Multiphysics Modeling of a Welded Furnace Roll for Improving Creep-Fatigue Life

This study proposes methods to improve the creep-fatigue lifetime using numerical analyses, including heat transfer analysis, creep-fatigue analysis, and CFD analysis to simulate the multiphysics involved in the roll service.

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ABSTRACT

Heat-transfer analysis, creep-fatigue analysis, and computational fluid dynamics (CFD) analysis were conducted to understand the failure of a welded roll in a continuous coating line and to propose solutions to improve the creep-fatigue lifetime. Analysis results showed three factors that contributed to the roll failure: difference of material properties between filler metal and base metal, furnace temperature variation during service, and high operating temperature. Based on these findings, two fatigue-life improvement methods, using the electron beam welding (EBW) process without filler metal to weld the roll and cooling the roll from inside to lower the shell temperature, were proposed. Creep-fatigue analyses showed both methods were effective in reducing the creep strain and stress to improve the roll fatigue life. Using EBW, the creep strain and stress in the interface between the filler metal and the base metal were completely eliminated. By lowering the shell temperature using the inside roll cooling, the creep strain and stress near the weld were significantly reduced. A cooling system was designed and evaluated using a fully coupled CFD and heat transfer analysis. A preliminary welding test showed that EBW could be implemented to weld the roll, and the CFD analysis results confirmed that effective inside roll cooling was difficult to achieve with the current design. In addition, the predicted highly localized maximum principal stress at the weld root can be used to explain the observed crack at the weld root, which indirectly validates the models.

KEYWORDS

• Creep • Fatigue • Multiphysics Modeling • Crack • Welding

Introduction

Creep and fatigue in combination is the main reason for the failure of many engineering components operating under high temperature and cyclic loading. Many studies have been conducted to investigate creep-fatigue crack initiation and growth (Refs. 1–3), creep and fatigue interactions (Refs. 4, 5), damage mechanism (Refs. 6, 7), lifetime predictions (Refs. 8–12), and hold time effect on creep and fatigue life (Refs. 13–15). Karl (Ref. 7) tested and modeled smooth and notched specimens of Type 304 stainless steel by applying several types of idealized fatigue loading to obtain a clear picture of the types of damage occurring in a steam turbine and similarly loaded mechanical systems. Zhu (Ref. 11) proposed a low-cycle, fatigue-creep life prediction model for general use in isothermal and thermo-mechanical loading based on the theory of ductility exhaustion. With better understanding of the creep-fatigue damage process, creep-fatigue assessment standards and codes (Refs. 16–19) were developed such as the ASME Boiler and Pressure Vessel Code (BPVC) Section III, Subsection NH, and the R5 assessment procedure.

ASME BPVC Section III, Subsection NH (Refs. 16–17), considers cyclic failure modes at elevated temperatures and provides creep-fatigue interaction rules and damage limits. The R5 assessment procedure (Refs. 18, 19) was developed in the UK to address both creep-fatigue crack initiation in initially defect-free components and the growth of flaws by creep and creep-fatigue mechanisms.

Although significant progress has been made to understand the creep-fatigue damage process and design the engineering components according to the ASME code or the R5 assessment procedures for elevated-temperature service, creep-fatigue failures are still observed in industries because real-world problems are far more complex than a well-controlled research environment. A large number of real-world problems have to be solved using multiphysics simulation tools to model the physics involved in a process or service. However, it is challenging to conduct a fully coupled numerical analysis among a separate continuum physics phenomena. Many successful multiphysics modeling efforts are based upon loose or one-way coupling because of computational cost and results mapping issues between multiphysics simulation tools (Ref. 20).

A catastrophic roll failure was observed in a continuous hot-dip coating...
line in a high-temperature roll position. The failure occurred in the weld joining the end bell to the roll shell and resulted in the complete 360-deg separation of the idle side end bell from the roll shell, as shown in Fig. 1. Historically, furnace rolls in this roll position have shorter service lives (less than one year) in comparison to other lower temperature roll positions. By examining the welded joint, there were two types of cracks found near the weld. The first type of crack initiated from the weld root and propagated to the weld’s outer surface, resulting in an separation between the roll shell and the end bell. The second type of crack initiated from one of the weld toes. The service record of the failed roll showed that the roll was routinely exposed to an operating temperature between 982° and 1066°C, with frequent temperature fluctuations of more than 500° C. Occasionally, the roll chamber temperature dropped to about 200° C. These temperature variations resulted in a cyclic thermal and mechanical process of the furnace roll in a continuous hot-dip coating line. The heat transfer analysis was conducted to predict the temperature history of the roll by modeling heat convection from hot air inside the furnace. The creep-fatigue analysis was performed to predict creep strain, stress, and deformation by inputting the predicted temperature history and applying mechanical loads. The deformation was validated by experimental measurement. Analysis results showed that the failure resulted from a creep-fatigue mechanism rather than a creep mechanism. The difference of material properties between the filler metal and the base metal is the root cause for the roll failure, which induces higher creep strain and stress in the interface between the weld and the HAZ (Ref. 21).

Finite element analyses, including a heat transfer analysis and a creep-fatigue analysis, were conducted to model the cyclic thermal and mechanical process of the furnace roll in a continuous hot-dip coating line. The heat transfer analysis was conducted to predict the temperature history of the roll by modeling heat convection from hot air inside the furnace. The creep-fatigue analysis was performed to predict creep strain, stress, and deformation by inputting the predicted temperature history and applying mechanical loads. The deformation was validated by experimental measurement. Analysis results showed that the failure resulted from a creep-fatigue mechanism rather than a creep mechanism. The difference of material properties between the filler metal and the base metal is the root cause for the roll failure, which induces higher creep strain and stress in the interface between the weld and the HAZ (Ref. 21).

The research in this paper is a continual study based on the conclusions of Ref. 21. The main objective of this study is to propose methods to improve the creep-fatigue lifetime using numerical analyses, including heat transfer analysis, creep-fatigue analysis, and CFD analysis, to simulate the multiphysics involved in the roll service. Based on the analytical results, two improvement methods using electric beam welding (EBW) and applying inside cooling were proposed and studied using numerical analysis. Analytical results confirmed that EBW was effective to improve the creep-fatigue life, and the inside roll cooling method was effective but difficult to implement in practice. The steel manufacturer confirmed that EBW without filler metal could be used to produce a defect-free weld of MO-RE®1 from a preliminary welding test. This proposed EBW solution could be an effective method to improve the creep-fatigue life of the furnace roll in the continuous hot-dip coating line, which could solve this long-term problem and provide huge cost savings for the steel manufacturer.

However, weld residual stresses were ignored in the present analyses due to two reasons. The first reason was that postweld heat treatment (PWHT) was applied to relieve residual stress after welding. The second reason was that the roll worked at a high temperature and residual stress could further be relieved during service. To confirm that EBW is still effective if weld residual stresses are included in the analysis, a follow-up study was performed to include weld residual stress as initial conditions during creep-fatigue analysis for a comprehensive assessment of the
creep-performance of the welded furnace roll. The results of the following study were reported in Ref. 22 in which both flux-cored arc welding (FCAW) and EBW were modeled to predict residual stress by inputting the detailed welding information, such as welding parameters and number of weld passes. The same conclusion that EBW without filler metal is an effective method to improve creep-fatigue life was obtained when including weld residual stress.

Analysis Procedure

Finite Element Model

A new design (Fig. 2A) of the furnace roll in the continuous hot-dip coating line was developed and consisted of two journals made of stainless steel 310 (SS310), two end bells made of high-temperature alloys MO-RE®1, and a roll shell made of MO-RE®1. There were two weld types in the roll: the shell weld joining the end bell to the shell and the journal weld joining the journal to the end bell. Because of loading and geometric symmetry, a half three-dimensional (3D) finite element model was used in the analysis and symmetric boundary conditions were applied in the symmetric plane, as shown in Fig. 2B.

Heat Transfer Analysis

The heat transfer analysis was governed by the following equation:

\[
\rho(T)c_p(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}[K_x(T) \frac{\partial T}{\partial x}] + \frac{\partial}{\partial y}[K_y(T) \frac{\partial T}{\partial y}] + \frac{\partial}{\partial z}[K_z(T) \frac{\partial T}{\partial z}]
\]

where \(\rho(T)\) is the density of material, \(c_p(T)\) is the specific heat, \(K_x(T), K_y(T), K_z(T)\) are the thermal conductivity coefficients for three space directions, \(T\) is the temperature, and \(t\) is the time elapsed. In the analysis, thermal conductivity was assumed to be the same in all three space directions.

Temperature-dependent material properties were included in the finite element model for material stainless steel 310 (Ref. 23, 24), MO-RE®1 (Ref. 25), and N117 (Ref. 26). Figure 3A shows that the filler metal has the highest elastic modulus and MO-RE®1 has the lowest elastic modulus among the three materials. Figure 3B shows that N117 has the lowest coefficient of thermal expansion (CTE) among the three materials. Figures 3C–E show comparisons of yield strength, tensile strength, and elongation between the three materials at different tempera-

![Image](https://via.placeholder.com/150)
There is an increase in the yield strength of materials MO-RE®1 and N117 from 600°C to 800°C. This phenomenon is known as yield strength anomaly (YSA) in which the yield strength actually increases at elevated temperatures. The mechanism of YSA could be attributed to the phase transformation and the precipitates at 800°C.

The roll was heated by heat convection from hot air inside the furnace. Surface heat convection \( q_s \) was calculated using Equation 2:

\[
q_s = h(T - T_s)
\]

(2)

where \( h \) was heat convection coefficient, \( T \) was the air temperature inside the furnace, \( T_s \) was the temperature on the outer and inner surfaces of the furnace roll. Since \( T \) and \( T_s \) were changed with the time and the location on the roll surface, a user subroutine was developed to automatically calculate the heat flux \( q_s \). The user subroutine was developed on the platform of ABAQUS (Ref. 27). For a given time and location on the roll surface, ABAQUS provided a temperature \( T \) to the subroutine. The subroutine determined \( T_s \) based on the heating zone shown in Fig. 4 and the heating process diagram shown in Fig. 5 and then calculated a heat flux \( q_s \). By inputting the heat flux to ABAQUS, a new temperature \( T \) was calculated and inputted to the subroutine. This looping process was done for all time increments and locations on the roll in the thermal analyses. As the roll temperature reached the furnace air temperature, the heat flux approached zero. By using the subroutine, the heat flux distributions on the roll and the heat flux transient changes during heating and cooling were modeled during the thermal analyses.

The typical heat convection coefficient \( h \) for air is between 10 and 1000 W/(m²K). Several heat transfer analyses were conducted to determine the heat convection coefficient to heat the roll based on the input furnace temperature, as shown in Fig. 5. It was found that the roll can be heated to the designated temperature according to the time specified in Fig. 5 in 24 h by inputting the heat convection coefficient, 20 W/m²°C. After heating for...
16 h, the roll was heated to about 200°C. After heating for 24 h, the roll was heated to about 1066°C. Then, the roll temperature was kept constant for 100 h and then cooled to about 200°C within 24 h. During creep-fatigue analysis, the heating cycle was repeated 10 times.

Creep-Fatigue Analysis

A creep-fatigue analysis procedure was developed using the ABAQUS commercial finite element code in which isotropic creep- and plasticity-coupled behavior was modeled by solving a coupled system of constitutive equations. This analysis procedure has been successfully used in modeling the creep behavior of a nuclear pipe system (Ref. 28). For simplicity, the power-law creep model was used in this study. The mechanical load and gravity were applied as a constant load and the thermal load was applied as low cyclic loads. Figure 5 shows a one-cycle thermal load in which the holding time is about 100 h. The long hold time made the power-law creep model suitable for the analysis of the furnace roll. During heating and cooling, a dynamic analysis was conducted and creep process was not modeled because the temperature quickly dropped to a low value. At a given temperature, the rate of steady-state creep can be calculated by the power law (Refs. 29, 30):

\[ \dot{\varepsilon} = A\sigma^n \]  

where \( \dot{\varepsilon} \) is creep strain rate, \( \sigma \) is the applied stress, \( A \) is a constant dependent on the material, and \( n \) is an exponent dependent on the creep mechanism. The creep constants \( A \) and \( n \) at different temperatures, listed in Table 1, were obtained by fitting the data from Refs. 23 to 26 and the data from an industrial customer.

Steel sheet tension of 31136 N was transferred to the roll through contact on one-fourth of the roll circumference over a width of 1270 mm in the center of the roll length, as shown in Fig. 6A. The combined force in the 45-

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**Table 2 — Air Properties as a Function of Temperature (Ref. 32)**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Specific Heat (J/kg°C)</th>
<th>Viscosity ((10^{-5} \text{ kg/m s}))</th>
<th>Thermal Conductivity ((10^{-2} \text{ W/m°C}))</th>
<th>Density ((\text{kg/m}^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.85</td>
<td>1004.9</td>
<td>1.846</td>
<td>2.624</td>
<td>1.177</td>
</tr>
<tr>
<td>101.85</td>
<td>1010.6</td>
<td>2.181</td>
<td>3.186</td>
<td>0.941</td>
</tr>
<tr>
<td>226.85</td>
<td>1029.5</td>
<td>2.670</td>
<td>4.041</td>
<td>0.706</td>
</tr>
<tr>
<td>326.85</td>
<td>1051.1</td>
<td>3.017</td>
<td>4.661</td>
<td>0.588</td>
</tr>
<tr>
<td>426.85</td>
<td>1075.0</td>
<td>3.332</td>
<td>5.236</td>
<td>0.504</td>
</tr>
<tr>
<td>526.85</td>
<td>1098.7</td>
<td>3.624</td>
<td>5.774</td>
<td>0.441</td>
</tr>
<tr>
<td>626.85</td>
<td>1120.9</td>
<td>3.897</td>
<td>6.276</td>
<td>0.392</td>
</tr>
<tr>
<td>726.85</td>
<td>1141.1</td>
<td>4.153</td>
<td>6.754</td>
<td>0.353</td>
</tr>
<tr>
<td>826.85</td>
<td>1158.9</td>
<td>4.396</td>
<td>7.209</td>
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<td>4.626</td>
<td>7.640</td>
<td>0.294</td>
</tr>
<tr>
<td>1026.85</td>
<td>1188.4</td>
<td>4.846</td>
<td>8.054</td>
<td>0.272</td>
</tr>
</tbody>
</table>
deg direction was 44033 N, as shown in Fig. 6A, which was applied on the area of 912073 mm² resulting in a pressure of 0.048 MPa. The finite element grids (see Fig. 6B) show the pressure applied to the surface that is a 90-deg section in the designed roll. Analyses were conducted to evaluate the individual effect of pressure and temperature on stress. It was found that the stress induced by pressure was much smaller than the temperature changes. Therefore, a constant pressure was applied in the analyses. Only the thermal load was applied as a cyclic load.

Weld residual stresses and welding processes were not modeled in this study because PWHT was used in producing the roll, and PWHT may reduce residual stresses from welding. In addition, the roll served in a high-temperature environment was essential for the creep process to reduce the weld residual stress further. A follow-up study (Ref. 22) was conducted to include weld residual stress during the creep-fatigue analyses. It was found that the same conclusions can be obtained with and without weld residual stress during the creep-fatigue analyses.

A Fully Coupled Heat Transfer and CFD Analysis

A fully coupled heat transfer and CFD analysis was conducted to simulate the effect of high-pressure air cooling inside the roll on the roll temperature, which was one of the proposed methods to improve the creep-fatigue life of the furnace roll in this study. The CFD analysis was governed by incompressible Navier-Stokes equations. The equations can be readily found in the ABAQUS manual (Ref. 26) and the CFD textbook (Ref. 31) and will not be discussed here. The CFD model and boundary conditions are discussed in detail below.
A cooling system was designed by modifying the new design of the furnace roll (Fig. 2A). The roll was enclosed by the journal welds, as shown in Fig. 7A. To allow air to flow into the roll, the journal at the right-hand side was redesigned to allow air flow into the roll through a center tube and out of the roll via the four holes around the center hole, as shown in Fig. 7B.

A one-fourth heat transfer model and a CFD model (Fig. 8) were created for computational efficiency to evaluate the effect of the cooling design on the temperature of the roll shell by considering the symmetry of geometry, air flow, and heat convection on the roll. The heat transfer model has solid parts that include the roll shell wall and the journals. The outer surface of the roll shell was heated from the hot air in the furnace, as shown in Fig. 8. The CFD model includes the fluid that is air in this analysis. The temperature-dependent properties are shown in Table 2. The CFD boundary conditions include inlet pressure (0.62 MPa), outlet pressure (0.1 MPa), no-slip/no-penetration conditions at a wall, and air temperature at the inlet (37°C). The inlet is the center hole and the outlet is the four holes, as shown in Fig. 7B.

The analysis was conducted using the cosimulation capability of the ABAQUS/CFD module and the ABAQUS/standard module. ABAQUS/CFD simulated the air flow inside the roll and ABAQUS/standard modeled the heat transfer between the air and the roll and in the roll. For a small time increment, a CFD analysis was conducted to predict temperature, pressure, and velocity of the air and output heat flux in the interface between the air and the roll. A heat transfer analysis was conducted by inputting the heat flux from the CFD analysis to predict the temperature in the roll and output the temperature in the interface between the air and the roll. This analysis process was repeated until the end of the simulated time. Since each time increment was small, this coupled heat transfer and CFD analysis was computationally expensive. Therefore, a one-fourth model
was used for this coupled analysis instead of a full 3D model.

**Analysis Results and Discussions**

**Effect of Cool-to Temperature on Creep-Fatigue Strain and Stress**

The temperature history of the failed roll showed that the roll experienced an operating temperature between 982°C and 1066°C, with furnace temperature variations more than 500°C. Occasionally, the furnace temperature dropped to 204°C and 427°C between temperature cycles. To identify the effect of the cool-to-temperature between cycles on the creep-fatigue strain and stress, sequentially coupled heat-transfer and creep-fatigue analyses were conducted for two cases. Case 1 cooled the furnace to a temperature of 204°C, and Case 2 cooled the furnace to a temperature of 427°C between thermal cycles. To identify the effect of the cool-to-temperature between cycles on the creep-fatigue strain and stress, sequentially coupled heat-transfer and creep-fatigue analyses were conducted for two cases. Case 1 cooled the furnace to a temperature of 204°C, and Case 2 cooled the furnace to a temperature of 427°C between thermal cycles.

Figure 9 shows the predicted distributions of effective creep strain for Case 1 and Case 2. The distributions of effective creep strain are identical between Case 1 and Case 2 since the only difference between these two cases is the temperature drops between loading cycles. Weld toes and weld root have high effective creep strain, as highlighted at locations 1–3 in Fig. 9.

Location 1 has the highest creep strains among the three locations. The predicted creep strain is low (0.29%). Ten cycles were modeled, which are equivalent to a two-month time period. With the time increasing, the accumulated creep strain will be higher. Although the predicted creep strain is low, an elastic-plastic-creep analysis has to be performed to model the plastic and creep process during roll service. A sensitivity study showed that a pure elastic-plastic analysis cannot predict the same stresses as the elastic-plastic-creep analysis.

Figure 10 shows the predicted distributions of the maximum principal stress for Case 1 and Case 2. Case 1 has a much higher maximum principal stress than Case 2. Compressive stresses were shown in the bottom of the weld with tensile stresses around it. These kinds of stress distributions resulted from the difference of the CTE expansion between the filler metal (N117) and the base metal (MORE®1). The CTE of the base metal MORE®1 is higher than the filler metal N117. At high temperatures, the base metal may expand more than the filler metal, while the filler metal restrains the base metal expansion to produce compressive plastic strains so the dimensions of the base metal become small. After cooling to a lower temperature, the filler metal will pull the base metal to the original dimensions. Thus, high tensile stresses show in the base metal and compressive stresses show in the bottom of the weld.

Figure 11 shows that a crack initiated from the weld root and then propagated through the weld. The weld macrograph was prepared by cutting one of the failed rolls. The crack is most likely induced by the high tensile maximum principal stress shown at the weld root in Fig. 10A. Therefore, the experimental results indirectly verified the model predictions. Although compressive stresses are shown in the weld before cracking, the stress distributions could be changed after cracking propagates through the weld. The tension induced from the thermal and mechanical loads would overcome the compressive stress and induce tensile stresses in the crack tip during the crack propagation.

Figure 12 shows the evolution of temperature, effective creep strain, and maximum principal stress at the weld root for Case 1. Effective creep strain and maximum principal stress increases as the time increases. The maximum principal stress increase results from the plastic strain accumulation. This result implies that the weld root is most likely the failure location since the stress range increases as the time increases. The weld-root crack shown in Fig. 11 confirms this analysis result.

Figure 13A shows a hoop stress distribution in Case 2 where the weld is in compression, and the base metal near the weld is in tension. Hoop stress was plotted to understand the
near-weld cracks found in the failed roll, as shown in Fig. 13B. The stress magnitude is low because the roll is at a temperature of 427°C. If the roll cools to room temperature, the stress magnitude would be higher. Although the modeled weld has a different orientation than the failed roll, the hoop stress pattern will be the same between the modeled weld and the failed weld. The tensile stress near the weld could induce the cracks near the weld as shown in Fig. 13C, D.

This study suggests that the cool-to temperature has a significant effect on creep strain and stress during temperature cycles. Therefore, controlling the cool-to temperature between cycles will reduce the creep-fatigue strain and stress to extend the creep-fatigue lifetime. In addition, the analyses also shows that the difference in material properties between the weld (N117) and the base metal (MO-RE®1) is the root cause of roll failure. If the same material is used for both the weld and base metal, the high creep-fatigue strain and stress could be reduced.

**Improvement Study 1: Electron Beam Welding**

The study of the effect of cool-to temperature between cycles on the creep-fatigue process shows that the different material properties between the base material and the filler metal are the root cause of high creep-fatigue strain and stress at the weld toes and the weld root. One option to reduce the high creep-fatigue strain and stress is to use the same material for both the filler metal and the base metal during the welding of the roll using FCAW. Another option is to use a newer welding process such as EBW without any filler metals. Since using the base metal as filler metal could result in weldability problems during FCAW of the roll, EBW was studied to explore the possibility of improving the creep-fatigue life. After welding using EBW, PWHT will be conducted to eliminate the weld residual stresses and restore material properties. Therefore, weld residual stress does not need to be included in the creep-fatigue analysis. The weld material properties could be assumed to be the same as the base material properties.

A ten-cycle creep-fatigue analysis was conducted by replacing the material properties in the weld with the base material properties while keeping the other conditions the same as Case 1 to study the effect of an electron-beam welded joint on creep-fatigue strain and stress. Figure 14 shows the predicted effective plastic strain and maximum principal stress with EBW without the use of filler metal. The effective creep strain plot uses the same scale as in Fig. 9. The striking difference in Figs. 14A and 9 illustrates the elimination of the localized concentration of an effective creep strain in Fig. 14A. Similarly, maximum principal stress is plotted as the same scale used in Fig. 10. It is found that high stress at the weld root disappears, as shown in Fig. 14B.

Analysis results show that EBW could be an effective method to improve the creep-fatigue life of the furnace roll in the continuous hot-dip coating line. A preliminary welding test shows that EBW could be used to produce a defect-free weld of MO-RE®1. A further study was conducted to predict the creep strain and stress in the electric beam welded roll by including the weld size, shape, and residual stress resulting from EBW (Ref. 30). Analysis results confirmed that EBW is an effective method to significantly reduce creep strain and stress.

**Improvement Study 2: Inside Cooling**

A material’s resistance to creep greatly depends upon the temperature to which the material is exposed. If the roll operating temperature can be lowered, the creep life of the roll could be extended. A method was numerically examined by applying cool air inside of the roll to lower the roll shell wall temperature. The temperature on the roll shell is the result of competing effects of inside surface...
cooling and outside surface heating by hot combustion flue gas originating from the direct fire furnace immediately below.

A heat transfer analysis was conducted using the analysis procedures discussed in the Finite Element Model section, where it was assumed that the cool air flows quickly inside the roll and could keep a temperature of 204°C (400°F) without being heated by the roll inner surface. The furnace temperature was cyclic from 1066°C to 204°C. Figure 15 shows the predicted temperature at three points on the roll shell for ten cycles. The predicted temperatures on the roll outer surface (N147), on the roll inner surface (N148), and on the inner surface of the end bell (N3284) are 668°C, 651°C, and 646°C, respectively. The temperature on the roll outer surfaces reduces from 1066°C to 668°C.

Creep-fatigue analysis was conducted using the analysis procedures discussed in the Finite Element Model section by inputting the predicted temperature history from the heat transfer analysis and applying mechanical loads. Figure 16 shows the predicted distribution of effective creep strain with inside cooling. Effective creep strain was significantly reduced by inner surface cooling of the roll by air, as illustrated by comparisons of Figs. 16 and 9.

Figure 17 shows the distribution of the predicted maximum principal stress with inside roll cooling. Stress at the weld root was reduced significantly with inside cooling, as illustrated by comparisons of Fig. 10A (without inside cooling) to Fig. 17 (with inside cooling). Figure 18 shows the evolution of temperature and maximum principal stress with inside cooling. The stress range with inside cooling is about 105 MPa, while the stress range without inside cooling is about 140 MPa, resulting in a 25% reduction.

The numerical evaluation of the inside cooling concept shows that the inside cooling method can lower the roll shell temperature, reduce the creep strain at the weld toe, and reduce the stress range at the weld root. Therefore, this method could be an effective way to improve the creep-fatigue life of the furnace roll in a production line.

Feasibility Study of Inside Cooling

A fully coupled heat transfer and CFD analysis was conducted using the one-fourth model (Fig. 8) to evaluate the effect of the cooling system design inside the roll on the temperature of the roll shell. In the design, cool air flowed into the roll through a center tube and out the roll via the four holes around the center hole. The outer surfaces of the roll were heated from the hot air in the furnace.

Before turning on the cool air, the roll was heated to the operating temperature according to the furnace-heating process — Fig. 5. Figure 19 shows the roll temperature at the start of cooling utilizing the cool air. To apply the cooling process smoothly, the cool-air pressure was linearly ramped up from atmospheric pressure to 0.62 MPa at the inlet in one minute.

Figure 20 shows the predicted air temperature inside the roll at 3, 15, and 27 s. At 3 s, the inlet pressure is 0.130 MPa. The air temperature near the end of the center tube is heated up by the hot roll shell. The air temperature is about 525 K. As time increases, the air temperature increases. At 27 s, the air temperature inside the roll reaches 800 K. Therefore, instead of cooling the roll shell using the flowing air, the air is heated by the roll shell. The design is not efficient to cool the roll shell.

Conclusion

Multiphysics analyses, including a heat transfer analysis, a creep-fatigue analysis, and a computational fluid dynamics analysis, were conducted to understand the failure of a welded roll in the vertical furnace of a continuous hot-dip coating line and propose solutions to improve the creep-fatigue lifetime. The heat transfer analysis was conducted to predict the temperature history of the welded roll by modeling heat convection heating from hot air inside the furnace using ABAQUS and a user-developed subroutine. The creep-fatigue analysis was performed by inputting the predicted temperature history, applying a mechanical load, and defining boundary conditions. The CFD analysis was used to evaluate a cooling system design that intends to cool the roll by flowing high-pressure cool air inside the roll. Based on the analysis results, the following conclusions could be drawn:

• Three factors: difference of material properties between the filler metal and base metal, furnace temperature variation during service, and high operating temperature contributed to the roll failure.

• Reducing the furnace temperature variation during roll service can lower the stress in the welded joint to improve the creep-fatigue life of the roll.

• Using EBW without filler metal to replace FCAW to weld the roll, the creep strain and stress in the interface between the filler metal and the base metal can be eliminated so the creep-fatigue life of the roll can be improved.

• Applying cool air inside the roll can lower the roll temperature to reduce the creep strain and stress to increase the roll lifetime, but it requires an effective cooling system design.

• The predicted high tensile hoop stress can be used to explain the observed cracks near the weld along the direction perpendicular to the roll hoop direction, and the predicted highly localized maximum principal stress at the weld root can be used to explain the observed crack at the weld root, which validates the models indirectly.

References


