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Case Study – Tempered Martensite Embrittlement

By

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Introduction

Tempered martensite embrittlement, temper embrittlement, or 500° F embrittlement, occurs in low alloy steels containing impurities of phosphorous, antimony, arsenic, and/or tin. When the steel is slow cooled or heated in the temperature range of 500° F., the resulting hardness typically falls within the hardness range of 46 to 50 Rockwell C scale. Chromium – molybdenum 4XXX series steels are the most vulnerable, and, even without impurities, show a significant reduction in ductility over the hardness range of 46 to 50 RC. Carbon steels do not have this problem.

Subject

Evaluation of two attachment holders to determine the cause of failure. The holders were examined by visual examination, hardness testing, metallographic examination, and fracture mechanics.

Visual Examination

Figure 1 –Sample 1 Fracture

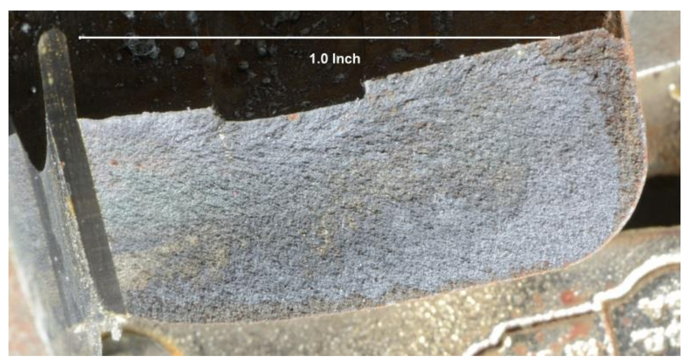

Figure 2 –Sample 2 Fracture

Figure 1 shows the fracture surface of Sample 1. This holder failed parallel to the parting line on the forging. The fracture was perpendicular to the forge flow lines in the holder.

Figure 2 shows the fracture surface of Sample 2. This holder appears to have been cracked twice. The right side of the fracture has more rust than the rest of the fracture surface. This fracture was very fine grained and the surface was very flat, indicating that the failure mode was brittle fracture.

Hardness Test

The hardness testing was done according to ASTM E 384 using a Knoop indenter and a 500 gram load. The results of the testing are given in the following table.

Hardness Test Data (Rockwell C Scale)					
Sample	KNOOP	STD DEV	MAX VALUE	MIN VALUE	HARDNESS
1	360.00	4.56	368.00	357.00	35.98 RC
2	464.00	5.22	469.00	457.00	44.80 RC

These two holders were heated considerably when they were removed with a cutting torch. Sample 1 was heated to about 1000º F. and Sample 2 was heated to about 800º F. by the removal process. The two holders were originally heat treated to the hardness range of 46 to 50 Rockwell C Scale, which encompasses the temper embrittlement range for chromium-molybdenum steels, such as 42CrMo.

Metallographic Examination

The magnification shown for the photos is the magnification at which the photos were taken. The photos shown in this report may be smaller or larger in size than the originals.

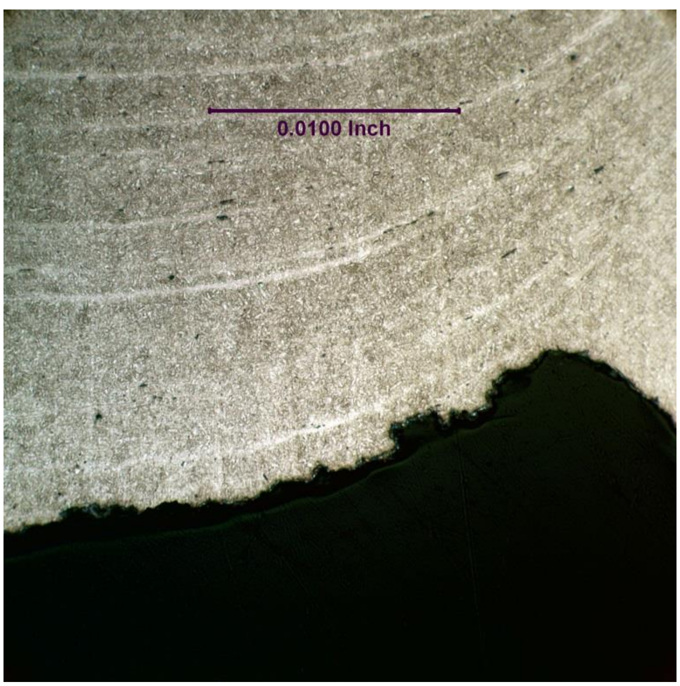

Figure 3 – 100X Sample 1 Forging Flow Lines

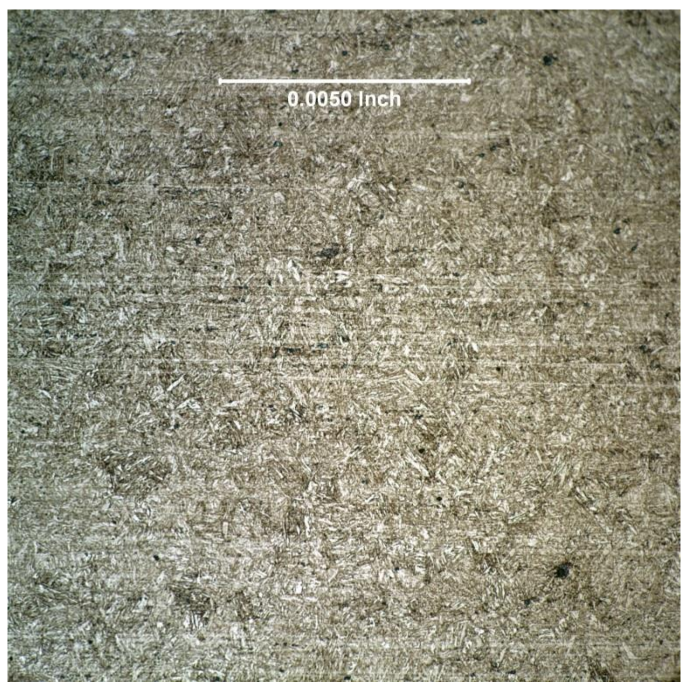

Figure 4 – 400X Sample 1 Microstructure

Figure 3 shows the forging flow lines in Sample 1. The flow lines are parallel to the fracture surface at the bottom of the photo. The strong presence of flow lines indicates that this holder may not have been normalized after forging and prior to heat treating. Steel normalized after forging and prior to heat treating has improved fracture toughness. During the energy crises in the early 1980's, it was attempted to drop the normalizing after forging, with disastrous results in terms of equipment failures and warranty costs which out-stripped the energy cost savings.

The microstructure of Sample 1, Figure 4, was fine grained tempered martensite. The grain size was determined to be 16.9 microns, which is ASTM grain size 9. The grain size indicates that the holder should have had good fracture toughness.

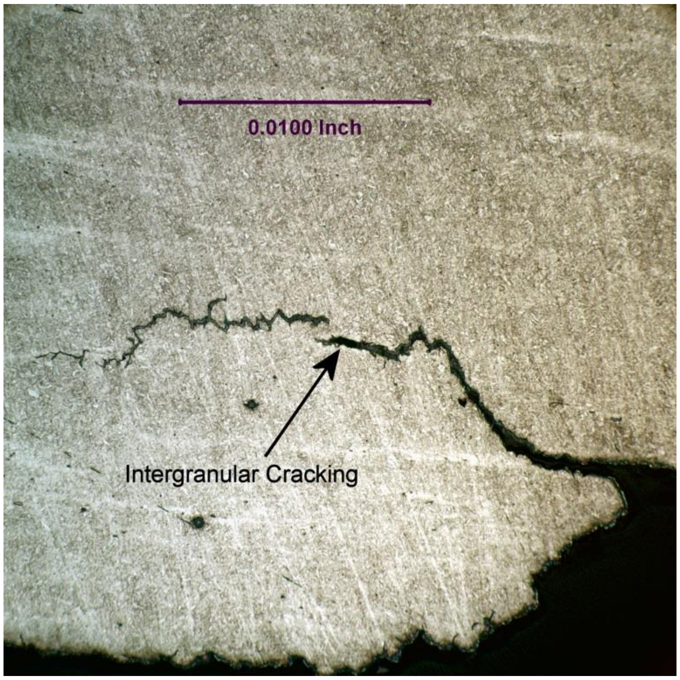

Figure 5 – 200X Sample 1 Intergranular Cracking

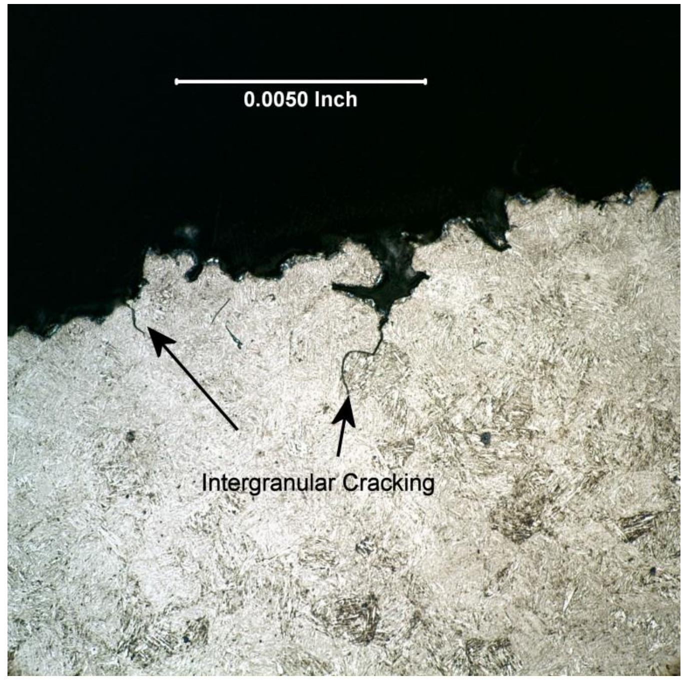

Figure 6 – 400X Sample 1 Intergranular Cracking

Figures 5 and 6 show intergranular cracking associated with the fracture of Sample 1. Intergranular cracking is a characteristic of brittle fracture. Brittle fracture in steels is the result of grain boundary weakening which is characteristic of temper embrittlement.

Figure 7 – 400X Sample 2 Microstructure

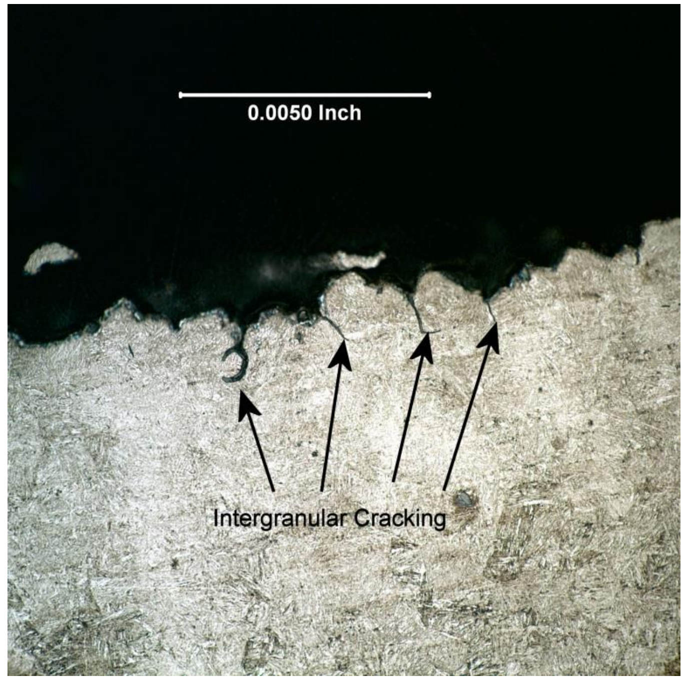

Figure 8 – 400X Sample 2 Intergranular Cracking

Figure 7 shows the microstructure of Sample 2. The grain size was determined to be 28 microns, and the ASTM grain size was 7.5, which is also fine grain steel. There was no evidence found of forging flow lines associated with the fracture.

Figure 8 is a section of the cross section through the fracture surface. The intergranular cracking clearly indicates that this fracture was brittle. The likely cause of the brittle fracture was temper embrittlement.

Fracture Mechanics

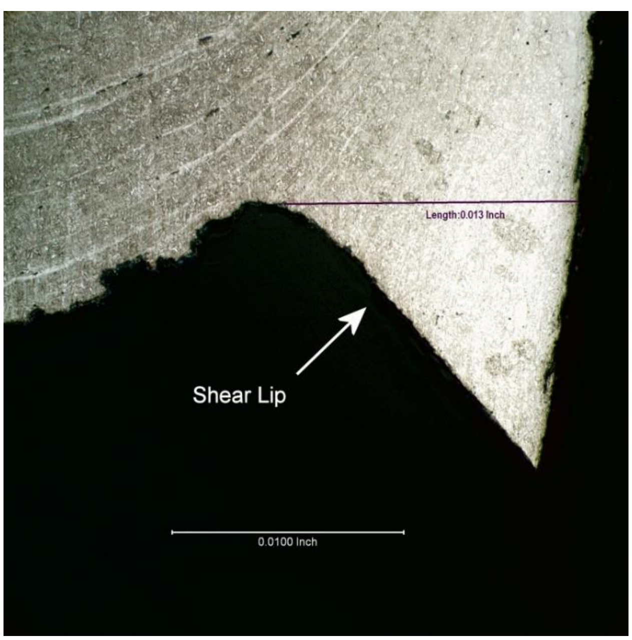

Figure 9 – 200X Sample 1 Shear Lip

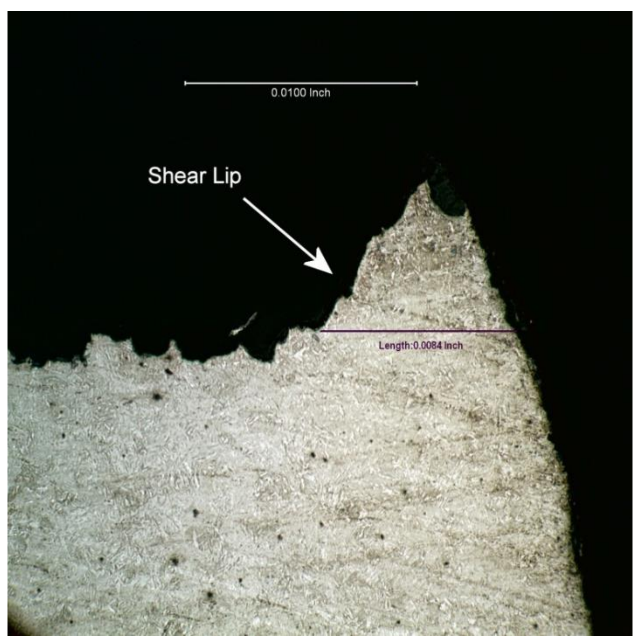

Figure 10 – 200X Sample 2 Shear Lip

There were shear lips present on both Samples 1 and 2. The size of the shear is empirically related to the fracture toughness in terms of Charpy impact strength. The use of fracture mechanics permits estimation of the Charpy impact strength at the time of failure.

Figure 9 shows the Sample 1 shear lip, which is 0.013 inches. Assuming that the holder was within the specified hardness range, the size of the shear lip indicates that the Charpy impact strength was 14.4 ft-lbs, which for 42CrMo steel is brittle fracture.

The shear lip associated with Sample 2 is shown in Figure 10. The size of this shear lip is 0.0084 inches, indicating that the Charpy impact strength at the time of failure was 11 ft-lbs. This is clearly brittle fracture.

Chromium-molybdenum steels should never be tempered between 400 and 700 degrees Fahrenheit. This corresponds to a hardness range of between 45 and 50 Rockwell C scale. The best combination of mechanical properties for 42CrMo steel is obtained by tempering in the range of 850 to 900 degrees Fahrenheit.

Conclusions

1. The two attachment holders failed by brittle fracture because they were tempered in the temper embrittlement hardness range for 42CrMo steels of 46 to 50 Rockwell C scale.

2. The two holders that were examined appear to be the correct grade of steel, were forged correctly, and were austenitized in the correct temperature range.

3. Sample 1 may not have been normalized after forging.

Recommendations

1. Change the hardness specification on the attachment holder engineering drawing to 38 to 44 Rockwell C Scale.

2. Add the requirement that the forgings be normalized prior to austenitizing, quenching, and tempering.