

Investigating The Correlation Between Mechanical Plastic Deformation And The Characteristics Of Zinc Whisker Growth On Galvanized Steel Plate

Asmita Bhandari, Bivushi Timilsina, Samia Sultana, Michelle Gervasio*

* *Corresponding Author: mgervasio@sbc.edu*

*The Margaret Jones Wyllie '45 Engineering Program
Sweet Briar College
Sweet Briar, Virginia, USA*

Abstract— Zinc whiskers are spontaneous metallic filaments that can form on galvanized steel surfaces and pose significant reliability concerns for electrical systems due to their potential to break and fall onto sensitive circuit components. Despite documented failures associated with zinc whiskers, the role of mechanically induced stress in promoting whisker formation remains insufficiently understood. This work focuses on investigating a correlation between the characteristics of zinc whisker formation on galvanized steel and the level of controlled uniaxial tensile deformation. Dogbone-shaped tensile specimens were machined from galvanized steel. Specimens were annealed at 150°C for one hour prior to being elongated to prescribed levels of strain using a universal testing machine. The specimens were characterized using SEM to document initial surface conditions and were then aged at 30°C under ambient humidity to promote whisker growth, and periodically imaged with SEM to identify whisker initiation and evolution. Preliminary results indicate that higher levels of tensile deformation lead to an increased number of zinc whiskers, suggesting a strong influence of mechanically induced stress on whisker nucleation and growth.

Keywords— Zinc Whiskers, BCF Theory, Galvanized Steel, Plastic Deformation

I. INTRODUCTION

Metal whiskers are a critical reliability concern in electrical and electronic systems because they can create unintended conductive paths that lead to short circuits, signal interference, or complete system failure. These failures are especially significant in systems engineering contexts where multiple subsystems such as sensors, control units, and feedback loops must operate reliably together. Even very small whiskers can bridge closely spaced conductors in modern electronics, potentially disrupting system functionality without warning. As electronic systems become more complex and integrated, such failure mechanisms must be carefully considered in system-level design and reliability analysis [3].

Across different engineering domains, whisker-induced failures have been documented in systems where electrical reliability is critical. In aerospace applications, whiskers have been observed in satellite and spacecraft electronics, contributing to unexpected short circuits and anomalies. In industrial environments, including power systems and control

equipment, whisker growth has been associated with intermittent faults and equipment malfunction. Similar issues have been reported in consumer electronics, where whiskers can degrade performance through signal interference over time. In automotive systems, whiskers have also been identified in sensor components; for instance, a NASA investigation found tin whiskers forming a resistive short between signal lines in an accelerator pedal assembly, demonstrating their potential to disrupt system behavior [4]. These cases illustrate how whisker-related failures can manifest across multiple systems and scales, reinforcing the need to consider their impact in engineering design and reliability analysis.

Zinc whiskers are of particular interest because zinc coatings are widely used on galvanized steel in many manufactured components for corrosion protection. These whiskers are small metallic filaments that grow spontaneously from zinc surfaces and can lead to failures in electronic systems [1]. Their growth is mainly driven by compressive stresses within the zinc coating, which cause zinc atoms to move toward the surface and form whiskers as a stress relief mechanism. In addition, crystal defects such as dislocations and changes in grain structure play an important role in the growth process. Since common manufacturing processes like stamping, punching, and cutting can introduce residual stresses and defects in materials, they are closely related to the conditions that promote zinc whisker growth.

Metal whisker formation can be understood through crystal growth mechanisms described by the Burton–Cabrera–Frank (BCF) theory. This theory explains how atomic-scale processes control the growth of crystalline structures through surface steps and defects. “The BCF theory explained the growth of facets with the help of screw dislocations.” [2] In this framework, dislocations act as continuous sources of steps, allowing atoms to attach and extend the structure without the need for repeated nucleation. This is important for whisker formation because it provides a mechanism for sustained, directional growth from localized defect sites. Additionally, “Crystals usually have many defects.” [2] These defects, including screw dislocations, enable continuous material transport and accumulation, supporting the formation and elongation of whiskers over time. As a result, BCF theory helps explain how whiskers grow as crystalline

structures driven by defect-assisted atomic attachment. This theoretical framework supports the idea that deformation-induced dislocations in galvanized steel may act as initiation sites for zinc whisker growth.

The purpose of this study is to investigate how mechanical plastic deformation influences zinc whisker growth on galvanized steel and to determine whether a threshold level of deformation exists that initiates whisker formation. This is achieved by applying controlled tensile strain to galvanized steel samples at varying levels and examining the resulting whisker growth characteristics, including density, morphology, and distribution. By comparing samples subjected to different amounts of strain, the study aims to identify a critical strain level at which whisker growth begins or significantly increases. Understanding this relationship provides insight into how mechanical stresses introduced during manufacturing or service conditions may contribute to whisker formation, and helps establish guidelines to reduce the risk of whisker-related failures in engineering applications.

II. MATERIALS AND METHODS

A. Materials and Speciman Selection

A sheet of galvanized steel with a thickness of 0.036" was purchased for specimen fabrication. Dogbone-shaped tensile specimens were selected whose geometry allows controlled uniaxial loading, produces a uniform stress distribution in the gage region, and is commonly used for generating reliable stress-strain curves. The dogbone shape also fit within the 5 cm × 2 cm × 0.5 cm dimensional limits of the SEM stage, which made it suitable for mechanical testing and later microstructural examination.

B. Specimen Preparation

Dogbone specimens were machined using the ProtoTRAK SMX CNC system. A machining fixture that replicated the final dogbone geometry was designed to ensure consistent dimensions and smooth transitions in the neck region. A total of 12 tensile specimens were produced. After machining, all samples were deburred and visually inspected for surface uniformity prior to testing.

C. Mechanical Deformation

Tensile deformation was performed using the MTS Insight 50 universal testing machine (Model 569332-01). The machine was operated with MTESTQuattro software.

Before each test, standard procedures were followed. The instrument was powered on, the interface was initialized, the load frame was aligned, the grips were tightened, and the safety shield was placed in position. The load cell was zeroed for every test, and the software automatically recognized the machine and fixtures.

Each specimen was elongated to one of four displacement levels: 0 in, 0.635 mm, 1.27 mm, and 1.905 mm all of which resulted in plastic deformation under the ultimate tensile strength of the specimen. Only properly aligned and fully gripped samples were tested. Any run that produced non-physical or noisy data was stopped according to laboratory quality-control practices.

D. Specimen Cleaning

After deformation, the specimens were cleaned in a Branson 1510 ultrasonic cleaner for 10 minutes to remove surface contaminants. Cleaned samples were dried and handled carefully to prevent recontamination prior to SEM imaging.

E. SEM Imaging

Surface morphology and whisker formation were examined using the Hitachi TM-4000 Tabletop SEM. Each specimen was labeled on the non-observed side to ensure consistent orientation. Before imaging, samples were checked to confirm the surfaces were clean and fully dry.

The SEM chamber was sealed and the vacuum cycle was started. Accelerating voltage, brightness, contrast, and magnification were adjusted carefully to prevent beam-induced damage to the zinc coating. After imaging, the chamber was vented and the specimens were removed. The instrument was then returned to vacuum-hold mode.

F. Aging Procedure

After deformation, specimens were set for aging in a Lindberg/Blue M gravity oven maintained at approximately 30°C. This allowed zinc whisker growth to progress over time under controlled conditions. SEM images will be taken after an aging period of approximately three weeks to document whisker growth.

SEM imaging was performed at approximately 500-hour intervals to monitor whisker growth progression over time. Imaging was conducted at three time points over an aging duration of approximately 4,000 hours.

After each SEM session, specimens were removed from the SEM chamber and returned to the oven to continue aging under identical conditions.

III. RESULTS AND DISCUSSION

Zinc whiskers were observed on all samples, including those with zero applied strain. This indicates that whisker formation can occur even after annealing. Figures 1-4 display the SEM images of the samples with varying strain levels. In each sample, the observed whiskers are circled in red.

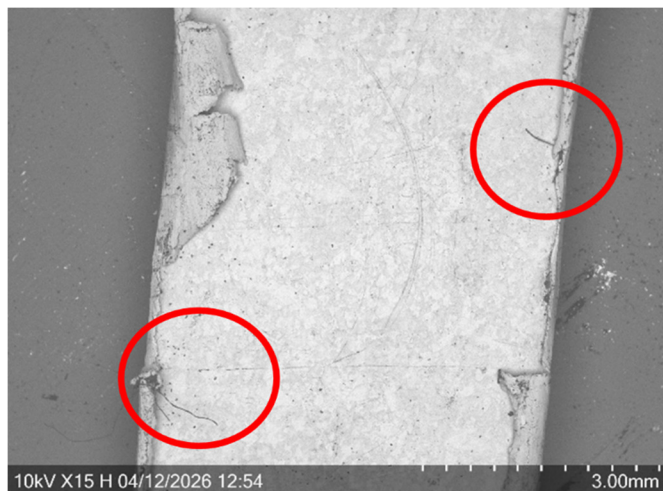


Fig. 1. Zinc whiskers observed in the unstrained sample in the curve region

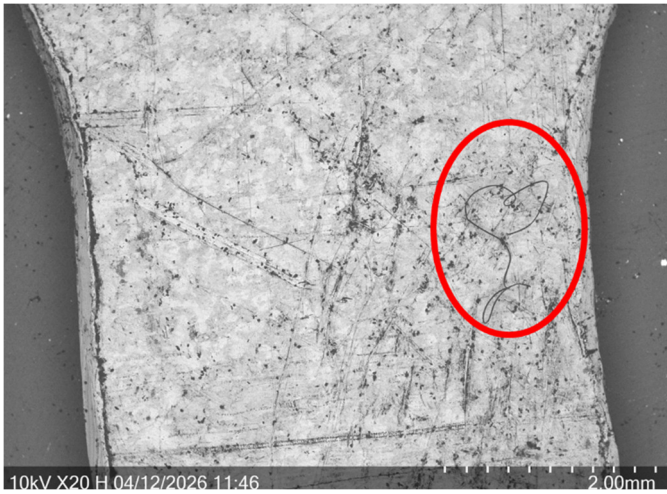


Fig. 2. Zinc whiskers observed in the curve region of the sample with 0.635 mm of elongation

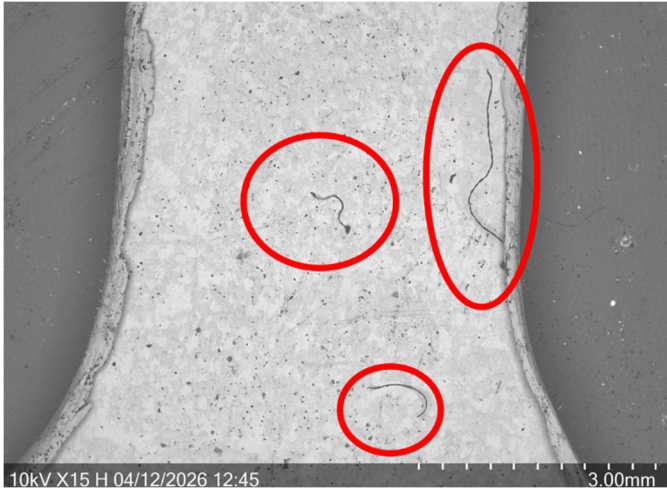


Fig. 3. Zinc whiskers observed in the curve region of the sample with 1.27 mm of elongation



Fig. 4. Zinc whiskers observed in the curve region of the sample with 1.905 mm of elongation

To evaluate the effect of applied strain, the total number of whiskers was counted for each sample and averaged across three trials for each strain level. The results showed that samples with zero strain consistently exhibited the lowest number of whiskers, while samples subjected to higher strain levels generally showed an increase in whisker count. This can be seen in Figure 5. However, the trend was not strictly linear across all samples, indicating variability in whisker formation. Notably, the 0.05 in strain samples exhibited a lower-than-expected whisker count, which may be attributed to contamination or handling effects during imaging.

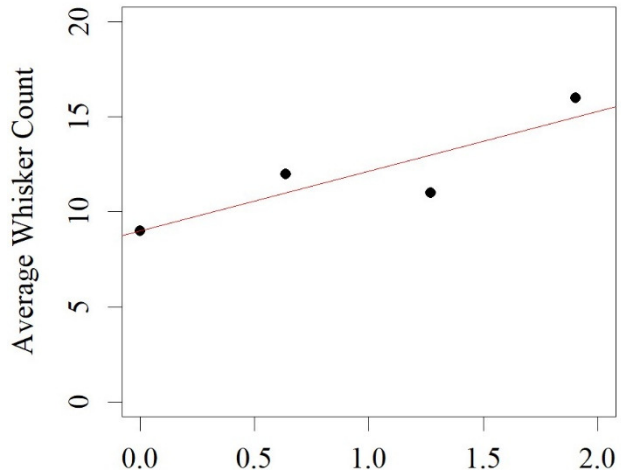


Fig. 5. Relationship between applied strain and the average total number of zinc whiskers observed across samples.

Additionally, the average whisker length was calculated for each individual sample across all three sets. The results demonstrate a positive correlation with increasing strain levels ($R^2=0.8776$), however, this trend is not likely to be significant due to the high standard deviation observed within each set, which were all similar in value to the average whisker length itself.

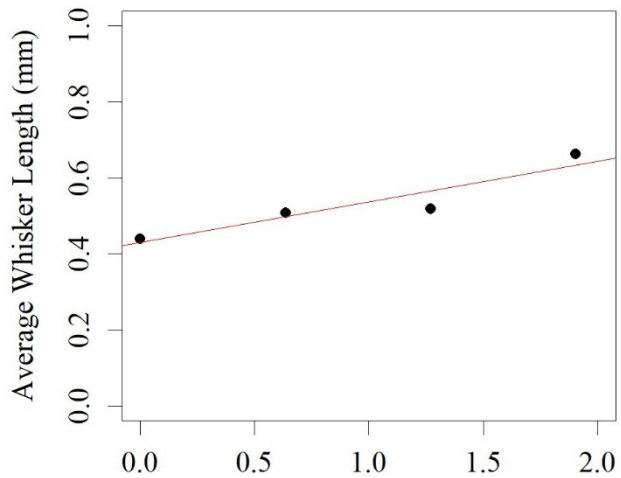


Fig. 6. Relationship between applied strain and the average length of zinc whiskers observed across samples.

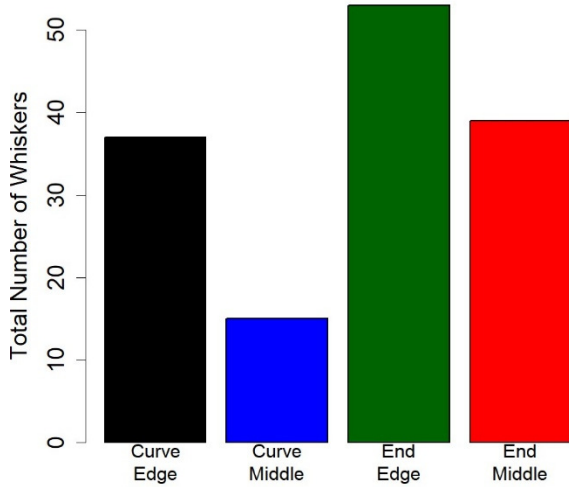


Fig. 7. Variation in Whisker Density Across Distinct Surface Locations

Figure 7, above, shows the distribution of whisker density across different surface regions of the specimen. The end edge region exhibits the highest whisker density, followed by the end middle and curve edge regions, while the curve middle region shows the lowest density. A visual representation of these locations can be seen below in Figure 8.

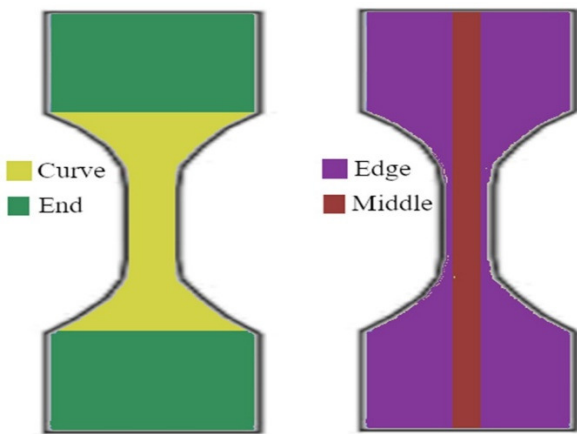


Fig. 8. Whisker location legend

Because the specimens were cut and machined into dogbone shapes, residual stresses and defects were introduced at the edges, which promoted more whisker formation in those regions. The data indicate that these residual stresses and their resulting dislocations were unable to be effectively annealed. Over time during the aging process, these stressed areas allowed whiskers to grow more rapidly, leading to higher density at the edges compared to the more uniform middle regions indicating that the process of cutting the metal introduced a higher dislocation density than the prescribed strain in this study.

IV. CONCLUSION

This study investigated how mechanical plastic deformation influences zinc whisker growth on galvanized steel. The results showed that increasing strain generally led to a higher number of whiskers, suggesting that deformation-induced stress plays an important role in whisker formation. The results also indicated that the cutting process created favorable conditions for whisker nucleation more so than tensile elongation. These findings indicate that care should be taken when fabricating galvanized steel parts, particularly that cut edges should be kept away from sensitive electronic circuitry.

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REFERENCES

- [1] L. Wu, M. A. Ashworth, and G. D. Wilcox, "Zinc whisker growth from electroplated finishes—a review," *Transactions of the IMF*, vol. 93, no. 2, pp. 1–8, 2015.
- [2] G. Ju et al., "Burton-Cabrera-Frank theory for surfaces with alternating step types," *Physical Review B*, vol. 105, no. 5, Feb. 2022, doi: <https://doi.org/10.1103/physrevb.105.054312>.
- [3] Technical Support to the National Highway Traffic Safety Administration (NHTSA) on the Reported Toyota Motor Corporation (TMC) Unintended Acceleration (UA) Investigation. DIANE Publishing.
- [4] P. G. Slade, *Electrical Contacts*. CRC Press, 2017.