Metallurgical Failure Analysis of Power Transmission Components

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When a power transmission component fails, it can adversely affect the performance of the assembly, often making the machine inoperable. Such failures can not only harm the reputation of the manufacturer, but can lead to litigation, recalls and delays in delivery due to quality concerns. Some failures can even result in bodily injury or death. Understanding why a part failed is critical to preventing similar failures from reoccurring. In the study of a failed part, the analyst must consider a broad range of possibilities for the failure. Although some failures can be attributed to a single primary cause, it is common for multiple secondary factors to contribute. The failure analyst must evaluate all of the evidence available to prepare a hypothesis about the causes of failure.

The most common type of failure that is studied is the fracture of a component. Fractures often have the most serious consequences, especially when load-bearing members lose their ability to carry their intended load. Other types of failures that can occur may be related to distortion, wear, or corrosion. A well-equipped materials laboratory will have most of the tools to effectively analyze a component that has experienced these types of failures. These tools include a low power stereomicroscope, metallographic equipment, hardness testers, spectrometers and a scanning electron microscope with energy dispersive X-ray spectroscopy (SEM-EDS) to name a few.

The process of analyzing a failed part starts with the collection of background information. It is important to know what the specified requirements for the part and the material are. That information is often available in the form of a part drawing and referenced material specifications. It is also important to know what the expected performance of the part is and how the failed part compared to that expectation. Any changes made to the manufacturing process should be reported to the failure analyst. Examples include vendor changes, design changes, material changes, thermal processing changes, etc.

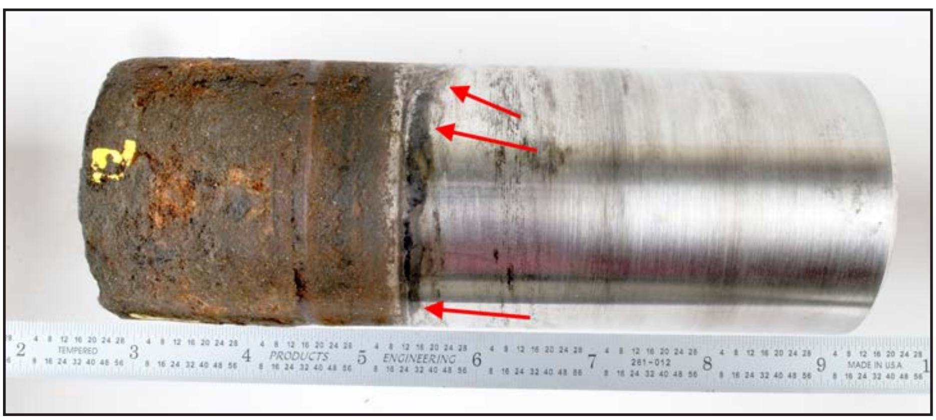

Figure 1 Fractured shaft, as received. Yellow marking indicates 12 o'clock position arbitrarily identified by Element New Berlin. Arrows indicate fretting damage.

Figure 2 Three o'clock position of shaft after rotating piece 90°. Arrows indicate pattern of fretting damage. Pattern of fretting damage suggested non-uniform contact on bearing. Pattern at 3 o'clock position indicated region of non-contact when bearing was present.

The next step in the failure analysis process is the visual examination of the part. Features to be noted, recorded and photographed in the visual examination include fractures, fracture origin regions, damage to the part, the presence of residues, corrosion products, and corrosion pits to name a few. In some cases, non-destructive testing (NDT) may be warranted if cracks are not readily visible or if they may be present below the surface. Chemical and hardness testing is performed in most cases to verify whether the part met the specified requirements. If enough material is available, tensile testing and impact testing is desirable to help understand the inherent mechanical properties of the metal.

After gathering as much background information as possible, the next step in most investigations is visual inspection and low power light microscopy. This is where the analyst performs a general assessment of the damage and features present on the part. For example, a fractured shaft that was used in an industrial application is presented in Figures 1 and 2. The yellow markings were made by Element to identify the 12 through 9 o'clock positions on the shaft. Markings such as these can prove invaluable in the course of an investigation to help orient the analyst and communicate the findings, especially after the part has been excised for further testing and analysis. It is obvious that the fractured end of the shaft, at the left portions of the images, was severely corroded. The arrows in the photographs indicate the presence of non-uniform fretting damage, suggesting that the fit with the bearing and the loads that were applied to the shaft were non-uniform. Although the fretting damage was located away from the fracture, it provided clues about the non-uniformity of the bearing fit and the loading on the part. This non-uniformity can lead to vibration and bending stresses on the shaft that can contribute to the failure of the part.

The fracture surface of the shaft is presented in Figure 3 after rotating the piece relative to Figures 1 and 2. The white arrows indicate the final fracture region. The final fracture region often consists of a rough texture or shear lip. The green arrows indicate the primary fracture origin region, which was judged to be approximately 180° away from the final fracture region. The blue arrows indicate ratchet marks. Ratchet marks are linear features, indicative of intersecting crack planes and are commonly present on fatigue-related fractures with multiple origins. As the blue arrows indicate, there were many fracture origins present around the circumference of the shaft. Ratchet marks are also associated with high stress concentration. The red arrows indicate the locations selected for further analysis via SEM-EDS. Section M was selected for metallographic analysis. It's critical for the analyst to carefully document, record and identify the features of the failed part and the damage present on the failed part in its as-received condition. The failed part will be handled, excised and examined in the laboratory. It can be critical to know the condition of the part, as-received, as the part can be damaged and sectioned during the investigative process.

Closer inspection of the fractures by low-power stereomicroscopy reveals a relatively rough texture with a notable amount of corrosion deposits and post-fracture mechanical rubbing damage, as shown in Figure 4. Inspection of the fracture and other features via electron microscopy is often the next step in the failure analysis process. Scanning electron microscopy is often utilized by the analyst to verify the fracture mode as features visible with a low power binocular microscope are not always resolvable, can be inconclusive and can sometimes be misleading. The scanning electron microscope can typically resolve features of interest up to 5,000×. In rare cases, magnifications up to 100,000× can be achieved. The light binocular microscopy is typically useful up to 50×. A scanning electron micrograph of the deposits present in the fracture origin region is presented in Figure 5.

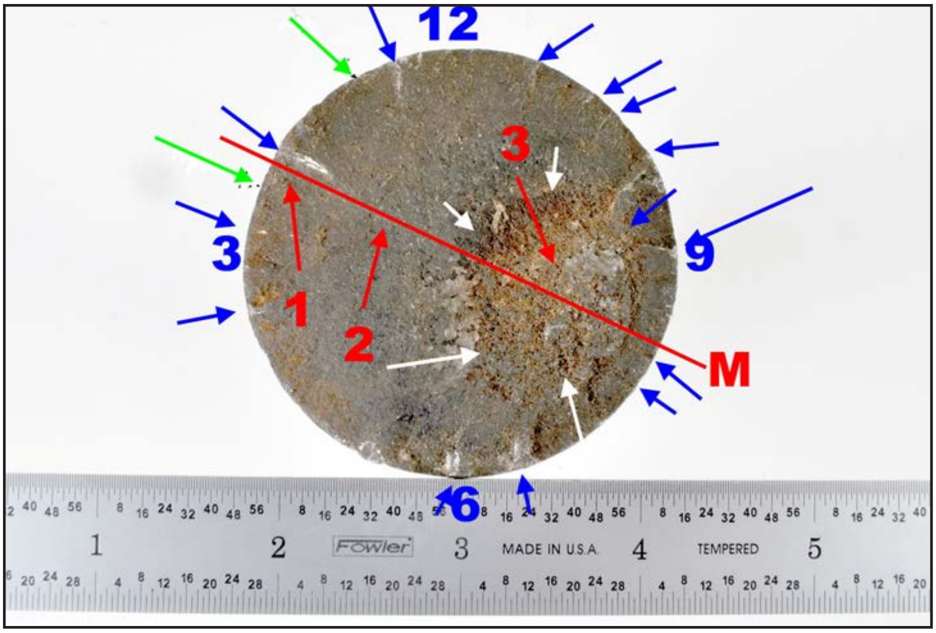

Figure 3 Fracture surface (Fig. 2, left). White arrows indicate final fracture region. Blue arrows indicate ratchet marks. Green arrows indicate fracture origin region. Red arrows indicate locations selected for further analysis. Section M selected for metallography.

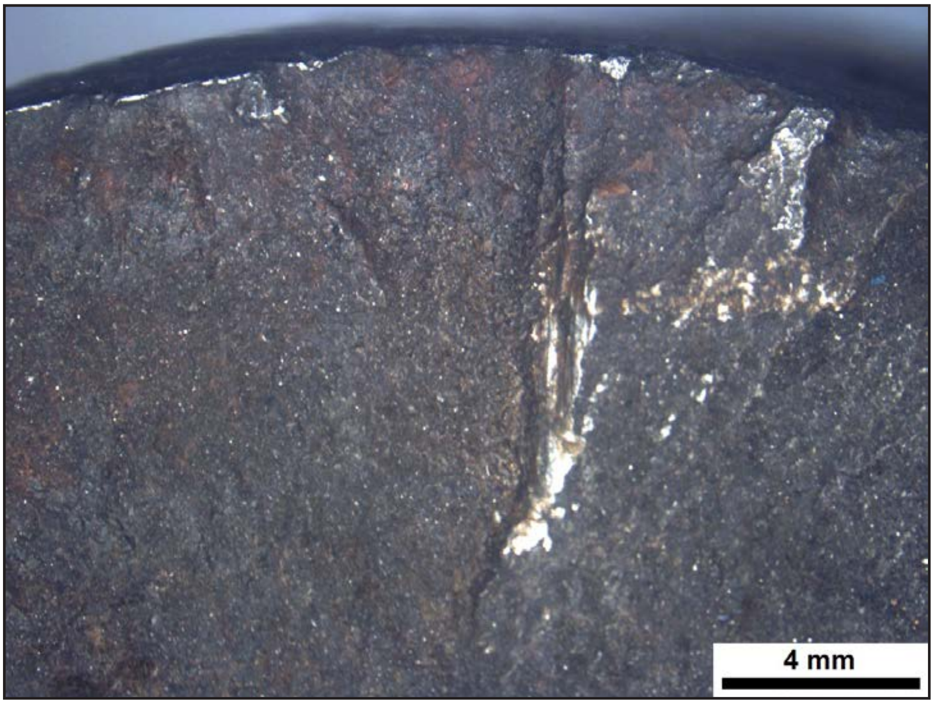

Figure 4 Magnified view of origin region (Fig. 3, top left), Location 1. Post-fracture mechanical rubbing damage, along with black and orange corrosion deposits, are evident in this view (original magnification (OM) 6×).

The corrosion deposits obscured the original fracture features, even after the piece had been gently cleaned. Location 1 is presented in Figure 6 after additional cleaning. The features detected beneath the corrosion deposits had the appearance of corrosive etching, indicating the shaft was present in a severely corrosive environment. The features in Figure 6 had a texture similar in comparison to pearlite lamellae, indicating the location shown had been etched.

Although the original fracture features were obscured by the corrosion deposits and mechanical rubbing damage, an evaluation of the corrosion deposits can still prove valuable via SEM. The EDS attachment to the SEM can provide a semi-quantitative assessment of the contaminants that are present of the part. This is often useful in a case where corrosion deposits are evident on the part. The results of the EDS analysis of various locations on the fracture surface are presented in Table 1. It is good practice to determine the elements present in the base metal first, so it can be determined which elements detected are present as contaminant material, and which elements detected are from the base material. The analysis of the base material is not intended to verify the composition of the steel as the EDS is only accurate up to approximately 0.1 weight percent. Often, the presence of trace elements in the steel with a composition of less than 0.1 weight percent, such as carbon, phosphorus and sulfur, are not detected in the base metal via EDS. Verification of the base metal composition is better suited to other techniques such as optical emission spectroscopy (OES).

Table 1 EDS Results (Relative Weight Percent)

Element	Base Metal	5 minute Clean	30 Minute Clean		
		Location 1	Location 1	Location 2	Location 3
Iron	99.6	30.9	65.3	4.6	49.0
Manganese	—	—	0.6	—	1.2
Chromium	0.3	—	0.2	—	—
Silicon	0.1	0.2	0.4	21.6	0.5
Aluminum	—	0.1	0.5	7.0	0.2
Sodium	—	1.4	3.5	0.1	1.2
Magnesium	—	—	—	0.3	0.9
Calcium	—	5.2	0.4	17.2	1.6
Titanium	—	—	—	0.5	—
Zirconium	—	—	—	0.3	—
Phosphorus	—	11.0	0.6	—	0.4
Sulfur	—	0.5	0.7	—	0.4
Carbon	—	16.5	18.8	12.2	20.8
Oxygen	—	34.2	9.0	36.0	23.8

— = Not Detected

Analysis completed using Energy Dispersive X-ray Spectroscopy (MA-15).

EDS analysis can detect and quantify elements from atomic no. 5 (boron) and greater on the Periodic Table. Relative percentages of the detected elements can be determined and are normalized to total 100%. Therefore, the results of these analyses are relative rather than absolute values.

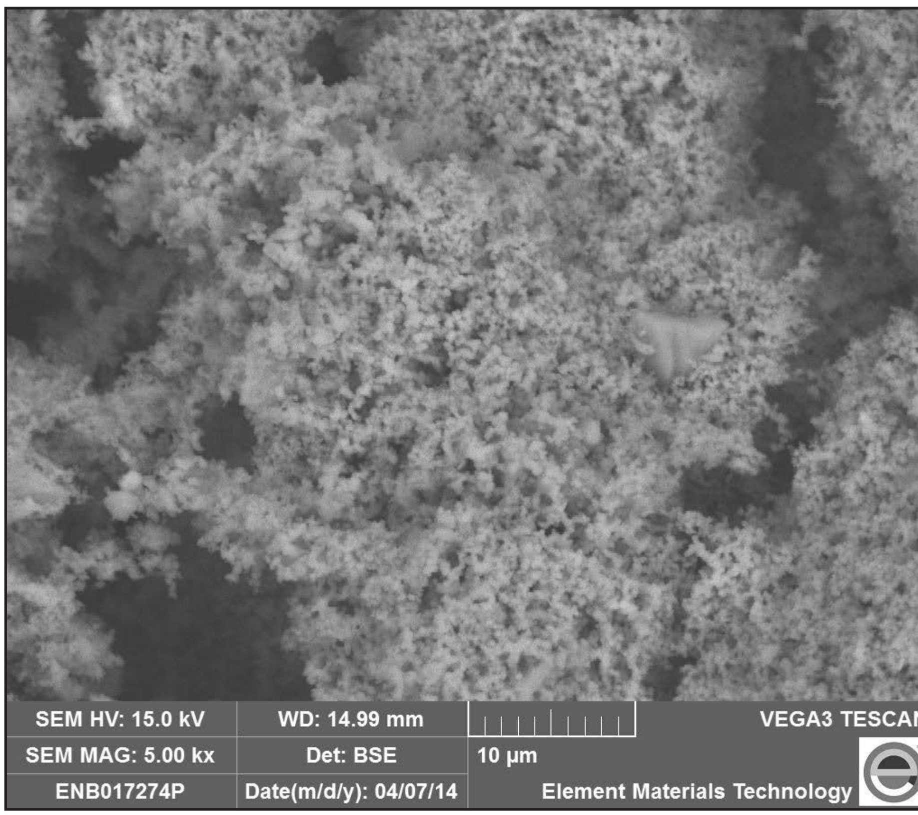

Figure 5 **Scanning electron micrograph of Location 1. Substantial amount of deposits were still present after preliminary cleaning of fracture surface. Features had oxidized appearance.**

In addition to the base metal elements, the EDS detected manganese, aluminum, sodium, magnesium, calcium, titanium, zirconium, phosphorus, sulfur, carbon and oxygen. The manganese may have been from the base metal. The aluminum, sodium, magnesium, calcium, titanium and zirconium were judged to be present as mineral deposits. The source of the phosphorus was not known, but the presence of phosphorus is often associated with detergents. The source of the sulfur was not known. The carbon was judged to be present as organic or carbonaceous deposits. The detection of oxygen indicated the presence of oxides or corrosion deposits on the steel. In general, the EDS detected foreign material present as mineral deposits, dirt, and oxidation products. Often, chlorine will be detected on corroded components. Chlorine, in the form of chlorides, is corrosive to steel in a moist, acidic environment. In this case, chlorine was not detected on the part.

Metallography is a particularly important step in the metallurgical failure analysis process. Examination of the microstructure can help verify whether proper thermal processes were applied to the part. Metallography can also identify whether material anomalies were present in the material that could have had a deleterious effect on

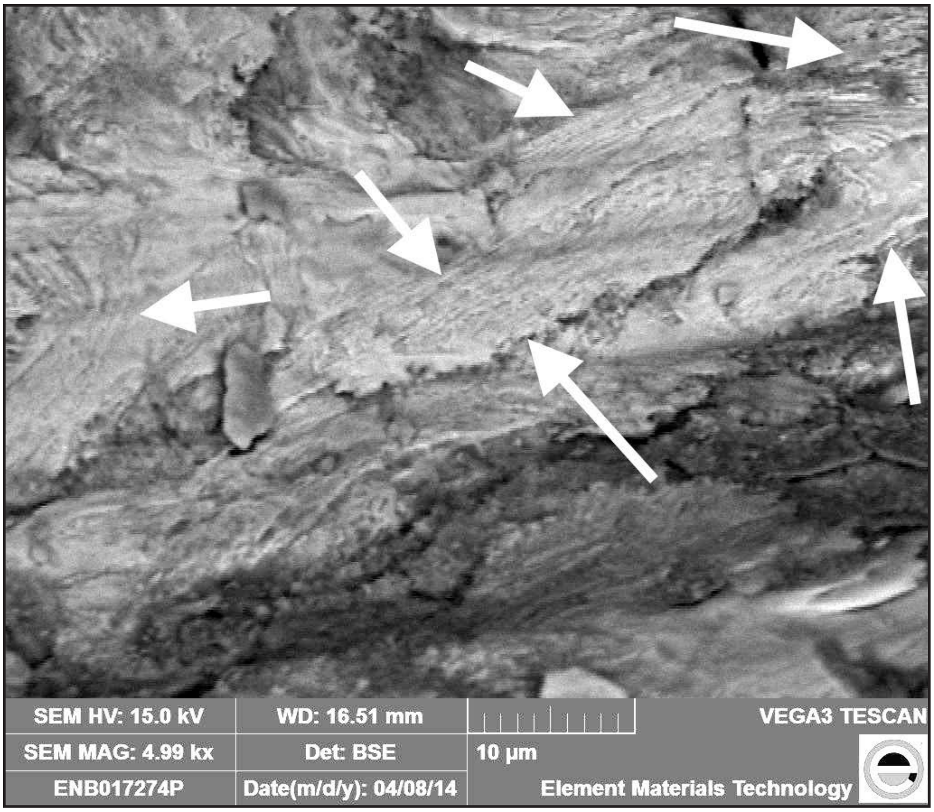

Figure 6 Scanning electron micrograph of Location 1 after additional cleaning. Arrows indicate features with appearance of corrosive etching into the pearlite lamellae on the steel.

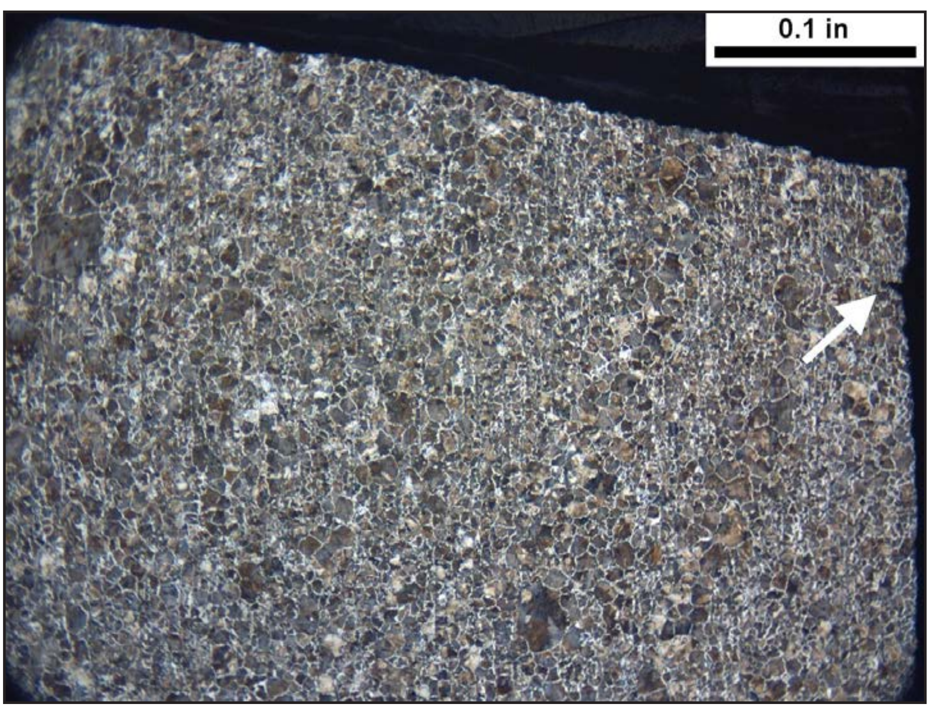

Figure 7 Section M — after etching. The fracture surface is at top portion of image. The microstructure consisted of pearlite and ferrite. The arrow indicates location of feature selected for closer inspection; 2% nital (OM 10×).

the part's performance. In this case the microstructure was judged to be normal for the material of manufacture, as shown in Figures 7 through 9. Some variation in the grain size was evident in the view. The grain structure was judged not to be a contributing factor in the failure of the part. A higher magnification view of the top right portion of Figure 7 is presented in Figure 8. A secondary crack, indicated by the white arrow, is at the right center portion of the image. The image was overexposed to show the gray scale that was present in the crack. A higher magnification view of the right center portion of Figure 8 is presented in Figure 9. The arrows indicate the presence of corrosion scale in the tip of the crack. The presence of corrosion scale in the tip of the crack is typical for corrosion fatigue related cracking. Corrosion fatigue can occur to a part due to a combination of cyclic stresses that exceed the fatigue strength of the part and corrosive attack that potentially initiates the cracking, but also accelerates the rate of cracking. Although some of the corrosion present on the part could have formed after the piece had failed, it was judged that corrosion fatigue was the mechanism of failure due to the presence of corrosion scale at the tip of the crack. The microstructure of the shaft otherwise consisted of pearlite and grain boundary ferrite, typical for plain carbon steel in the annealed or normalized condition.

After all the information is collected, a final conclusion can be made based on the evidence available. In this case, the following conclusions were determined:

- The fracture of the shaft was judged to be due to a combination of cyclic stresses that exceeded the fatigue strength of the part and corrosive attack that potentially initiated the cracking, but also accelerated the rate of cracking. This type of cracking is also known as corrosion fatigue. Although most of the original fracture features on the surface of the part were obliterated by corrosion damage, ratchet marks, indicative of intersecting crack planes and high stress concentration, were evident on the fracture surface. Ratchet marks are characteristic of fatigue-related cracking. Substantial corrosion products were present along the outer diameter of the shaft.
- Metallographic analysis of the shaft revealed the presence of a secondary crack near the fracture origin region. Corrosion scale was present at the tip of the crack. The presence of corrosion scale at the tip of a crack is commonly associated with corrosion fatigue. It was therefore judged that corrosion not only took place after the part fractured, but contributed to the progression of cracking. The microstructure otherwise consisted of pearlite and grain boundary ferrite, typical of plain carbon steel in the annealed or normalized condition.

Follow on activities, such as a stress analysis of the system, may be in order to help understand remedies to prevent failures from occurring again. Often, a stress analysis in the design of a system may not account for anomalous conditions such as corrosion pitting, non-uniform contact between the bearing and shaft, or mechanisms such as corrosion fatigue. In this case, a stress analysis was beyond the scope of the project. Sometimes, an investigation such as this may be performed in stages, or, budgetary restraints may prohibit certain types of testes and analyses from being performed.

The metallurgical failure analysis of a part can help determine conditions that contributed to failure that the design engineer might not have thought of in the design stages of the assembly. The failure analysis investigation or process can be thought of as a forensic puzzle. The more pieces of the puzzle are in place, the more conclusive the investigation will be. It is often tempting to ask the analyst to minimize the amount of testing performed to save time and money. It may also be tempting to withhold background information about the part for fear of biasing the analyst's final conclusion. It should be understood, however, that restricting the amount of testing and withholding important information will effectively take away pieces of the forensic puzzle that can prove critical to achieving the correct final conclusion. If the reasons for failure are not properly understood, corrective actions to prevent future failures may be ineffective. When the investigation is complete, it is often up to the parties involved to collectively determine the best course of corrective action to prevent similar events from occurring again. **PTE**

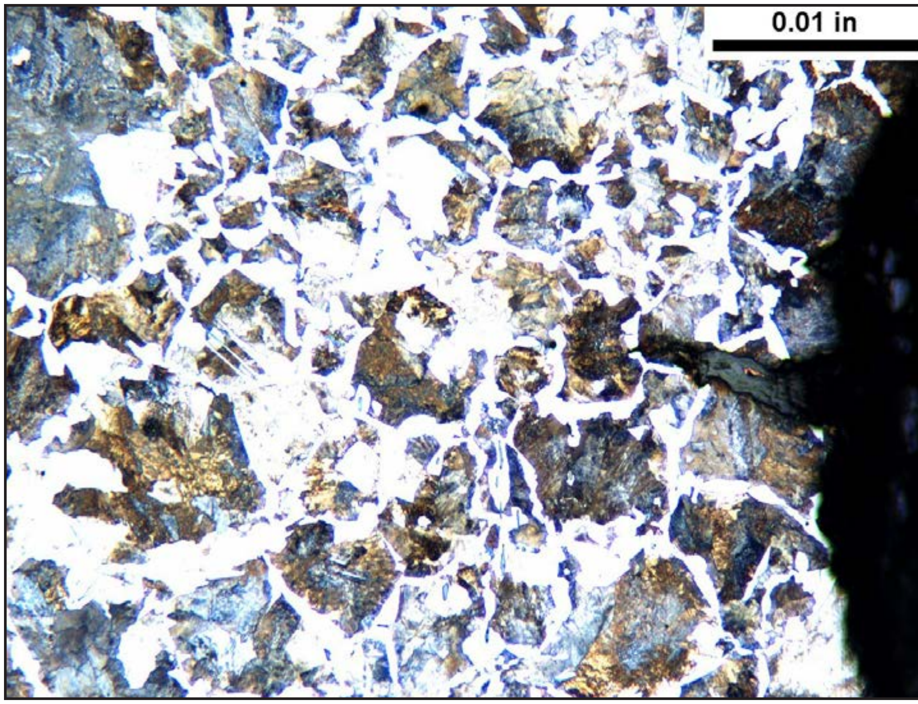

Figure 8 **Higher magnification view of the right-center portion of Figure 7, as indicated by the arrow in Figure 7. Secondary crack is evident at right portion of image. Image was overexposed to show crack, indicated by arrow; 2% nital (OM 100×).**

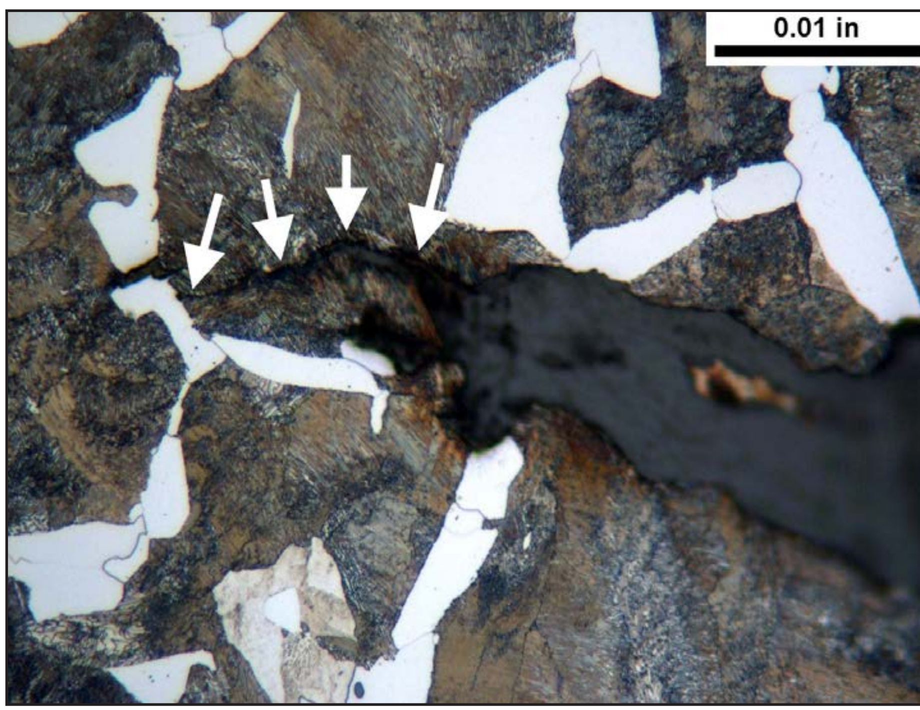

Figure 9 **A higher magnification view of the right-center portion of Figure 8. Arrows indicate the presence of corrosion scale in tip of crack; 2% nital (OM 500×)**

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