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Case Study: Low Cycle Fatigue

By

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Subject

Failure analysis of a Grade 8 Flange Bolt secured with a flat washer and nut to determine the cause of failure. The bolt was examined by visual examination, hardness testing, scanning electron microscopic examination, metallographic examination, and fracture mechanics.

Visual Examination

Figure 1 – Bolt Head

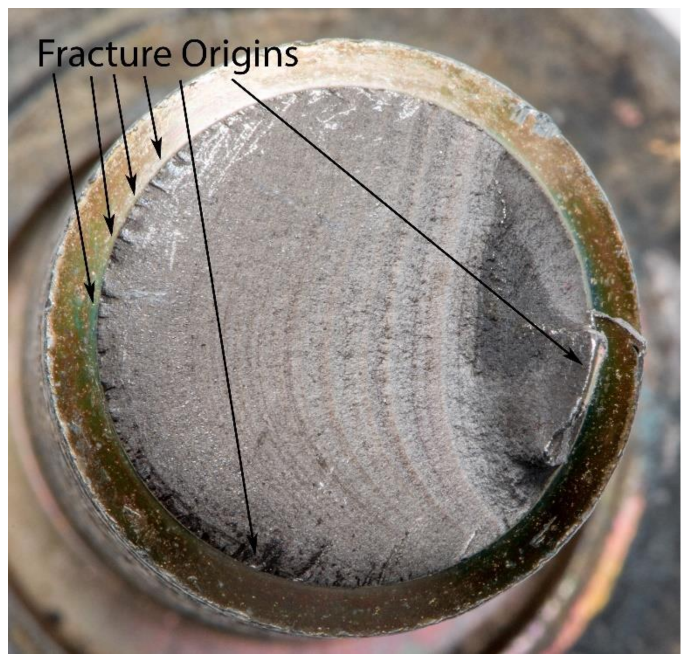

Figure 2 – Multiple Fracture Origins

The bolt head, shown in Figure 1, indicates that the bolt was a Grade 8, manufactured in the United States.

Figure 2 shows at least 36 fracture origins around the circumference of the bolt. It appears that initial overloading occurred from many different directions. Multiple fracture origins are typical with fatigue fracture.

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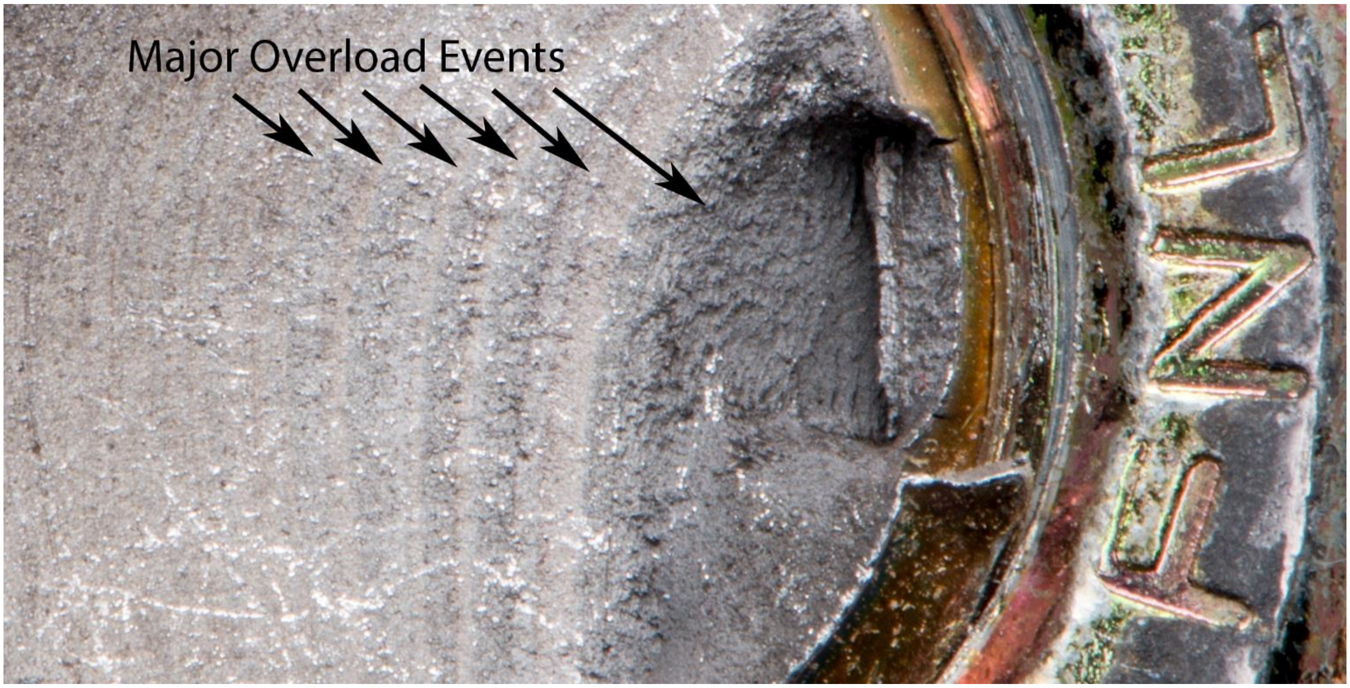

Figure 3 – Major Cyclic Overload Events

Figure 3 shows the fracture surface on the nut side of the bolt. There appears to have been over a dozen major overload events that occurred prior to the bolt failure. The actual fatigue striations are visible on the right side of the fracture surface.

Visual examination shows that the bolt failed by fatigue, with occasional very high load conditions.

Hardness Testing

The hardness testing was done according to ASTM E385, using a Vickers indenter and a 500 gram load. The results of the testing are given in the table that follows.

Delirious Bolt Hardness Data (Rockwell C Scale)					
Location	Vickers	STD DEV	MAX VALUE	MIN VALUE	HARDNESS
Core	333.00	13.13	346.00	313.00	33.62 HRC

The hardness range for an SAE J429 Grade 8 bolt is between 33 and 39 on the Rockwell C scale. The hardness of this bolt was 33.6 Rockwell C scale, and within the specified range.

Scanning Electron Microscopic Examination

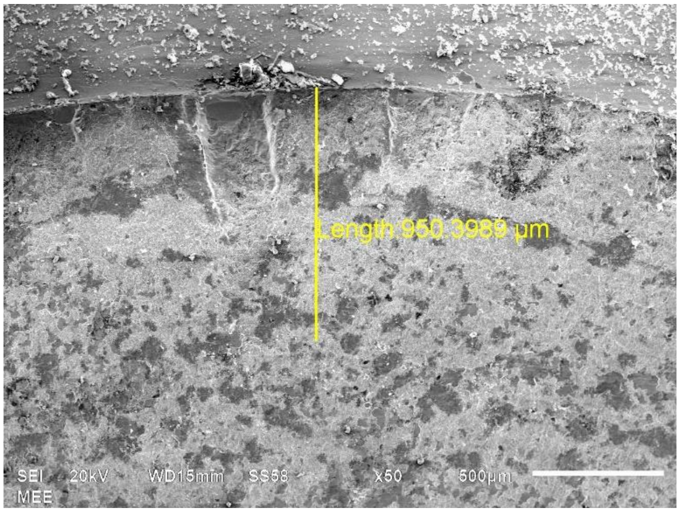

Figure 4 – 50X Fracture Surface near Fracture Origins

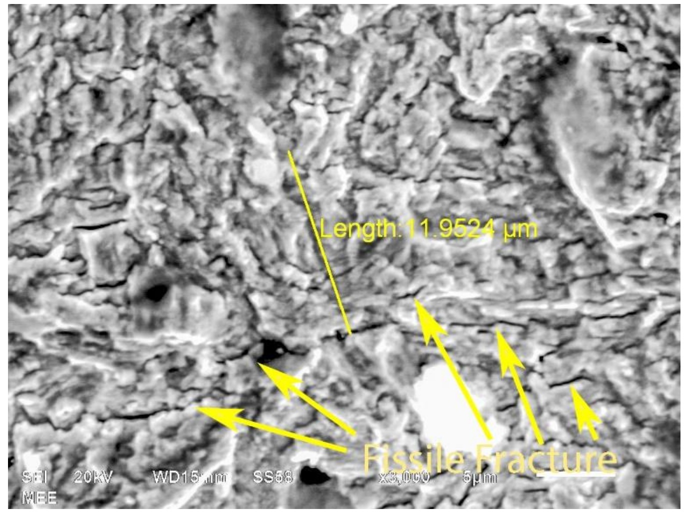

Figure 5 – 3000X Fatigue and Fissile Fracture

Figure 4 shows the fracture surface near several fracture origins. The location of this photo is on the left side of the fracture surface shown in Figure 2. The distance marking of 950.4 microns is from the fracture origin to the location of Figure 5. Figure 5 shows the fracture surface at higher magnification and shows very fine fatigue striations. The length shown in this photo is 11.95 microns. In that space there were 30 fatigue striations. The striation spacing was 1.57 X 10^{-5} inches, indicating low cycle fatigue. There are numerous secondary cracks or fissile fractures, shown in Figure 5. Fissile fractures occur when the cyclic load exceeds the tensile strength of the material.

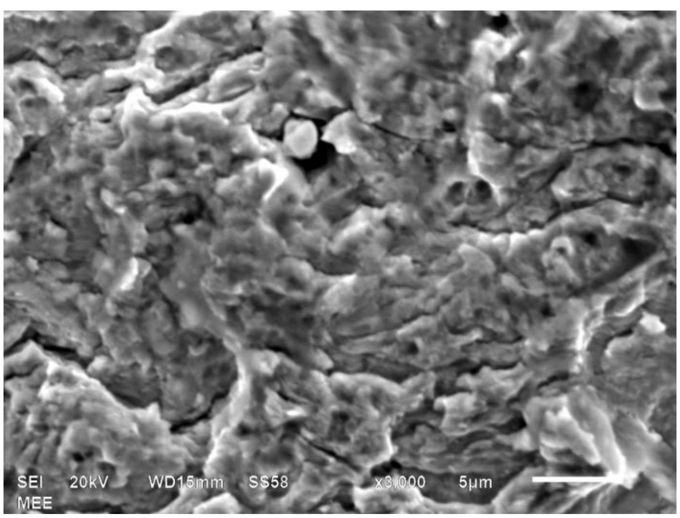

Figure 6 – 3000X Fracture Surface near Overload Band

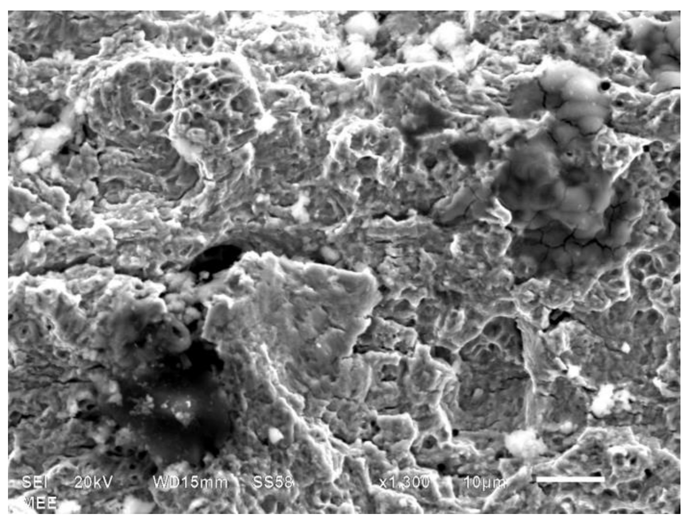

Figure 7 – 1300X Fracture Surface near Overload Band

Figure 6 shows the fracture surface near an overload band near the center of the bolt, see Figure 2. Shown in the photo is a combination of fine fatigue striations and coarser striations, plus fissile fracture.

Figure 7 shows the fracture surface in the second band from the right in Figure 2. At this location, ductile rupture is added to the fatigue and fissile fracture. The ductile rupture shown at this location is not unusual.

The scanning electron microscopic examination showed that the bolt failed by low cycle fatigue with frequent high stress overloads exceeding the bolt's strength.

Metallographic Examination

The magnification shown for the photos is the magnification at which the photos were taken.

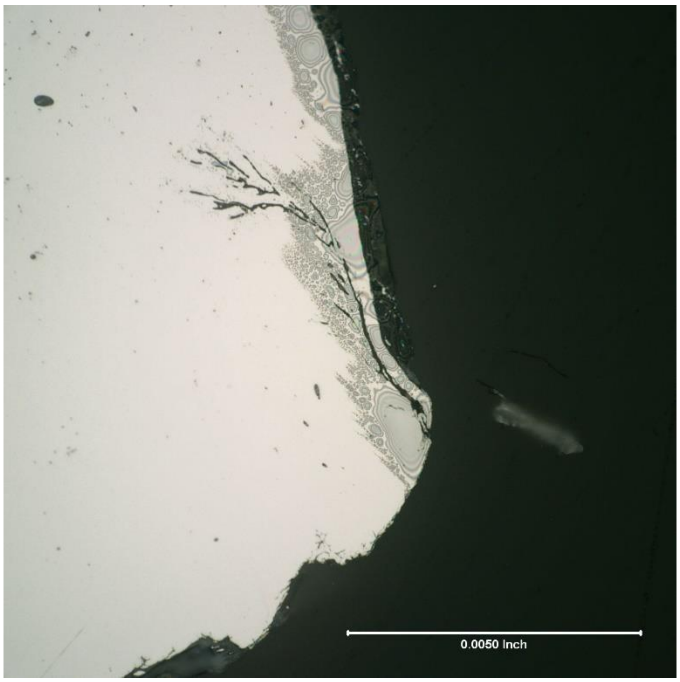

Figure 8 – 400X Rolled Thread Crest

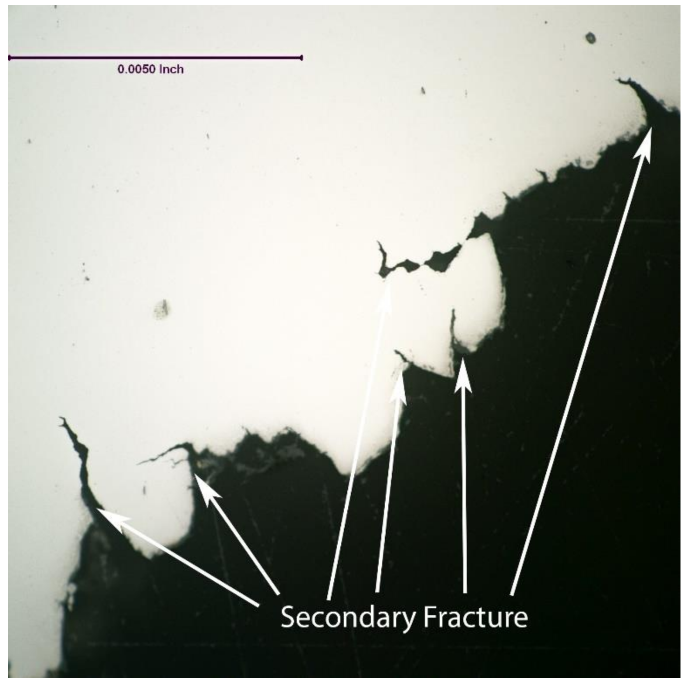

Figure 9 – 400X Fracture Surface

Figure 8 shows the crest of one of the bolt threads. The cracking of the crest indicates that the threads were formed by thread rolling, which produces the most fatigue resistant bolts.

Figure 9 is a cross section through the fracture surface. Secondary or fissile fracturing was quite evident at this location. It appears that some of the cracking could have been intergranular, indicating impact loading.

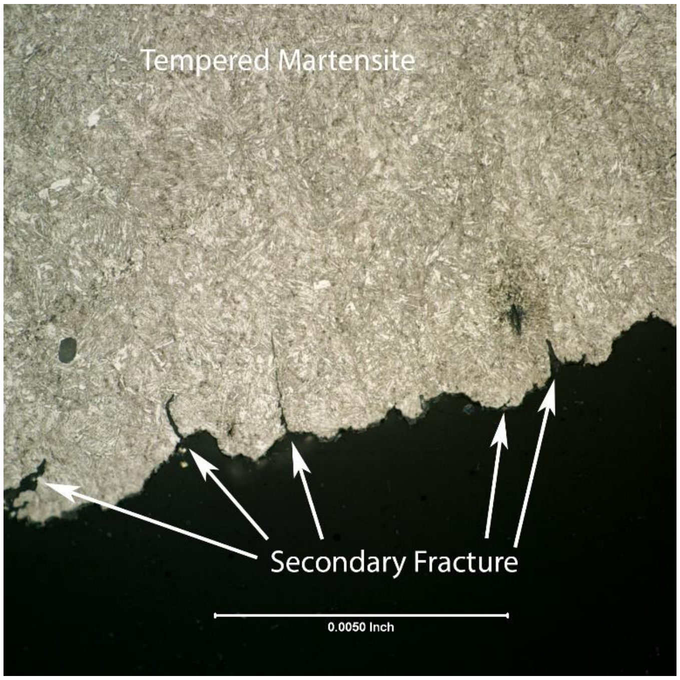

Figure 10 – 400X Microstructure Associated with the Fracture Surface

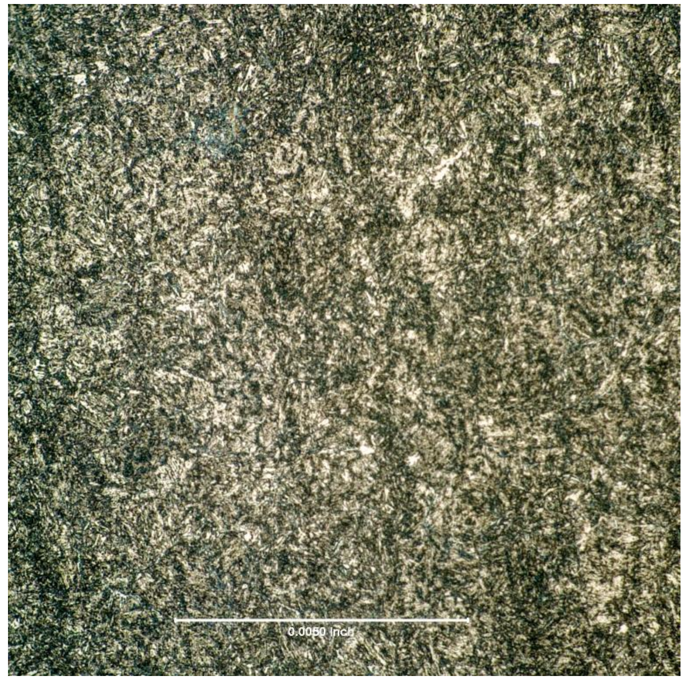

Figure 11 – 400X Core Mictrostructure

Figure 10 shows the tempered martensitic microstructure associated with the fracture surface. The microstructure was very fine grained, which increases the fatigue resistance of the bolt. There was secondary fissile fracture present.

Figure 11 shows the very fine grained tempered martensite core microstructure. There were no microstructural defects found with the bolt.

Fracture Mechanics

Fracture mechanics can be used to estimate the stress levels that were on the parts at the time of fracture. Knowing the location and spacing of the fatigue striations permits the estimation of the cyclic fatigue stress by the following equation: $\Delta\sigma = \frac{E\sqrt{\frac{spacing}{6}}}{Y\sqrt{a}}$. The terms are defined below:

$\Delta\sigma$	The applied cyclic stress.
E	The modulus of elasticity equal to 30,000,000 psi for steel alloys.
a	The distance the fatigue striations progressed from the fracture origin.
Y	A constant equal to 2.1. It is defined by the shape of the crack.

For this bolt, "*a*" was equal to 0.0374 inches, and the striation spacing was 1.57 X 10^{-5} inches.

The estimated cyclic stress, based on the fatigue striations shown in Figure 5, was 119,000 psi. The endurance limit for this bolt was about 50,000 psi. The loading on the bolt was very close to the bolt's yield strength and exceeded the bolt's endurance limit.

There are two probable causes of failure of this bolt: 1) The bolt was not fully torqued at installation, or was loosened during operation, which is the most common cause of fatigue failure of flange bolts secured with flat washer nuts; or 2) The bolted joint actually had peak cyclic loading that exceeded the tensile strength of the bolt.

Conclusions

1. The bolt failed by very low cycle fatigue with high cyclic stress, indicating that the bolt had not been fully torqued after it was installed or was loosened during operation.

2. The bolt was of excellent quality and met the hardness and microstructure requirements of an SAE 249 Grade 8 bolt.

3. The presence of fissile fracturing indicates the bolt was loaded beyond its tensile strength multiple times.