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Case Study: Intergranular Failure

By

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Subject

Failure analysis of a three-inch diameter drive shaft to determine the cause of failure, and to recommend reworking to prevent additional failures. The shaft was examined using chemical analysis, hardness testing, and metallographic examination.

Chemical Analysis

The chemical analysis was done according to the following ASTM Specifications: E1019 for carbon and sulfur, and E415 for the other elements. The results of the analysis are given in Table 1.

Table 1
Chemical Analysis of Shaft
(Percent by Weight)

Element	Shaft	4340 Spec.
Carbon	0.41	0.38 - 0.43
Manganese	0.71	0.60 - 0.80
Phosphorous	0.011	0.035 Max.
Sulfur	0.007	0.040 Max.
Silicon	0.21	0.15 - 0.30
Nickel	1.65	1.65 - 2.00
Chromium	0.79	0.70 - 0.90
Molybdenum	0.23	0.20 - 0.30
Copper	0.17	
Aluminum	0.02	
Vanadium	0.01	
Niobium	<0.005	
Titanium	<0.005	
Boron	<0.0005	

Trace element analysis was done to determine if tin, antimony, or arsenic were present. These three elements can cause tempered martensite embrittlement. The aluminum and vanadium are grain refiners and will cause a finer grain size than normal for quenched and tempered 4340. Niobium, titanium, and boron were too low in concentration to have any effect.

Hardness Tests

The hardness testing was done according to ASTM E384, using a Vickers indenter and a 500 gram load. The results of the testing are given in Table 2.

Table 2
Hardness of 3 Inch Drive Shaft

Sample	Vickers	STD DEV	MAX VALUE	MIN VALUE	HARDNESS RC	BHN
1	553.00	7.79	559.00	540.00	52.52	520
1 - Surface	596.00	15.86	621.00	582.00	55.00	560
2	566.00	8.31	578.00	559.00	53.30	530
2 - surface	618.00	13.37	631.00	602.00	56.22	590
3	566.00	8.98	580.00	555.00	53.30	530

The hardness specification of the 3 inch drive shaft was 238 to 340 Brinell. The shaft was snap-tempered at 400^o F. after quenching, and, based on hardness, the final tempering was missed. The optimum combination of fracture toughness, strength, and fatigue resistance of 4340 occurs at a hardness of 360 Brinell.

Table 3 gives the expected tempered hardness for a shaft having the composition listed in Table 1. The values are based on a study conducted by Bethlehem Steel in the mid 1970's. I have found it to be very accurate.

Table 3
Expected Hardness at Tempering Temperature

Tempering Temperature in ^{o}F	Vickers	Brinell	Rockwell C
400	595	560	55
600	532	496	51
700	489	457	48.5
800	455	421	45
1100	350	331	35.5

This shaft should have been tempered at 1050^o F. to have had optimum performance.

Metallographic Examination

Sample 1 was taken from the fracture indicated in Figure 4. Figure 5 shows the presence of intergranular fracture on the fracture surface shown in Figure 4, and secondary intergranular fracture perpendicular to the primary fracture surface, indicating very brittle steel.

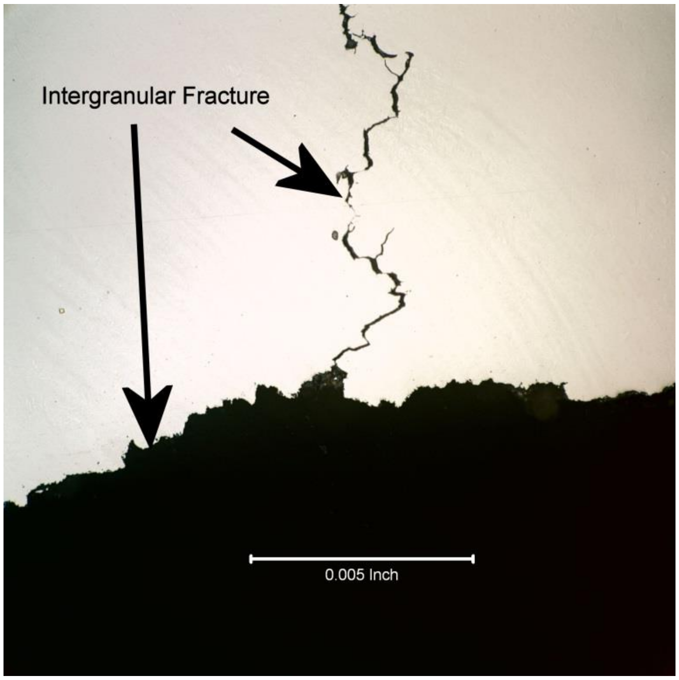

Figure 1 – 400X Intergranular Fracture, Sample 1

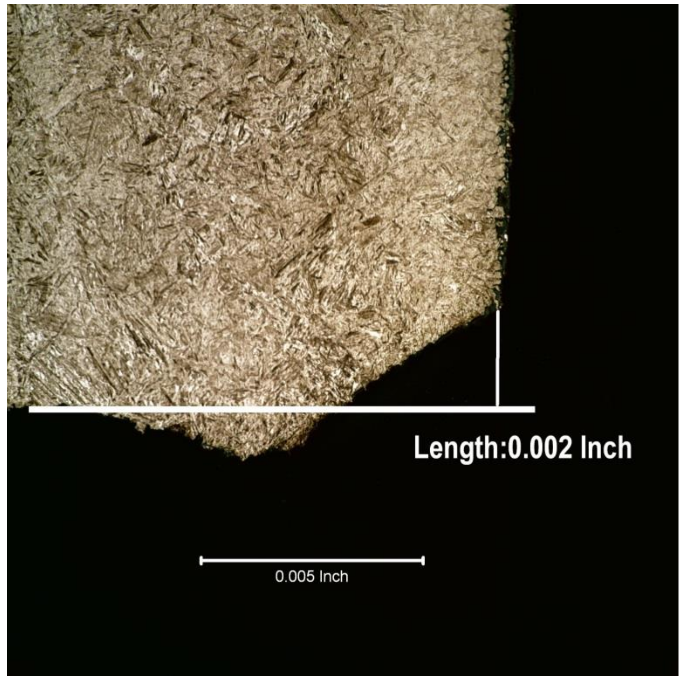

Figure 2 – 400X Shear Lip, Sample 1

Figure 1 shows the tempered martensite microstructure and shear lip associated with Sample 1. The martensitic microstructure was very fine grained, indicating that the shaft was austenitized at the correct temperature. The shear lip, Figure 2, was approximately 0.002 inch. The size of the shear lip was used to estimate the Charpy Impact Strength at this location, which was estimated to be 4 foot-pounds. Charpy Impact Strengths of steel at room temperature of less than 20 foot-pounds is considered brittle.

The Sample 2 fracture area is shown in Figure 3. The presence of intergranular fracture of the tempered martensite indicated very brittle steel. The presence of Bainite and pearlite, Figure 4, indicated that the quench rate was not high enough to produce a 100% martensitic microstructure, but, considering the overall size of the shaft, that was not unusual. The small area of Bainite and pearlite had little to no effect on the strength and toughness of the shaft.

Figure 3 – 400X Intergranular Fracture, Sample 2

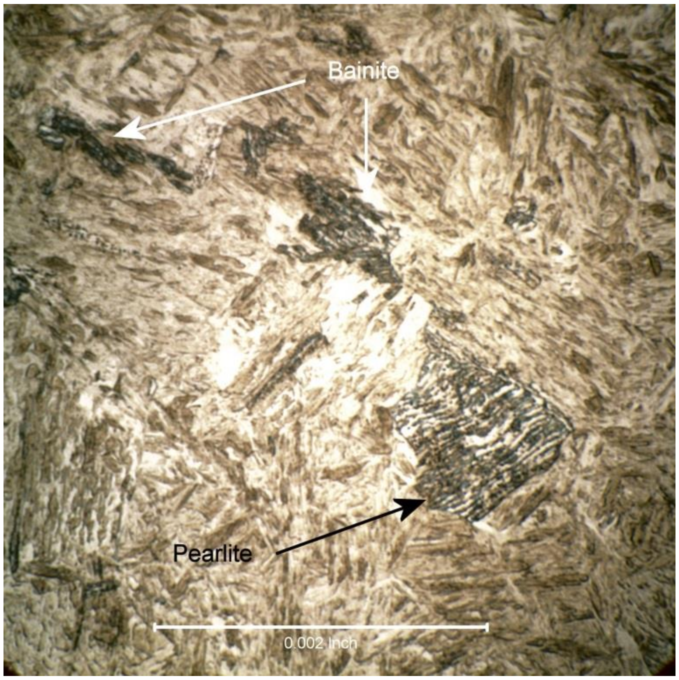

Figure 4 – 1500X Bainite and Pearlite, Sample 2

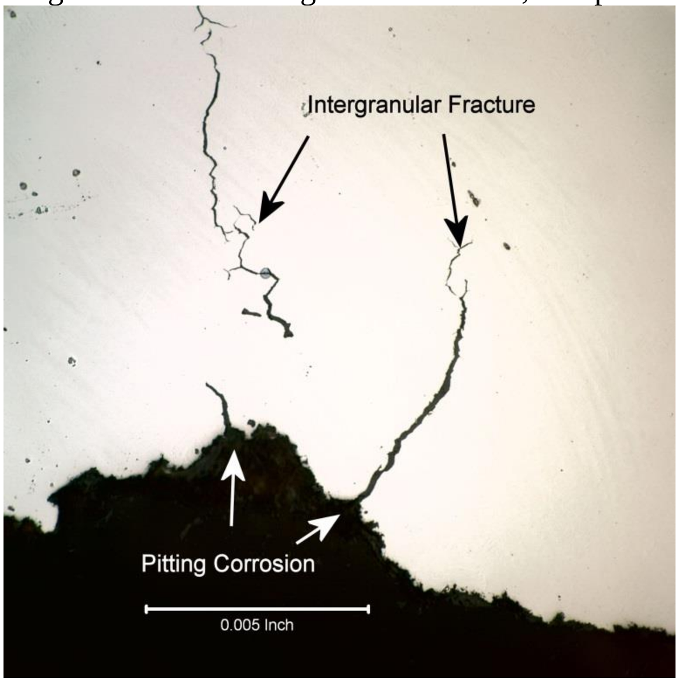

Figure 5 – 400X Pitting Corrosion and Intergranular Fracture, Sample 3

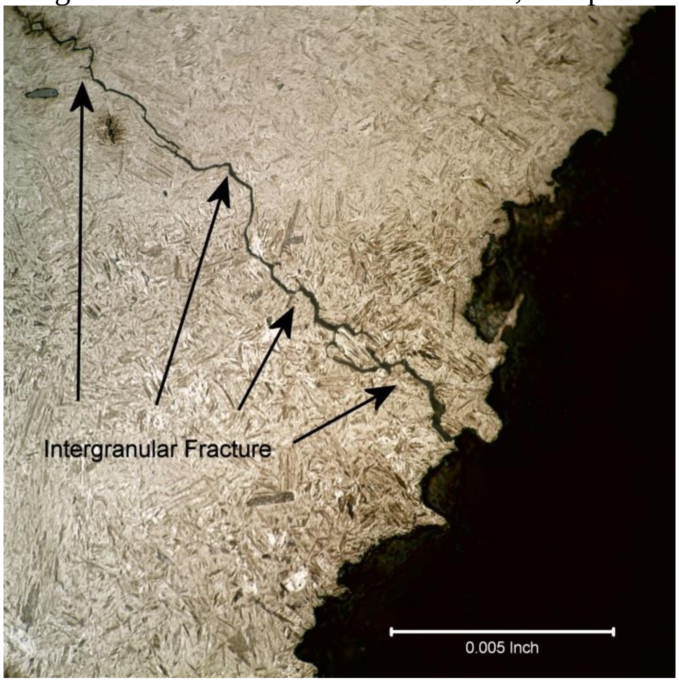

Figure 6 – 400X Intergranular Fracture, Sample 3

Sample 3 was taken near the fracture origin in the shaft. Figure 5 shows pitting corrosion and intergranular fracture. The pitting corrosion occurred after the shaft had been broken. The surface with the pitting corrosion was the original fracture surface. The intergranular fractures, indicated in Figures 5 and 6, were secondary cracks.

Discussion

The shafts that had been heat treated in the same manner as this one were not usable. They had insufficient fracture toughness for the intended application. To be usable, the shafts needed to be re-tempered. Re-tempering would likely have resulted in a change in size and possible distortion. The shafts needed to be tempered at a minimum of 800^{o} F. to avoid the 200,000 psi embrittlement range for chromium, molybdenum, nickel steels. Tempering in air at higher temperatures would have resulted in the formation of iron oxide scale. Tempering at 800^{o} F. would have minimized the dimensional changes and distortion. After tempering, each shaft would have had to be inspected to determine if it was still within specified dimensions, straightness, and roundness. Out of tolerance shafts would have had to have been scrapped.

Conclusion

1) The 3 inch diameter drive shafts were unusable as they were currently heat treated because they had insufficient fracture toughness for their intended application.

2) Cause of failure was not heat treating the shaft to the required hardness specification.

Recommendation

Based on my examination of the shaft, I recommended: 1) Re-tempering the 3 inch diameter drive shafts at 800^{o} F. and re-inspecting shafts for dimensions, straightness, and roundness; and, 2) Scrapping shafts that were not within tolerance.