be virtually eliminated. With this elimination, one finds that gear dynamics are mainly excited by steady state phenomena such as transmission error, friction and axial shuttling of the mesh force. This paper will first provide a historical progression of the dynamic factor equations that are based on impact theory and will define when this methodology is appropriate. The paper will then discuss the various steady state modeling approaches and will use one of these approaches to demonstrate the effects of manufacturing deviations on predicted dynamic loads.

ISBN: 1-55589-914-1 Pages: 11

07FTM11. Helicopter Accessory Gear Failure Analysis Involving Wear and Bending Fatigue

Authors: **G. Blake and D. Schwerin**

Gear tooth wear is a very difficult phenomenon to predict analytically. The failure mode of wear is closely correlated to the lambda ratio, and can manifest into more severe failure modes, such as bending. Presented is a failure analysis in which this occurred. A legacy aerospace gear mesh experienced nine failures within a two-year time period. The failures occurred after more than eight years in service and within tight range of cycles to one another. Each failure resulted in the loss of all gear teeth with origins consistent with classic bending fatigue.

Non-failed gears, with slightly lower time than the failed gears, were removed from service and inspected. Gear metrology measurements quantified a significant amount of wear. The flank form of these worn gears was measured and the measured data used to analytically predict the new dynamic load distribution and bending stress. To predict if the failure mode of wear was expected for this gear mesh, an empirical relationship of wear to lambda ratio was created using field data from multiple gear meshes in multiple applications. Presented are the metallurgical failure analysis findings, dynamic gear mesh analysis, the empirical wear rate curve developed, and design changes.

ISBN: 1-55589-915-8 Pages: 12

07FTM12. The Effect of Start-Up Load Conditions on Gearbox Performance and Life – Failure Analysis and Case Study

Author: **R.J. Drago**

When gearboxes are used in applications in which the connected load has high inertia, the starting torque transmitted by the gearbox can be much higher than the rated load of the prime mover. Power plants often require several evaporative cooling towers or large banks of air cooled condensers (ACC) to discharge waste heat. Because of the very large size of the fans used in these applications, they fall into this category of high inertia starting load devices. When started from zero speed, a very high torque is required to accelerate the fan to normal operating speed. If the fan is started infrequently and run continuously for long periods of time, this high starting torque is of minimal significance. However, when the fan is started and stopped frequently, the number of cycles at the high starting torque can accumulate to a point where they can cause extensive fatigue damage, even if the gear system is adequately rated.

Where the gear unit is marginally rated, very early, catastrophic gear failure is often the result. As part of the overall investigation of several failures in such gearboxes, we measured starting torque on a typical installation, examined many failed gears, and calculated the load capacity ratings for the gearboxes under actual operating conditions. This paper describes the failures observed, the testing conducted, the data analyses and the effect of the high measured starting torque on the life and performance of the gear systems. The test results revealed surprising results, especially during starts where the fan was already wind-milling due to natural air flow in the ACC bank.

ISBN: 1-55589-916-5 Pages: 12

07FTM13. Influence of Grinding Burn on the Load Carrying Capacity of Parts under Rolling Stress

Authors: **F. Klocke, T. Schröder and C. Gorgels**

The demand for continuous improvement concerning economic efficiency of products and processes leads to an increasing cost pressure in manufacturing and design of power transmissions. Also, the power density of gears has been increased which leads to a demand for higher gear quality. In more and more cases this can only be achieved using hard finishing processes.

The demand for higher gear qualities leads to an increased use of gear grinding, which incurs the risk of thermal damage, such as grinding burn on the gear flank. The influence of thermal damage on the set in operation is nevertheless hard to judge so that damaged gears are often scrapped. This leads to increasing failure costs.

The lack of knowledge of the effect of grinding burn on the load carrying capacity of gears leads to the point that the same degree of damage is judged differently by different companies. Therefore, it is necessary to do trials with thermally damaged parts in order to know how much a certain degree of thermal damage influences the load carrying capacity.

The investigations described in this report are aimed at determining the load carrying capacity of parts under rolling stress. Thermally damaged rollers are employed on a roller test rig, since with this analogy process the part geometry is easier to describe and easier to damage reproducibly.

ISBN: 1-55589-917-2 Pages: 10

07FTM14. Roughness and Lubricant Chemistry Effects in Micropitting

Authors: **A. Olver, D. Dini, E. Lainé, D. Hua, and T. Beveridge**

Micropitting has been studied using a disc machine in which a central carburized steel test roller contacts three, harder, counter-rollers with closely controlled surface roughness. Roughness was varied using different finishing techniques, and the effects of different oil base-stocks and additives were investigated.

Damage on the test rollers included dense micropitting and “micropitting erosion” in which tens of microns of the test surface were completely removed. This phenomenon is particularly damaging in gear teeth where it has the potential to destroy profile accuracy. It was found that anti-wear additives led to a high rate of micropitting erosion, and the effect correlated more or less inversely with simple sliding wear results. There were also appreciable effects from base-stock chemistry.

The key parameter affecting the severity of damage seemed to be the near-surface shear stress amplitude arising from the evolved roughness; different chemistries led to the evolution of different roughness during initial running and to different contact stresses and levels of damage.

ISBN: 1-55589-918-9 Pages: 8

07FTM15. Experience with a Disc Rig Micropitting Test

Authors: **M. Talks and W. Bennett**

The experimental work carried out was aimed at developing a test method that was able to consistently produce micropitting damage and could discriminate between good oil (i.e., one that rarely produces micropitting in service) and a poor oil (i.e., one that does produce micropitting in service).

The disc rig control system allows test parameters such as entrainment velocity, contact stress and slide/roll ratio at the disc/roller contacts to be accurately and independently controlled. This enables the effect of key parameters to be studied in isolation, which is something that cannot be easily achieved using conventional gear test rigs.

A test procedure has been developed which provides a good level of repeatability and discrimination between oils. In addition, a study of the effect of slide/roll ratio (SRR) has shown that the severity of micropitting damage increases as SRR increased, whereas at 0% SRR no micropitting occurred, and, at negative SRRs, microcracking occurred, but not micropitting. This is the way that SRR seems to affect micropitting in gears.

ISBN: 1-55589-919-6 Pages: 9

07FTM16. Straight Bevel Gear Cutting and Grinding on CNC Free Form Machines

Author: **H. Stadtfeld**

Manufacturing of straight bevel gears was in the past only possible on specially-dedicated machines. One type of straight bevel gears are those cut with a circular cutter with a circumferential blade arrangement. The machines and the gears they manufacture have the Gleason trade name Coniflex®. The cutters are arranged in the machine under an angle in an interlocking arrangement which allows a completing cutting process. The two interlocking cutters have to be adjusted independently during setup, which is complicated and time consuming.

The outdated mechanical machines have never been replaced by full CNC machines, but there is still a considerable demand in a high variety of low quantities of straight bevel ears. Just recently it was discovered that it is possible to connect one of the interlocking straight bevel gear cutter disks to a free form bevel gear generator and cut straight bevel gears of identical geometry compared to the dedicated mechanical straight bevel gear generator. A conversion based on a vector approach delivers basic settings as they are used in modern free form machines. The advantages are quick setup, high accuracy, easy corrections and high repeatability.

ISBN: 1-55589-920-2 Pages: 10

07FTM17. Simulation Model for the Emulation of the Dynamic Behavior of Bevel Gears

Authors: **C. Brecher, T. Schröder and A. Gacka**

The impact of bevel gear deviations on the noise excitation behavior can only be examined under varying working conditions such as different rotational speed and torque. The vibration excitation of bevel gears resulting from the tooth contact is primarily determined by the contact conditions and the stiffness properties of the gears. By the use of a detailed tooth contact analysis, the geometry based gear properties can be developed and provided for a dynamical analysis of the tooth mesh.

A model has been developed for the simulation of the dynamic behavior of bevel gears. With the aid of a load-free tooth contact analysis, the geometry-based part of the path excitation is determined. With a tooth contact analysis under load, the path excitation caused by deflections can be calculated. The geometry based part of the path excitation and a characteristic surface of the excitation values is created and provided for dynamic simulation.

This dynamic model is able to consider every deviation of the micro- and macrogeometry from the ideal flank topography, i.e., waves and/or grooves in the surface structure, in combination with two and three dimensional flank deviations like profile deviations, helix deviations and twists. It is also possible to consider the influence of friction and the contact impact caused by load and/or manufacturing errors with a test rig to verify the calculations.

ISBN: 1-55589-921-9 Pages: 8

07FTM18. Bevel Gear Model

Author: **Ted Krenzer**

The paper presents a method for developing an accurate generic bevel gear model including both the face milling and face hobbing processes. Starting with gear blank geometry, gear and pinion basic generator machine settings are calculated. The contact pattern and rolling quality are specified and held to the second order in terms of pattern length, contact bias and motion error. Based on the setup, a grid of tooth points are found including the tooth flank, fillet and, if it exists, the undercut area. It is proposed as the model for the next generation of bevel gear strength calculations in that the procedure produces true bevel gear geometry, uses blank design parameters as input and is vendor independent except for cutter diameter.

ISBN: 1-55589-922-6 Pages: 10

07FTM19. How to Determine the MTBF of Gearboxes

Author: **G. Antony**

Mean Time Between Failures (MTBF) became a frequently used value describing reliability of components, assemblies, and systems. While MTBF was originally introduced and used mainly in conjunction with electronic components and systems, the definition and application for mechanical components, such as gearboxes, is not broadly available, used, or recognized. In the field of gears, it is difficult to obtain an MTBF from the manufacturer due to the lack of applicable, generally recognized definitions and standards. The paper will evaluate, compare and suggest ways in determining a gearbox MTBF based on the already established, proven, design calculation standards and test methods used in the gear design.

ISBN: 1-55589-923-3 Pages: 9

2006 PAPERS

06FTM01. The Effects of Super Finishing on Bending Fatigue

Author: **G. Blake**

A super finishing study was designed and conducted for bending fatigue. AMS6265 parts were created: with and without super finishing. Bending fatigue was tested using Single Tooth Fatigue (STF) and RR Moore rotating beam methods. The STF parts were designed with tooth geometry replicating a spiral bevel gear section. Two lots of material were processed. Thus, a minimum of two carburized and hardened lots, two shot peen batches and two super finishing cycles (if applicable) were processed per sample group. A detailed metallurgical evaluation was performed to characterize the material and compare to actual spiral bevel gears. Analysis of the test data concluded no statistical difference in bending fatigue strength.

ISBN: 1-55589-883-1 Pages: 14

06FTM02. Isotropic Superfinishing of S-76C+ Main Transmission Gears

Authors: **B. Hansen, M. Salerno and L. Winkelmann**

Isotropic superfinishing was applied to the third stage spur bull gear and mating pinions along with the second stage bevel gears of a Sikorsky S-76C+ main gearbox. The gearbox completed the standard Acceptance Test Procedure (ATP) and a 200-hour endurance test. During these tests noise, vibration, and operating temperatures were shown to be significantly reduced due to lower friction. A description of the tests, performance data and a general description of the process is presented.

ISBN: 1-55589-884-7 Pages: 12

06FTM03. Detailed Procedure for the Optimum Design of an Epicyclic Transmission Using Plastic Gears

Authors: **I. Regalado and A. Hernández**

Shows the steps to get an optimum (volume based) design for an epicyclic transmission using plastic materials, the tooth proportions of ANSI/AGMA 1006-A97, the recommendations given in ANSI/AGMA 6023-A88, and ANSI/AGMA 2101-C95. It gives the effect of changing the number of planets, the bending fatigue and contact strength of the plastic materials, and the temperature effects on the size of the gears. The design procedure starts with a preliminary analysis of gear performance in a proposed (not optimized) transmission; going step by step to an optimum design for the given load conditions and expected minimum life.

ISBN: 1-55589-885-8 Pages: 11

06FTM04. Precision Planetary Servo Gearheads

Authors: **G.G. Antony and A. Pantelides**

Automated machines use servomotors to perform complex motions. Planetary gearheads are frequently used in conjunction with servomotors to match the inertias, lower the speed, boost the torque, and at the same time provide a mechanical interface for pulleys, cams, drums and other mechanical components. This paper covers topics such as: reasons why planetary gear systems are chosen for “servo applications”; what influences the planetary servo gear positioning accuracy and repeatability; rating practices to establish a “comparability” of different torques; and, an introduction of a simple method to determine the required gearbox torque rating for a servo-application based on motor torque data.

ISBN: 1-55589-886-6 Pages: 11

06FTM05. Development of a Gear Rating Standard – A Case Study of AGMA 6014-A06

Author: **F.C. Uherek**

The AGMA Mill Gearing Committee completed AGMA 6014 for grinding mill and kiln service gear rating. The approach the committee took in the development of this standard to determine the content is reviewed. Through a review of previous standards, the performance history of applications for long life (over 20 years), and considering the large gear size, the committee achieved consensus on a rating method, which was derived from ANSI/AGMA 2001-D04. A factor comparison between 6014 and 2001 is presented, as well as their interaction, to explain the goal of the committee to develop a document that reflects actual field experience of in-service operating gear sets.

ISBN: 1-55589-887-4 Pages: 8

06FTM06. An Analytical Approach to the Prediction of Micropitting on Case Carburized Gears

Authors: **D. Barnett, J.P. Elderkin and W. Bennett**

Micropitting is an area of gear failure that influences gear noise and transmission error. This paper outlines an approach to analyzing micropitting by looking at the critical factors for a given gear design. A practical procedure, which incorporates a three-dimensional spring model, was used to predict the micropitting wear rate and the position that wear would take place on test gear pairs. Case studies have been included that directly compare the predicted levels of micropitting with those actually measured. Simplified formulations suitable for manual calculations are also discussed.

ISBN: 1-55589-888-2 Pages: 15

06FTM07. Improvement of Standardized Test Methods for Evaluating the Lubricant Influence on Micropitting and Pitting Resistance of Case Carburized Gears

Authors: **B.-R. Höhn, P. Oster, T. Radev, G. Steinberger and T. Tobie**

Micropitting and pitting are fatigue failures that occur on case carburized gears. The performance of lubricants in regard to micropitting and pitting can be evaluated by test methods. The FVA-FZG-micropitting test consists of two parts: a load stage test followed by an endurance test. The tests require relatively high costs and are time consuming. Therefore, an analogous short test method was developed to classify candidate lubricants, and supplement the existing test. The results of the short test method are given. The FVA-FZG-pitting test is for limited-life using test gears, which are ground without controlled profile or helix modifications. Although the flank roughness is restricted, the appearance of micropitting can cause a wide statistical spread of pitting test life. Thus, there was potential improvement in the test results reproducibility. In the test gears were superfinished to prevent micropitting, and given flank modifications for improved test relevance. The paper describes test procedures and shows basic examples of test results.

ISBN: 1-55589-889-0 Pages: 11

06FTM08. An Evaluation of FZG Micropitting Test Procedures and Results for the Crowned AGMA Test Gears

Authors: **D.R. Houser, S. Shon and J. Harianto**

This paper reports on surface fatigue testing. The goal was to develop models for predicting wear. As part of this goal, the study reports on developing an understanding of the stresses and wear predictors using FZG tests. Since the focus was on micropitting, the first tests used the method described in FVA Information Sheet No. 54/I-IV. Later, the procedure was modified to account for higher contact stress levels that are predicted for the heavily crowned and tip relieved AGMA test gears that were manufactured as a part of the AGMA tribology test program. This paper provides extensive analysis that includes detailed topography measurements of the tooth profiles, predictions of contact stresses and contact patterns. It discusses factors that affect contact stresses, flash temperatures, and test film thickness.

ISBN: 1-55589-890-4 Pages: 12

06FTM09. Opportunities to Replace Wrought Gears with High Performance PM Gears in Automotive Applications

Authors: **U. Engström, D. Milligan, P. Johansson and S. Dizdar**

Powder metallurgy (PM) enables production of components with complex geometries such as gears. The cost effective use of PM components in automotive applications has showed a continuous growth. This growth is due to the net shape capability, while maintaining performance. Gears for automotive applications are complex in shape and require both geometrical accuracy and high mechanical performance in terms of tooth durability. By utilizing selective densification of the teeth, these performance requirements can be met at a low cost. In this paper a PM process consisting of compaction, sintering, surface densification, and finally heat treatment has been studied to assess the feasibility of production. Helical and spur gears were used where the densification, as well as the resulting gear quality and durability, were tested.

ISBN: 1-55589-891-2 Pages: 7

06FTM10. Fabrication, Assembly and Test of a High Ratio, Ultra Safe, High Contact Ratio, Double Helical Planetary Transmission for Helicopter Applications

Authors: **F.W. Brown, M.J. Robuck, M. Kozachyn, J.R. Lawrence and T.E. Beck**

An ultra-safe, high ratio planetary transmission, for application as a helicopter main rotor final drive, has been designed, fabricated and tested. The transmission improvements are reduced weight, reduced noise and improved fail-safety and efficiency. This paper discusses the fabrication, assembly and testing of the planetary transmission. An existing planetary transmission utilized a two-stage conventional spur gear design with fixed internal ring gears. The new double helical planetary (DHP) system design uses a compound planetary arrangement with staggered planets and high contact ratio gearing in a unique configuration. Double helical gears in the planet to ring meshes balance axial tooth forces without axial planet bearing reactions. The spur gear sun to planet meshes are staggered to achieve a compact arrangement. The sun gear is fully floating.

ISBN: 1-55589-892-0 Pages: 12

06FTM11. On Tooth Failure Analysis in Small-Teeth-Number Gearing: An Analytical Approach

Author: **S.P. Radzevich**

This paper is an analytical study of tooth failure in gearing having small numbers of teeth. For the analysis, tooth contact stresses and combined shear stresses are investigated. The study is based on gear tooth loading, accounting for load variations with time and other gear parameters in various phases of tooth meshing. The contact and shear stresses are by simultaneous: (a) contact stresses together with (b) stresses caused by the pinion and gear sliding. While developed for use in gearing with low numbers of teeth, the method can be used for computation of stresses in gearing having more teeth. The results of the research could be used with AGMA 908-B89 for gears having less than 12 teeth.

ISBN: 1-55589-893-9 Pages: 22

06FTM12. A Crane Gear Failure Analysis – Case Study, Observations, Lessons Learned, Recommendations

Author: **R.J. Drago**

The gearboxes used in cranes have proven themselves to be reliable. However, some gear failures have caused a reevaluation of the design, configuration, and manufacture of gearboxes in large cranes. Since crane gearboxes do not operate continuously, gear system fatigue characteristics have not been in the forefront of system operation. Studies have indicated that in many cases usage rates, loading, and in many cases both, have increased. In some applications, crane usage has increased by factors of two, or three, or even more, and gear loading has similarly increased. This higher usage makes the cumulative effects of fatigue much more important. This paper presents a case study of one particular crane gear failure, including failure analysis and resultant remedial actions, along with a discussion of the results and implications from extensive gearbox inspections that were conducted as a result of the initial failure.

ISBN: 1-55589-894-7 Pages: 10

06FTM13. Economic Aspects of Vacuum Carburizing

Author: **J. Kowalewski**

This paper presents the aspects of vacuum carburizing technology that have an impact on process costs and quality improvements in the final product. There is an interest in furnaces for vacuum carburizing due to the demand for products with overall metallurgical quality and low unit cost. Vacuum carburizing technology produces work with minimum distortion, and desired surface metallurgy. Systems can provide “cold to cold” (cold work going in, cold work coming out) and fully automatic operation that reduces operator involvement, thus minimizing labor. Considering upstream and downstream requirements, vacuum carburizing can provide a total reduction of costs. This technology differs considerably from traditional gas carburizing both in the equipment used and in the process economy.

ISBN: 1-55589-895-5 Pages: 6

06FTM14. The Optimal High Speed Cutting of Bevel Gears – New Tools and New Cutting Parameters

Author: **H.J. Stadtfeld**

High speed carbide dry cutting improvements have a dependency of many important parameters upon the particular job situation, which makes it difficult for a manufacturing engineer to establish an optimal cutting scenario. An analysis of the different parameters and their influence on the cutting process, allows the establishment of five, nearly independent areas of attention: blade geometry and placement in the cutter head; cutting edge micro geometry; surface condition of front face and side relief surfaces; speeds and feeds in the cutting process; and, kinematic relationship between tool and work (climb or conventional cutting, vector feet). This paper presents explanations and guidelines for optimal high speed cutting depending on cutting method, part geometry and manufacturing environment. Also, how to choose the blade system, thus giving the manufacturing engineer information to support optimizing cutter performance, tool life and part quality.

ISBN: 1-55589-896-3 Pages: 13

06FTM15. Optimal Tooth Modifications in Spiral Bevel Gears Introduced by Machine Tool Setting Variation

Author: **V. Simon**

A method for the determination of optimal tooth modifications in spiral bevel gears based on load distribution, minimized tooth root stresses, and reduced transmission errors is presented. Modifications are introduced into the pinion tooth surface considering the bending and shearing deflections of gear teeth, local contact deformations of mating surfaces, gear body bending and torsion, deflections of the supporting shafts, and manufacturing and alignment of mating members. By applying a set of machine tool setting parameters, the maximum tooth contact pressure can be reduced by 5.4%, the tooth fillet stresses in the pinion by 8% and the angular position error of the driven gear by 48%, based on a spiral bevel gear pair manufactured by machine tool settings determined by a commonly used method.

ISBN: 1-55589-897-1 Pages: 12

06FTM16. Certificate for Involute Gear Evaluation Software

Author: F. Härtig

A test for the verification of involute gear software has been developed at the Physikalisch-Technische Bundesanstalt (PTB). This paper shows the critical influence on measurement uncertainty of uncertified involute evaluation software. Beside the test parameter information, the most dominant effects of software errors will be explained. The algorithms developed during this project should influence and help complete the existing standards and their guidelines.

ISBN: 1-55589-898-4 Pages: 5

2005 PAPERS

05FTM01. Fine Pitch, Plastic Face Gears: Design and Manufacture

Authors: **I. Laskin and E. Reiter**

Face gear technology has attracted attention. Products benefiting include those which use molded plastic gears. More applications could benefit, justifying the need for more information on the special features of face gears, their design and manufacture, in comparison to other non-parallel-shaft gears. A description of manufacturing methods, particularly in plastic molding is given with inter-related design and gear performance issues. New methods of graphic modeling are included with descriptions of face gear configurations and applications.

ISBN: 1-55589-849-1 Pages: 11

05FTM02. The Effects of Pre Rough Machine Processing on Dimensional Distortion During Carburizing

Author: **G. Blake**

A study to isolate the influence of pre-rough machine processing on final dimensional distortion. Methods are discussed to aid process development and minimize dimensional change during carburizing. The study examined the distortion during carburizing between five possible raw material starting conditions. Coupons were used and manufactured from each population of material processing. Dimensions were made before and after carburizing using a scanning coordinate measurement machine. The results show that dimensional distortion during carburizing increases with mechanical and thermal processing.

ISBN: 1-55589-850-5 Pages: 18

05FTM03. Modeling Gear Distortion

Author: **P.C. Clarke**

Dealing with carburize case hardened gear distortion and growth is a challenge for the global gear industry. Attempts started in 1978 with computer programs to calculate distortion and growth, plus residual stress distributions for a gear and evolved by gathering distortion data for a wide range of sizes, shapes, grinding allowances with trends for different geometries. A spread sheet program with gear dimensional input, calculates the distortions and growths, and then calculates the modified dimensions for required protuberance and the minimum carburized case depth. Case histories illustrate the consequences of various geometries and future developments are discussed.

ISBN: 1-55589-851-3 Pages: 12

05FTM04. Tooth Meshing Stiffness Optimization Based on Gear Tooth Form Determination for a Production Process Using Different Tools

Authors: **U. Kissling, M. Raabe, M. Fish**

The variation of the tooth meshing stiffness is a source of noise and the exact calculation of tooth form is important for the stiffness determination. For this purpose, software was written with the concept of an unlimited number of tools such as hobs, grinding disk, and honing defining a manufacturing sequence. Stiffness variation can be improved by optimization of final gear geometry with a calculation of the contact path under load. The meshing stiffness is derived making it possible to study the effect of a proposed profile correction of a gear under different loads. Calculations with AGMA2001 or ISO6336 check the point with the highest root stress. Effect of a grinding notch is also included.

ISBN: 1-55589-852-1 Pages: 11

05FTM05. Computerized Design of Face Hobbed Hypoid Gears: Tooth Surface Generation, Contact Analysis and Stress Calculation

Authors: **M. Vimercati and A. Piazza**

Face milled hypoid gears have been widely studied. Aim of this paper is just to propose an accurate tool for computerized design of face hobbed hypoid gears. A mathematical model able to compute detailed gear tooth surface is presented. Then, the obtained surfaces will be employed as input for an advanced contact solver that, using a hybrid method combining finite element technique with semi analytical solutions, is able to efficiently carry out contact analysis under light and heavy loads and stress calculation of these gears.

ISBN: 1-55589-853-3 Pages: 13

05FTM06. A Model to Predict Friction Losses of Hypoid Gears

Authors: **H. Xu, A. Kahraman and D.R. Houser**

A model to predict friction-related mechanical efficiency losses of hypoid gear pairs is proposed, which combines a commercial available finite element based gear contact analysis model and a friction coefficient model with a mechanical efficiency formulation. The contact analysis model is used to provide contact pressures and other contact parameters required by the friction coefficient model. The instantaneous friction coefficient is computed by using a validated formula that is developed based on a thermal elastohydrodynamic lubrication (EHL) model. Computed friction coefficient distributions are then used to calculate the friction forces and the resultant instantaneous mechanical efficiency losses of the hypoid gear pair at a given mesh angle. The model is applied to study the influence of speed, load, surface roughness, and lubricant temperature as well as assembly errors on the mechanical efficiency of an example face-hobbed hypoid gear pair.

ISBN: 1-55589-854-8 Pages: 15

05FTM07. Spiral Bevel and Hypoid Gear Cutting Technology Update

Author: **T.J. Maiuri**

Spiral bevel and hypoid gear cutting technology has changed significantly over the years. The machines, tools, materials, coatings and processes have steadily advanced to the current state of the art. This paper will cover the progression from mechanical machines with complex drive trains using the five cut method of cutting gears with coolant, to machines with direct drive CNC technology dry cutting gears by the completing method with carbide and high speed steel tools. The latest cutting tool materials and tool coatings will be discussed. Production examples from the automotive and truck industries will be provided, as well as examples from the gear jobbing industry.

ISBN: 1-55589-855-6 Pages: 20

05FTM08. New Developments in Tooth Contact Analysis (TCA) and Loaded TCA for Spiral Bevel and Hypoid Gear Drives

Authors: **Q. Fan and L. Wilcox**

Tooth Contact Analysis (TCA) and Loaded Tooth Contact Analysis (LTCA) are two powerful tools for the design and analysis of spiral bevel and hypoid gear drives. TCA and LTCA respectively simulate gear meshing contact characteristics under light load and under significant load. Application of CNC hypoid gear generators has brought new concepts in design of spiral bevel and hypoid gears with sophisticated modifications. This paper presents new developments in TCA and LTCA of spiral bevel and hypoid gears. The first part of the paper describes a new universal tooth surface generation model with consideration of capabilities of CNC bevel gear generators. The universal model is based on the kinematical modeling of the basic machine settings and motions of a virtual bevel gear generator which simulates the hypoid gear generator and integrates both face milling and face hobbing processes. Mathematical descriptions of gear tooth surfaces are represented by a series of coordinate transformations in terms of surface point position vector, unit normal, and unit tangent. Accordingly, a generalized TCA algorithm and program are developed. In the second part of this paper the development of a finite element analysis (FEA) based LTCA is presented. The LTCA contact model is formulated using TCA generated tooth surface and fillet geometries. The FEA models accommodate multiple pairs of meshing teeth to consider a realistic load distribution among the adjacent teeth. An improved flexibility matrix algorithm is formulated by introducing specialized gap elements with considerations of deflection and deformation due to tooth bending, shearing, local Hertzian contact, and axle stiffness. Two numerical examples, a face-hobbing design and a face milling design, are illustrated to verify the developed mathematical models and programs.

ISBN: 1-55589-856-4 Pages: 12

05FTM09. Hypoid Gear Lapping Wear Coefficient and Simulation

Authors: **C. Gosselin, Q. Jiang, K. Jenski and J. Masseth**

Hypoid gears are usually hard finished after heat treatment using lapping. Because of the rolling and sliding motion inherent to hypoid gears, the lapping compound abrades and refines the tooth surface to achieve smoothness in rolling action and produce high quality gear sets. The pinions and gears are lapped in pairs and must therefore remain as coordinated pairs for the rest of their lives. However, heat treatment distortion can vary significantly. Thus, developing a lapping sequence for manufacturing requires both time and experienced technicians who can establish lapping operating positions and sequence times to produce quality gear sets both in terms of performance and cost. This development is generally trial and error. In this paper, the lapping process is simulated using advanced modeling tools such as gear vectorial simulation for the tooth surfaces and path of contact and reverse engineering to analyze the tooth contact pattern of existing gear sets under load (static LTCA). Test gear sets are measured using a CMM prior to a special lapping cycle where the position of the gear sets on the lapper does not change, and then re-measured after lapping in order to establish how much, and where, material was removed. A wear constant named “wear coefficient” specific to the lapping compound composition is then calculated. Based on the obtained wear coefficient value, an algorithm for simulating the lapping process is presented. Gear sets lapped on the production line are used for simulation case studies. Results show that it is possible to predict how much and where material will be removed, thereby opening the door to better understanding of the lapping process.

ISBN: 1-55589-857-2 Pages: 16

05FTM10. Finite Element Study of the Ikona Gear Tooth Profile

Authors: **J.R. Colbourne and S. Liu**

The Ikona gear tooth profile is a patented non-involute tooth profile for internal gear pairs. Gears with this profile have the following properties: the teeth are conjugate; the contact ratio is very high; there is no tip interference, even when only a one-tooth difference between the pinion and internal gear; there is minimal backlash; and the gears can be cut on conventional gear-cutting machines. Large reduction ratios can be achieved by a single gear pair and a high contact ratio results in lower tooth stresses than for a similar involute gear. Plus, minimal backlash makes the Ikona profile ideal for many applications, such as servo-drives, medical prostheses, and robots. Stress analysis of these gears assumes that the contact force is equal at each contacting tooth pair. Finite element results demonstrate how the number of tooth pairs in contact may increase under load. Finally, an estimate will be presented, showing the variation of tooth force between the contacting teeth.

ISBN: 1-55589-858-0 Pages: 9

05FTM11. Low Loss Gears

Authors: **B.-R. Höhn, K. Michaelis and A. Wimmer**

In most transmission systems one power loss sources is the loaded gear mesh. High losses lead to high energy consumption, high temperatures, early oil ageing, increased failure risk and high cooling requirements. In many cases high efficiency is not the main focus and design criteria as load capacity or vibration excitation predominate the gear shape design. Those design criteria can counteract high efficiency. The influences of gear geometry parameters on gear efficiency, load capacity, and excitation are shown. Design preference guidelines can be followed to a varying extent which leads to more or less unconventional, but more efficient gear design. Low loss gears can save substantial energy in comparison to conventional gears. The power loss reduction is dependent on the operating conditions and can add up to 70% of the power loss of conventional gears. Such low loss gears have significant advantages in terms of energy consumption, heat development, and cooling requirements.

ISBN: 1-55589-859-9 Pages: 11

05FTM12. Modal Failure Analysis of a Gear and Drive Ring Assembly

Author: **D.D. Behlke**

After years of successful reliable applications, a component failure on a new application cannot be explained with static stress analyses; modal failure analyses may be required. Finite element modal analyses were used to identify the mode and its frequency that cause a high range gear and drive ring assembly to fail prematurely. A Campbell Diagram was used to identify modes in the operating range of a six-speed transmission that could cause the drive ring to fail. Redesigning the assembly to move the critical modes out of the operating range is described.

ISBN: 1-55589-860-2 Pages: 8

05FTM13. Evaluation of the Scuffing Resistance of Isotropic Superfinished Precision Gears

Authors: **P.W. Niskanen, B. Hansen and L. Winkelmann**

Aerospace gears are often engineered to operate near the upper bounds of their theoretical design allowables. Due to this, scuffing is a primary failure mode for aerospace gears. Isotropic superfinishing improved Rolling/Sliding Contact Fatigue up to nine times that of baseline test specimens. Tests demonstrated the ability to successfully carry 30 percent higher loads for at least three times the life of the baseline samples. A study was conducted on actual gears having an isotropic superfinish. This study showed superfinishing technology increased a gear's resistance to contact fatigue by a factor of three, and increased bending fatigue resistance by at least 10 percent. The paper discusses an additional study which is underway to determine the scuffing resistance of isotropic superfinished aerospace gears to that of baseline ground gears. These tests were conducted using a method that progressively increases lubricant temperature until scuffing occurs, rather than the traditional load increasing method used in FZG testing rigs. The results of the current testing reveals that isotropic superfinished SAE 9310 specimens show at least a 40 F higher lubricant temperature at the point of scuffing compared to as-ground baseline gears.

ISBN: 1-55589-861-0 Pages: 10

05FTM14. Determining the Shaper Cut Helical Gear Fillet Profile

Author: **G. Lian**

This paper describes a root fillet form calculating method for a helical gear generated with a shaper cutter. The shaper cutter considered has an involute main profile and elliptical cutter edge in the transverse plane. Since the fillet profile cannot be determined with closed form equations, a Newton's approximation method was used in the calculation procedure. The paper will also explore the feasibility of using a shaper tool algorithm for approximating a hobbed fillet form. Finally, the paper will also discuss some of the applications of fillet form calculation procedures such as form diameter (start of involute) calculation and finishing stock analysis.

ISBN: 1-55589-862-9 Pages: 16

05FTM15. Repair of Helicopter Gears

Authors: **S. Rao, D. McPherson and G. Sroka,**

In order to reduce costs by extending the operational life of the sun and input pinion gears of a helicopter transmission, scraped gears were subject to a superfinishing process. This process was found to remove minor foreign object damage by uniformly removing a minimal amount of material on the gear teeth, while meeting original manufacturing specifications for geometry. The process also resulted in enhanced surface quality and did not exhibit detrimental metallurgical effects on the surface or sub-surface of the teeth. The process was also found to eliminate gray staining, an early precursor to pitting. This paper describes the results of the helicopter gear repair project and includes the geometry and metallurgical evaluations on the repaired gear. Further effort to characterize the durability and strength characteristics of the repaired gear is ongoing.

ISBN: 1-55589-863-7 Pages: 9

05FTM16. CH47D Engine Transmission Input Pinion Seeded Fault Test

Authors: **J.P. Petrella, J.S. Kachelries and S.M. Holder, and T.E. Neupert**

This paper summarizes an Engine Transmission Input Pinion Seeded Fault Test that was accomplished as a portion of the validation process for the Transmission Vibration Diagnostic System (TVDS) Analyzer. The test specimen was a high speed engine transmission input pinion with a known defect (i.e., seeded fault) machined into a high stress area of a gear tooth root. During the testing, the TVDS analyzer monitored the test pinion real time to provide a sufficient warning time of the impending failure. The TVDS data was evaluated along with a post-test evaluation of the fatigue crack. During the post-test fractographic evaluation, arrest lines and fatigue striations were analyzed to develop crack propagation data as a function of the number of applied load cycles. This data was then correlated to better understand the potential warning signals the TVDS system could provide that would allow the pilot enough time to unload the suspect engine transmission.

ISBN: 1-55589-864-5 Pages: 11

05FTM17. Influences of Bearing Life Considerations on Gear Drive Design

Author: **F.C. Uherek**

Historically, catalog gear drives have been designed with 5000 hours of L10 bearing life at service factor 1.0 power. Advances in bearing analysis methods have brought new considerations to the design and selection process. The impact of new modeling techniques, additional considerations, and various extensions to the traditional bearing fatigue calculations are explored. The modeling of these various additions to a traditional catalog L10 calculation is illustrated by bearing selections for cases of single, double, and triple reduction gear drives. A roadmap is presented listing critical considerations when applying various bearing manufacturer recommendations.

ISBN: 1-55589-865-3 Pages: 13

05FTM18. Planet Pac: Increasing Epicyclic Power Density and Performance through Integration

Author: **D.R. Lucas**

Epicyclical gear systems are typically equipped with straddle-mounted planetary idlers and are supported by pins on the input and output sides of a carrier. These carriers can be either one-piece or two-piece carrier designs. Traditionally many of the higher power rated epicyclic gear systems use cylindrical roller bearings to support the planetary gears. This paper will demonstrate that using a preloaded taper roller bearing in an integrated package should be the preferred choice for this application to increase the bearing capacity, power density, and fatigue life performance. Based on DIN281-4 calculations, this patented, fully integrated solution allows for calculated bearing fatigue lives to be 5 times greater than a non-integrated solution and more than 1.5 times greater than a semi-integrated solution, without changing the planet gear envelope.

ISBN: 1-55589-866-1 Pages: 7

05FTM19. The Application of Very Large, Weld Fabricated, Carburized, Hardened & Hard Finished Advanced Technology Gears in Steel Mill Gear Drives

Authors: **R.J. Drago, R. Cunningham and S. Cymbala**

In the 1980's, Advanced Technology Gear (ATG) steel rolling mill gear drives consisting of carburized pinions in mesh with very large, weld fabricated, high through hardened gears were introduced to improve capacity. Recently, even the improvements obtained from these ATG gear sets were not sufficient to meet higher production rates and rolling loads. For greater load capacity ATG sets have been developed consisting of carburized, hardened pinions in mesh with very large, weld fabricated, carburized and hard finished gears. Single and double helical gears of this type, ranging in size from 80 to 136 inches pitch diameter have been implemented in several steel rolling applications. This paper describes the conditions that require the use of these gears and the technology required to design, manufacture, and, especially, heat treat, these very special, very large gear sets.

ISBN: 1-55589-867-0 Pages: 16

05FTM20. Dual Drive Conveyor Speed Reducer Failure Analysis

Author: **M. Konruff**

With increasing requirements, many conveyor systems utilize dual drive arrangements to increase output. Dual drives can provide an economical solution by utilizing smaller, more efficient, system designs. However, multiple drive conveyors must proportion the load between drives and load sharing without some type of control is difficult to achieve. This paper presents a case study on a failure analysis of a coal mine dual drive conveyor system that experienced gear reducer failures between 2 to 18months. Physical and metallurgical inspection of failed gearing did not indicate material or workmanship defects, but indicated overload. In order to determine the cause of the failures, strain gage load testing was performed. The testing of the conveyor drives revealed load sharing problems which that will be reviewed.

ISBN: 1-55589-868-8 Pages: 9

2004 PAPERS

04FTM1. Gear Noise – Challenge and Success Based on Optimized Gear Geometries

Authors: **F. Hoppe and B. Pinnekamp**

Airborne and structure borne noise behavior becomes more and more an important feature for industrial applications. Noise excitation requirements may differ with applications. Industrial conveyor belts or cement mills are less sensitive with respect to noise emission than military applications, such as navy ship propulsion. This paper describes requirements and solutions with regard to noise behavior focusing on examples taken from wind turbine gear transmissions and navy applications. The individual approaches have to be a suitable compromise to meet the challenge of noise requirement and cost optimization without restrictions on gear load carrying capacity. Therefore, the paper shows requirements and measurements examples from shop and field tests in comparison to gear micro geometry and calculation results.

ISBN: 1-55589-824-6 Pages: 15

04FTM2. Noise Optimized Modifications: Renaissance of the Generating Grinders?

Author: **H. Geiser**

While load and stress optimized tooth modifications may be normal in production, noise and vibration optimized tooth modifications need higher production accuracies and more complex modifications than with crowning and root or tip relief. Topological modifications show advantages for low noise and vibration behavior due to the higher variability in direction of contact pattern. Unfortunately, a load optimized tooth flank modification is not always a noise optimized modification—a compromise between optimized load distribution and low noise has to be found. In a practical example the calculation possibilities will be demonstrated on how an optimized tooth modification can be found. To satisfy the new requirements the gear grinder manufacturers needed to improve their machines. This improvement was possible with the substitution for the mechanical transmissions in the grinder with the modern CNC controls. By introducing a torque motor as the main table drive of a grinder, together with the direct mounted encoder, an advantage is offered in comparison to the mechanical drive. Problems like worm gear wear, backlash and deviations are eliminated. This, and the possibility of topological modifications, could now lead to a renascence of the generating grinders.

ISBN: 1-55589-825-4 Pages: 9

04FTM3. A Method to Define Profile Modification of Spur Gear and Minimize the Transmission Error

Authors: **M. Beghini, F. Presicce, and C. Santus**

The object of this presentation is to propose a simple method to reduce the transmission error for a given spur gear set, at a nominal torque, by means of profile modification parameters. Iterative simulations with advanced software are needed. A hybrid method has been used, combining the finite element technique with semi analytical solutions. A two dimensional analysis is thought to be adequate for this kind of work; in fact, the resulting software does not require much time for model definition and simulations, with very high precision in the results. The starting configuration is presented. At each subsequent step, little alteration of one parameter is introduced, and the best improvement in terms of static transmission error is followed, until a minimum peak-to-peak value is achieved. At the end a check is needed to verify that the tip relief is enough to avoid the non-conjugate contact on the tip corner for a smooth transfer load.

ISBN: 1-55589-826-2 Pages: 11

04FTM4. Influence of Surface Roughness on Gear Pitting Behavior

Authors: **T.C. Jao, M.T. Devlin, J.L. Milner, R.N. Iyer, and M.R. Hoeprich**

In earlier studies, surface roughness had been shown to have a significant influence on gear pitting life. Within a relatively small range of surface roughness (Ra = 0.1–0.3 micron), gear pitting life as measured by the FZG pitting test decreases as the gear surface roughness increases. This inverse relationship between gear surface roughness and pitting life is well understood in the field. To determine whether this inverse relationship is applicable to a wider range of surface roughness values, a pitting study was conducted using gears whose surface roughness ranges from 0.1–0.6 micron. The results were not completely expected. The study showed that the micropitting area is radically expanded when the gear surface roughness is close to the upper limit of the range studied. At the same time, the formation of macropitting is also greatly delayed. Not only is the pitting life significantly longer, but the initiation of macropitting can occur near or slightly beyond the pitch line. The paper discusses how high surface roughness introduces a wear mechanism that delays the formation of macropits.

ISBN: 1-55589-827-0 Pages: 12

04FTM5. Investigations on the Micropitting Load Capacity of Case Carburized Gears

Authors: **B.-R. Höhn, P. Oster, U. Schrade and T. Tobie**

Micropitting is fatigue damage that is frequently observed on case carburized gears. It is controlled by conditions of the tribological system of tooth flank surface and lubricant. The oil film thickness has been found to be a dominant parameter. Based on the results of investigations a calculation method to evaluate the risk of micropitting respectively to determine a safety factor for micropitting on case carburized gears was developed. The calculation method is based on the result of the micropitting test as a lubricant tribological parameter, but enables the gear designer to take major influences such as operating conditions, gear geometry and gear size of the actual application into consideration. The paper summarizes important results of the continuous experimental investigations and introduces the proposed calculation method for rating the micropitting load capacity of case carburized gears.

ISBN: 1-55589-828-9 Pages: 15

04FTM6. The Effect of a ZnDTP Anti-Wear Additive on Micropitting Resistance of Carburized Steel Rollers

Authors: **C. Benyajati and A.V. Olver**

Zinc di-alkyl dithio-phosphate (ZnDTP) compounds are widely used in engine and transmission oils both as anti-oxidants and as anti-wear additives. However, recent work has shown that many anti-wear additives appear to have a detrimental effect on the resistance of gears and other contacting components to various types of rolling contact fatigue, including micropitting. The paper examines the effect of a secondary C6 ZnDTP presence in low viscosity synthetic base oil on the resistance to micropitting and wear of carburized steel rollers, using a triple-contact disk tester. It was found that the additive caused severe micropitting and associated wear, whereas the pure base oil did not give rise to any micropitting. It was further found that the additive was not detrimental unless it was present during the first 100 000 cycles of the test when it was found to exert a strong effect on the development of roughness on the counter-rollers. It is concluded that the additive is detrimental to micropitting resistance because it retards wear-in of the contact surfaces, favoring the development of damaging fatigue cracks. This contrast with some earlier speculation that suggested a direct chemical effect could be responsible.

ISBN: 1-55589-829-7 Pages: 10

04FTM7. A Short Procedure to Evaluate Micropitting Using the New AGMA Designed Gears

Authors: **K.J. Buzdygon and A.B. Cardis**

At the 1998 AGMA Fall Technical Meeting, encouraging results of a prototype micropitting test using specially designed gears on the standard FZG test rig were reported. Additional gear sets became available from AGMA in 2000. Subsequently, several sets of these experimental AGMA test gears were used in an attempt to develop a relatively short test procedure to evaluate micropitting. The detailed results of these tests are discussed in the paper. The procedure involved running the test gears on the standard FZG test rig with oil circulation for 168 hours. At the end of test, the gears are rated for micropitting, weight loss, pitting, and scuffing. Five commercially available ISO VG 320 gear oils, with performance in the FVA Procedure 54 micropitting test ranging from FLS 9-low to FLS >10-high, were evaluated using this procedure. The degree of micropitting coverage ranged from 34% to 7% in the new test procedure. Micropitting generally originated in the middle of the gear tooth, instead of the root or tip. Overall, there was excellent correlation of the degree of micropitting damage between the new test procedure and FVA Procedure 54.

ISBN: 1-55589-830-0 Pages: 8

04FTM8. Generalized Excitation of Traveling Wave Vibration in Gears

Author: **P.B. Talbert**

Rotation of gears under load creates dynamic loading between the gears at tooth mesh frequency and its harmonics. The dynamic loading can excite traveling wave vibration in the gears. The strain associated with the traveling wave vibration can be excessive and result in high cycle fatigue of the gears. Prior investigations have examined traveling wave excitation for specific configurations, such as a sequential star system with a fixed planetary carrier. Gear mesh excitation of traveling wave vibration can be generalized to include the following: (1) any number of gears surrounding the center gear, (2) non-symmetric spacing of the surrounding gears, (3) non-equal power transfer of the surrounding gears, and (4) the effect of periodic features in the center gear. A closed form expression is developed to quantify the relative excitation of traveling wave vibration for each nodal diameter. This expression for the relative excitation is verified using analytical finite element examples.

ISBN: 1-55589-831-9 Pages: 13

04FTM9. Design of a High Ratio, Ultra Safe, High Contact Ratio, Double Helical Compound Planetary Transmission for Helicopter Applications

Authors: **F.W. Brown, M.J. Robuck, G.K. Roddis and T.E. Beck**

An ultra-safe, high ratio planetary transmission, for application as a helicopter main rotor drive, has been designed under the sponsorship of NRTC-RITA. It is anticipated that this new planetary transmission offers improvements relative to the current state-of-the-art including, reduced weight, reduced transmitted noise and improved fail-safety. This paper discusses the analysis and design results for the subject planetary transmission. Fabrication and testing of the transmission will be conducted in subsequent phases of the project. Typically, the final stage in helicopter main rotor transmission is the most critical and usually the heaviest assembly in the drive system for any rotary wing aircraft. The new ultra-safe, high ratio planetary transmission design utilizes a compound planetary configuration with a 17.5:1 reduction ratio which would replace a conventional two stage simple planetary transmission. The new design uses split-torque paths and high combined contact ratio gearing.

ISBN: 1-55589-832-7 Pages: 12

04FTM10. The Failure Investigation and Replacement of a Large Marine Gear

Authors: **P. Hopkins, B. Shaw, J. Varo, and A. Kennedy**

The paper presents details of a recent gearbox problem encountered on a naval ship and the final solution bringing the ship back to full ability. The problem occurred on the main wheel of a large, high power Naval gearbox. The investigation showed that pitting damage had developed as a result of loose side plate bolts, which led on to bending fatigue cracking. Additional investigations and monitoring established that the damage had been assisted by increased usage at high power levels, as well as a small number of significant overloads. Assessment of the gearbox design was that it had been running very close to original design limits. Repairs were then carried out to remove and arrest any damage present, and monitoring procedures were put in place to ensure no further damage developed. Risk assessments were performed to allow the ship to continue to meet its demands. Full repair options were then considered and replacement gear elements designed and produced to increase future abilities and safety factors. The paper covers the discovery of the problem, failure investigation, the in-situ repair, risk assessment of continued running, prevention of further damage, damage monitoring, the permanent repair assessment, design, manufacture and installation of replacement gears, and trials.

ISBN: 1-55589-833-5 Pages: 11

04FTM11. Gear Lubrication as a Reliability Partner

Author: **M. Holloway**

Performance lubrication is quickly becoming a component of preventive, predictive, proactive and reliability based maintenance programs. Using the best gear lubricant, coupled with system condition, monitoring and analysis, actually reduces overall operating expenses dramatically. Various techniques such as system conditioning, oil and equipment analysis, along with product selection and management are valuable tools which convert many maintenance departments into reliability centers. These concepts and others are discussed in this informative hands-on discussion which will review best maintenance practices from various companies and review how to implement similar programs.

ISBN: 1-55589-834-3 Pages: 8

04FTM12. Improved Tooth Load Distribution in an Involute Spline Joint Using Lead Modifications Based on Finite Element Analysis

Authors: **F.W. Brown, J.D. Hayes and G.K. Roddis**

Involute splines are prone to non-uniform contact loading along their length, especially in lightweight, flexible applications such as a helicopter main rotor shaft-to-rotor hub joint. A significantly improved tooth load distribution is achieved by applying, to the internally splined member, complex lead corrections which vary continuously along the length of the spline. Rotor hub splines with analytically determined lead corrections were manufactured and tested under design load conditions. A standard rotor shaft-to-hub joint, which uses a step lead correction between splines, was also tested as a baseline. Test data indicated that the complex lead corrections resulted in a nearly uniform contact load distribution along the length of the spline at the design torque load. The data also showed that the load distribution for the splines with the complex lead corrections was significantly improved relative to the baseline splines.

ISBN: 1-55589-835-1 Pages: 16

04FTM13. Superfinishing Motor Vehicle Ring and Pinion Gears

Authors: **L. Winkelmann, J. Holland and R. Nanning**

Today, the automotive market is focusing on “lubed for life” differentials requiring no service for the life of the vehicle. Premature differential failure can be caused by bearing failures as well as ring and pinion failure. By super finishing the lapped ring and pinion gear sets to a surface roughness less than 10 micro inch, lubricant, bearing and gear lives can be significantly increased because of the concomitant elimination of wear and the temperature spike associated with break-in. It was assumed that super finishing technology could not preserve the contact pattern of the lapped and matched gear set. This paper discusses a mass finishing operation which overcomes these obstacles and meets the needs of a manufacturing facility. Gear metrology, contact patterns, transmission error and actual performance data for super finished gear sets will be presented along with the super finishing process.

ISBN: 1-55589-836-6 Pages: 16

04FTMS1. Stress Analysis of Gear Drives Based on Boundary Element Method

Author: **D. Vecchiato**

The stress analysis is performed as a part of TCA (Tooth Contact Analysis) for a gear drive. Unlike the existing approaches, the proposed one does not require application of commercial codes (like ANSYS or ABAQUS) for derivation of contact model and determination of contact and bending stresses. The contacting model is derived directly by using the equations of tooth surfaces determined analytically. The boundary element approach allows to reduce substantially the number of nodes of the model. Determination of stresses caused by applied load is obtained directly for the applied contacting model for any position of meshing. The developed approach is illustrated by stress analysis of helical gears with modified geometry.

ISBN: 1-55589-837-8 Pages: 16

2002 PAPERS

02FTM1. The Effect of Chemically Accelerated Vibratory Finishing on Gear Metrology

Authors: **L. Winklemann, M. Michaud, G. Sroka, J. Arvin and A. Manesh**

Chemically accelerated vibratory finishing is a commercially proven process that is capable of isotropically superfinishing metals to an Ra < 1.0 in. Gears have less friction, run significantly cooler and have lower noise and vibration when this technology is applied. Scuffing, contact fatigue (pitting), and bending fatigue are also reduced or eliminated both in laboratory testing and field trials. This paper presents studies done on aerospace Q13 spiral bevel gears showing that the amount of metal removed to superfinish the surface is both negligible and controllable. Media selection and metal removal monitoring procedures are described ensuring uniform surface finishing, controllability and preservation of gear metrology.

ISBN: 1-55589-801-7 Pages: 18

02FTM2. Development and Application of Computer-Aided Design and Tooth Contact Analysis of Spiral-Type Gears with Cylindrical Worm

Authors: **V.I. Goldfarb and E.S. Trubachov**

This paper presents the method of step-by-step computer-aided design of spiroid-type gears, which involves gear scheme design, geometric calculation of gearing, drive design, calculation of machine settings and tooth-contact analysis. Models of operating and generating gearing have been developed, including models of manufacture and assembly errors, force and temperature deformations acting in real gearing, and drive element wear. Possibilities of CAD-technique application are shown to solve design and manufacture tasks for gearboxes and gear-motors with spiroid-type gears.

ISBN: 1-55589-802-5 Pages: 15

02FTM3. The Application of Statistical Stability and Capability for Gear Cutting Machine Acceptance Criteria

Author: **T.J. Maiuri**

Over the years the criteria for gear cutting machine acceptance has changed. In the past, cutting a standard test gear or cutting a customer gear to their specification was all that was expected for machine acceptance. Today, statistical process control (SPC) is required for virtually every machine runoff. This paper will cover the basic theory of stability and capability and its application to bevel and cylindrical gear cutting machine acceptance criteria. Actual case studies will be presented to demonstrate the utilization of these SPC techniques.

ISBN: 1-55589-803-3 Pages: 26

02FTM4. Multibody-System-Simulation of Drive Trains of Wind Turbines

Author: **B. Schlecht**

During the last years a multitude of wind turbines have been put into operation with continuously increased power output. Wind turbines with 6 MW output are in the stage of development, a simple extrapolation to larger dimensions of wind turbines on the basis of existing plants and operational experiences is questionable. This paper deals with the simulation of the dynamic behavior of the complete drive train of a wind turbine by using a detailed Multi-System-Model with special respect of the gear box internals. Starting with the model creation and the analysis of the natural frequencies, various load cases in the time domain will be discussed.

ISBN: 1-55589-804-1 Pages: 13

02FTM5. Crack Length and Depth Determination in an Integrated Carburized Gear/Bearing

Authors: **R. Drago and J. Kachelries**

In an effort to determine if processing cracks posed a safety of flight concern, several gears that contained cracks were designated to undergo a rigorous bench test. Prior to the start of the test, it was necessary to document, nondestructively, all of the crack dimensions. This paper will present a specially modified magnetic rubber inspection technique to determine crack lengths as short as 0.006 inch, and a unique, highly sensitive, laboratory eddy current inspection technique to estimate crack depths up to +/– 0.003 inch.

ISBN: 1-55589-805-2 Pages: 9

02FTM6. Contemporary Gear Hobbing – Tools and Process Strategies

Author: **C. Kobialka**

Gear manufacturing without coolant lubrication is getting more and more important. Modern hobbing machines are designed to cope with dry hobbing. In the last years, carbide hobs were prevailing in high-speed hobbing due to their excellent thermal stability. Today, this high performance rate is confronted with rather high tool costs and critical tool handling. Powder metallurgical HSS combined with extremely wear resistant coating on the base of (Ti, Al) N offer interesting alternatives for dry hobbing. It is evident that existing conventional hob geometries can be optimized respecting limiting factors like maximum chip thickness and maximum depth of scallops.

ISBN: 1-55589-806-8 Pages: 11

02FTM7. Selecting the Best Carburizing Method for the Heat Treatment of Gears

Authors: **D. Herring, G. Lindell, D. Breuer and B. Madlock**

Vacuum carburizing has proven itself a robust heat treatment process and a viable alternative to atmosphere carburizing. This paper will present scientific data in support of this choice. A comparison of atmosphere carburized gears requiring press quenching to achieve dimensional tolerances in a "one piece at a time" heat treating operation, with a vacuum carburized processing a full load of gears that have been high gas pressure quenched within required tolerances.

ISBN: 1-55589-807-6 Pages: 13

02FTM8. Compliant Spindle in Lapping and Testing Machines

Author: **B. McGlasson**

This paper presents theory, analysis and results of a novel spindle design with application to bevel gear lapping and testing machines. The spindle design includes a rotationally compliant element which can substantially reduce the dynamic forces induced between the gear members while rolling under load. The theory of this spindle concept is presented using simplified models, providing the explanation for the process benefits it brings. Analysis and simulations give additional insight into the dynamics of the system. Finally, actual lapping and testing machine results are presented.

ISBN: 1-55589-808-4 Pages: 11

02FTM9. Gear RollScan for High Speed Gear Measurement

Author: **A. Pommer**

This presentation features a revolutionary new method for the complete topographical measurement of gears. The Gear RollScan system is similar to one-flank gear rolling inspection. However, the master gear has measuring tracks on selected flanks. With two master gears in roll contact, both the left and right flanks of the specimen can be inspected simultaneously. After a specified number of rotations, every measuring track on the master gears will contact every flank of the specimen this measuring device will always find the worst tooth.

ISBN: 1-55589-809-2 Pages: 10

02FTM10. Comparing the Gear Ratings from ISO and AGMA

Author: **O. LaBath**

In the early 1980's several technical papers were given comparing gear ratings from ISO and AGMA showing some interesting and diverse differences in the trends when the gear geometry was changed slightly. These changes included addendum modification coefficients and helix angle. Differences also existed when the hardness and hardening methods were changed. This paper will use rating programs developed by an AGMA committee to compare AGMA and ISO ratings while having the same gear geometry for both ratings. This will allow consistent trend analysis by only changing one gear geometry parameter while holding other geometry items constant.

ISBN: 1-55589-810-6 Pages: 17

02FTM11. Gear Design Optimization Procedure that Identifies Robust, Minimum Stress and Minimum Noise Gear Pair Designs

Author: **D. Houser**

Typical gear design procedures are based on an iterative process that uses rather basic formulas to predict stresses. Modifications such as tip relief and lead crowning are based on experience and these modifications are usually selected after the design has been considered. In this process, noise is usually an afterthought left to be chosen by the designer after the geometric design has been established. This paper starts with micro-topographies in the form of profile and lead modifications. Then, evaluations are made on the load distribution, bending and contact stresses, transmission error, film thickness, flash temperature, etc. for a large number of designs. The key to this analysis is the rapid evaluation of the load distribution.

ISBN: 1-55589-811-4 Pages: 15

02FTMS1 Design and Stress Analysis of New Version of Novikov-Wildhaber Helical Gears

Author: **I. Gonzalez-Perez**

This paper covers design, generation, tooth contact analysis and stress analysis of a new type of Novikov-Wildhaber helical gear drive. Great advantages of the developed gear drive in comparison with the previous ones will be discussed, including: reduction of noise and vibration caused by errors of alignment, the possibility of grinding, and application of hardened materials and reduction of stresses. These achievements are obtained by application of: new geometry based on application of parabolic rack-cutters, double-crowning of pinion and parabolic type of transmission errors.

ISBN: 1-55589-812-2 Pages: 25

2001 PAPERS

01FTM1. Carbide Hobbing Case Study

Author: **Y. Kotlyar**

Carbide hobbing improves productivity and cost, however many questions remain regarding the best application, carbide material, hob sharpening, coating and re-coating, hob handling, consistency and optimum hob wear, best cutting conditions, and concerns for the initial cutting tool investment. This paper is a case study of a successful implementation of carbide hobbing for an annual output of 250,000 gears, average lot size of about 200–300 gears, producing gears of about 150 different sizes and pitches, with 4 setups per day on average.

ISBN: 1-55589-780-0 Pages: 16

01FTM2. The Ultimate Motion Graph for "Noiseless" Gears

Authors: **H.J. Stadtfeld and U. Geiser**

Gear noise is a common problem in all bevel and hypoid gear drives. A variety of expensive gear geometry optimizations are applied daily in all hypoid gear manufacturing plants, to reduce gear noise. In many cases those efforts have little success. This paper will present "The Ultimate Motion Graph," a concept for modulating the tooth surfaces that uses modifications to cancel operating dynamic disturbances that are typically generated by any gear types.

ISBN: 1-55589-781-9 Pages: 16

01FTM3. Automated Spiral Bevel Gear Pattern Inspection

Authors: **S.T. Nguyen, A. Manesh, K. Duckworth and S. Wiener**

Manufacturing processes for precision spiral bevel gears are operator intensive, making them particularly costly in today's small lot production environment. This problem is compounded by production requirements for replacement parts that have not been produced for many years. The paper will introduce a new closed loop system capable of reducing development costs by 90% and bevel gear grinder setup time by 80%. In addition, a capability to produce non-standard designs without part data summaries is reviewed. Advancements will also be presented for accepting precision gears using an electronic digital master in lieu of a physical master.

ISBN: 1-55589-782-7 Pages: 15

01FTM4. How to Inspect Large Cylindrical Gears with an Outside Diameter of More Than 40 Inches

Author: **G. Mikoleizig**

This paper discusses the design and function of the relevant machines used for individual error measurements such as lead and profile form as well as gear pitch and runout. The author will cover different types of inspection machines such as: stationary, CNC-controlled gear measuring centers, and transportable equipment for checking individual parameters directly on the gear cutting or gear grinding machine.

ISBN: 1-55589-783-5 Pages: 20

01FTM5. Traceability of Gears – New Ideas, Recent Developments

Authors: **F. Härtig and F. Wäldele**

Some national standard tolerances for cylindrical gears lie in, and even below, the range of instrument measurement uncertainties. This paper presents a concept based on three fundamental goals: reduction of measurement uncertainty, construction of work piece-like standards, and shortening of the traceability chain. One of the focal points is the development of a standard measuring device as an additional metrological frame integrated into a coordinate measuring machine.

ISBN: 1-55589-784-3 Pages: 6

01FTM6. Performance-Based Gear-Error Inspection, Specification, and Manufacturing-Source Diagnostics

Authors: **W.D. Mark and C.P. Reagor**

This paper will show that a frequency-domain approach for the specification of gear tooth tolerance limits is related to gear performance and transmission errors. In addition, it is shown that one can compute, from detailed tooth measurements, the specific tooth error contributions that cause any particularly troublesome rotational harmonic contributions to transmission error, thereby permitting manufacturing source identification of troublesome operation.

ISBN: 1-55589-785-1 Pages: 15

01FTM7. Chemically Accelerated Vibratory Finishing for the Elimination of Wear and Pitting of Alloy Steel Gears

Authors: **M. Michaud, G. Sroka and L. Winkelmann**

Chemically accelerated vibratory finishing eliminates wear and contact fatigue, resulting in gears surviving higher power densities for a longer life compared to traditional finishes. Studies have confirmed this process is metallurgically safe for both through hardened and case carburized alloy steels. The superfinish can achieve an Ra < 1.5 µinch, while maintaining tolerance levels. Metrology, topography, scanning electron microscopy, hydrogen embrittlement, contact fatigue, and lubrication results are presented.

ISBN: 1-55589-786-4 Pages: 16

01FTM8. The Effect of Spacing Errors and Runout on Transverse Load Sharing and the Dynamic Factor of Spur and Helical Gears

Authors: **H. Wijaya, D.R. Houser and J. Harianto**

This paper addresses the effect of two common manufacturing errors on the performance of spur and helical gears; spacing error and gear runout. In spacing error analysis, load sharing for two worst-case scenarios are treated, one where a tooth is out of position and the second where stepped index errors are applied. The analyzed results are then used as inputs to predict gear dynamic loads, dynamic tooth stresses and dynamic factors for gear rating.

ISBN: 1-55589-787-8 Pages: 16

01FTM9. New Opportunities with Molded Gears

Authors: **R.E. Kleiss, A.L. Kapelevich and N.J. Kleiss Jr.**

Unique tooth geometry that might be difficult or even impossible to achieve with cut gears can be applied to molded gears. This paper will investigate two types of gears that have been designed, molded and tested in plastic. The first is an asymmetric mesh with dissimilar 23 and 35-degree pressure angles. The second is an orbiting transmission with a 65-degree pressure angle. Both transmissions have higher load potential than traditional design approaches.

ISBN: 1-55589-788-6 Pages: 11

01FTM10. Design Technologies of High Speed Gear Transmission

Author: **J. Wang**

This paper discusses a few critical factors and their effects on high speed gear transmissions. The first factor is centrifugal force and its effect on tooth root strength, tooth expansion and backlash and the interference fit between gear and shaft. The second is system dynamics, including critical speed, dynamic balancing and the torsional effects of flexible couplings. The third is the windage loss with different combinations of helix and rotation direction, lubricant flow rate, flow distribution and their effects on tooth bulk temperature field and tooth thermal expansion.

ISBN: 1-55589-789-4 Pages: 8

01FTM11. Kinematic and Force Analysis of a Spur Gear System with Separation of Sliding and Rolling between Meshing Profiles

Author: **D.E. Tananko**

This paper describes a comprehensive study of the novel gear design with physical separation between sliding and rolling motions of the mesh gear contact point. The sliding motion is accommodated by shear deformation of a thin-layered rubber-metal laminate allowing very high compression loads. Several important advantages will be presented when comparing the composite gear design to the conventional involute profile.

ISBN: 1-55589-790-8 Pages: 50

01FTMS1. Optical Technique for Gear Contouring

Author: **F. Sciammarella**

This paper presents an optical technique (projection moiré) that is compact and can provide a quick full field analysis of high precision gears. Comparisons are made between mechanical and optical profiles obtained of a gear tooth.

ISBN: 1-55589-791-6 Pages: 12

2000 PAPERS

2000FTM1. Minimization of In-Process Corrosion of Aerospace Gears

Authors: **S.T. Nguyen, A. Manesh, and J. Reeves**

This paper discusses problems and root causes associated with the corrosion of aerospace gears during the manufacturing process.

Specimens of common base materials used in precision gearing were subjected to process conditions that contribute to corrosion initiation including: different coolant types and concentrations, material heat treat conditions, base material magnetism, surface finish and iron particles in coolant.

ISBN: 1-55589-762-2 Pages: 7

2000FTM2. The Calculation of Optimum Surface Carbon Content for Carburized Case Hardened Gears

Author: **P.C. Clarke**

At present, there is not a method to calculate eutectoid carbon from chemical analysis and the eutectoid carbon is not the best element upon which to base surface carbon requirements. This paper will define the conditions and propose a method to calculate an optimum carbon level to minimize the possibilities of retained austenite, cementite and bainite.

ISBN: 1-55589-763-0 Pages: 8

2000FTM3. Comparison of New Gear Metallurgy Documents, ISO 6336-5 and AGMA 923 with Gear Rating Standards AGMA 2001 and 2003

Author: **A.A. Swiglo**

This paper will compare and contrast these four documents. What's new, what's different and what's hidden in the footnotes. Knowing the differences will be important to the users of these documents.

ISBN: 1-55589-764-9 Pages: 110

2000FTM4. Parametric Influences in the ISO Project Concerning Worm Gear Rating

Author: **M. Octrue**

This paper analyzes the influence of different parameters in CD ISO 14561 Load Capacity Calculation of Worm Gears such as; efficiency, wear load capacity, pitting, deflection and tooth root stress. The influencing parameters are divided into different categories such as external parameters of loading conditions, environmental parameters of lubricant temperature and driving and driven machines.

ISBN: 1-55589-765-7 Pages: 10

2000FTM5. Systematic Investigations on the Influence of Viscosity Index Improvers on EHL-Film Thickness

Authors: **B.-R. Hohn, K. Michaelis and F. Kopatsch**

This paper compares film thickness calculations to measurements taken using polymer containing oils in a twin disk machine. Results will show all polymer containing oils form lower film thicknesses than straight mineral oils of the same viscosity after shearing. A polymer correction factor is derived from test results improving the accuracy of film thickness calculation.

ISBN: 1-55589-766-5 Pages: 11

2000FTM6. Did the Natural Convection Exist in Mechanical Power Transmissions? Theoretical and Experimental Results

Author: **M. Pasquier**

ISO TR14179 parts 1 and 2, give values of total heat exchange coefficients in the case of natural convection and forced convection. This paper will compare the values of total heat exchange obtained from a theoretical study to the values given in the ISO Technical Reports.

ISBN: 1-55589-767-3 Pages: 10

2000FTM7. An Analytical-FEM Tool for the Design and Optimization of Aerospace Gleason Spiral Bevel Gears

Author: **C. Gorla, F. Rosa, and P.G. Schiannini**

To save time and money during the design process a tool based on analytical algorithms and on FEM models is introduced. As a first step, the conjugate surfaces theory is applied to a bevel set. An analytical tooth contact analysis is performed to determine the theoretical contact points on flank surfaces versus the meshing points. Information is then derived by the contact analysis and used to generate Finite Element models of the gear pair on the basis of the theoretical contact pattern. A final simulation by means of FEM models takes into account load sharing between tooth pairs.

ISBN: 1-55589-768-1 Pages: 12

2000FTM8. Stock Distribution Optimization in Fixed Setting Hypoid Pinions

Author: **C. Gosselin and J. Masseth**

This paper presents an algorithm used to optimize the stock distribution between the roughing and finishing cuts for fixed setting spiral bevel and hypoid members. The optimization is based on the Surface Match algorithm, where differences between the roughing and finishing spiral angle, pressure angle and tooth taper are minimized in order to obtain rough and finished tooth flanks that are parallel.

ISBN: 1-55589-769-7 Pages: 8

2000FTM9. Cylindrical Gear Inspection and Bevel Gear Inspection – A Simple Task by Means of Dedicated CNC-Controlled Gear Inspection Machines

Author: **G. Mikoleizig**

This paper will discuss the design, function, software management and probe systems of the inspection machines. Analytical tooth contact analysis of a cylindrical gear set by means of the combined effects of gear and pinion is shown on the basis of individual profile and alignment measurements. A fully automatic correction system will be introduced for checking the flank form on spiral bevel gears.

ISBN: 1-55589-770-3 Pages: 25

2000FTM10. Bending Fatigue Investigation under Variable Load Conditions on Case Carburized Gears

Authors: **B.-R. Hohn, P. Oster, K. Michaelis, Th. Suchandt and K. Stahl**

Variable load spectrum tests are carried out at different load levels in a step program and at random loading. The results of step programmed tests show a substantial influence of the period of the programmed subsequence of fatigue life. Fatigue life decreases when the subsequence period is shortened. With substantially shortened subsequences in step programmed test nearly the same fatigue life is reached as in random load tests.

ISBN: 1-55589-771-1 Pages: 14

2000FTM11. UltraSafe Gear Systems – Single Tooth Bending Fatigue Test Results

Authors: **R.J. Drago, A. Isaacson and N. Sonti**

This paper will discuss a system from a point of view of "what happens when a failure occurs." Gears were manufactured with seeded faults to simulate unexpected defects in various portions of the highly loaded gear tooth and rim sections. Crack propagation was monitored by measuring effective mesh stiffness and applied loading to provide both warning of an impending failure and a reasonable period operation after initiation of a failure for a safe landing.

ISBN: 1-55589-772-7 Pages: 9

2000FTM12. The Finite Strips Method as an Alternative to the Finite Elements in Gear Tooth Stress and Strain Analysis

Authors: **C. Gosselin and P. Gagnon**

The Finite Strip Method (FSM), which may be considered a subset of the Finite Element Method (FEM), is presented as an alternative to (FEM) that requires very little meshing effort and can be applied to virtually any tooth geometry while offering precision comparable to that of Finite Elements. This paper will cover the (FSM) model for spur and helical gears, plates of variable thickness such as the teeth of face gear members and for spiral bevel and hypoid gears.

ISBN: 1-55589-773-8 Pages: 11

2000FTMS1. Effects of Helix Slope and Form Deviation on the Contact and Fillet Stresses of Helical Gears

Authors: **R. Guilbault**

An investigation is conducted on the effects of helix slope and form deviation tolerances specified for grades 5 and 7 of the ANSI/AGMA ISO 1328-1 for cylindrical gears. The results show and almost linear correspondence between deviation amplitude and tooth load and fillet stress increases: using grade 7 instead of grade 5 can double the tooth flank load increase and associated fillet stress increase. Results also show that effects are even more significant on the maximum contact pressure.

ISBN: 1-55589-774-6 Pages: 21