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Case Study: Brittle Drive Shaft Failure

By

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Subject

Failure analysis of 3 inch Drive Shaft to determine the cause of failure, and if the shafts could be reworked to prevent additional failures. The shaft was examined by visual examination, chemical analysis, hardness testing, and metallographic examination.

Visual Examination

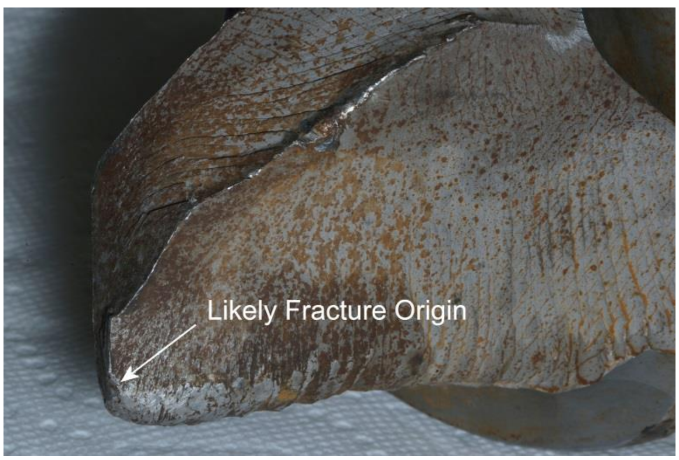

Figure 1 – Likely Fracture Origin

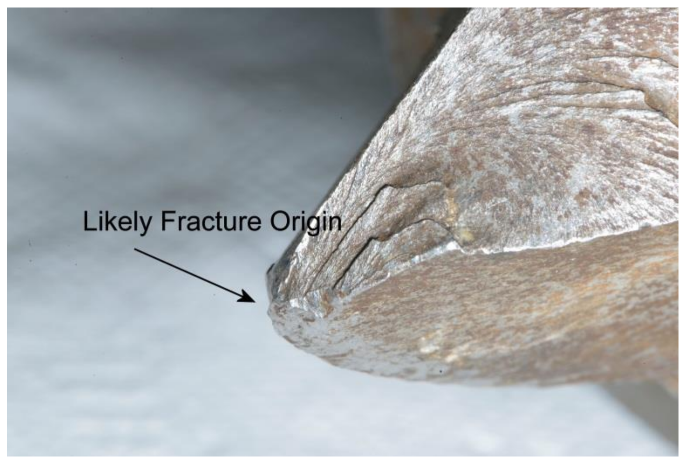

Figure 2 – Likely Fracture Origin

Figures 1 and 2 show the likely fracture origin. The shaft had been damaged by repeated impacts at this location, but the fracture pattern indicated that the fracture origin was likely at the tip.

Figure 3 shows the fracture surface near the end of the fracture. There were conditions present – the flat fracture pattern, very small shear lip, and a fine crystalline texture - that indicated that the fracture was brittle.

Figure 4 shows the initial saw cut through the shaft made to obtain samples for chemical analysis, hardness testing, and metallographic examination. The gray pattern at the bottom of the hex was brittle fracture. This was caused by hitting the shaft section with a small hammer as part of the examination, and indicated the very brittle condition of the shaft.

Figure 3 – Flat Fracture and Very Small Shear Lip

Figure 4 – Saw Cut and Brittle Fracture

Chemical Analysis

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

Table 1
Chemical Analysis of Drive 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 elements were not found. 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. Fine grain size increases the fracture toughness and fatigue resistance of the 4340 steel. Niobium, titanium, and boron were too low in concentration to have any effect.

Hardness Tests

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 likely tempered at 400^o F. after quenching. 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, which I have found 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.

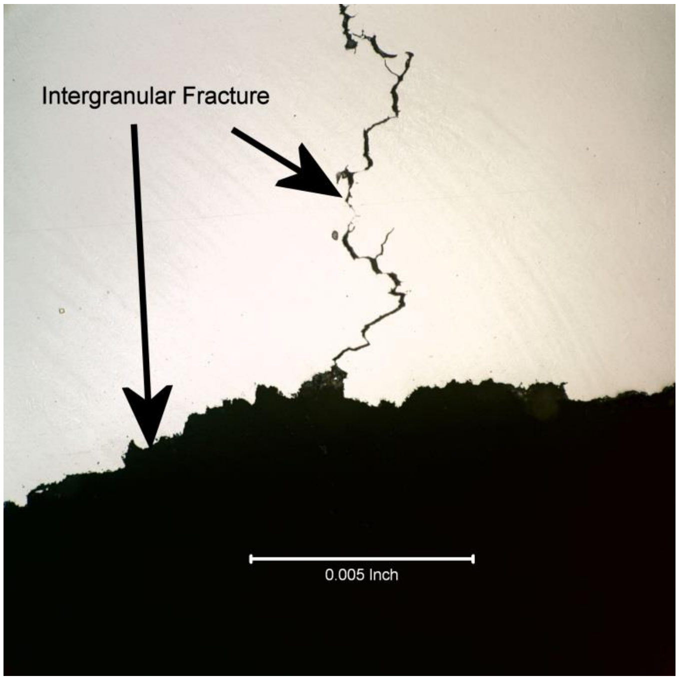

Figure 5 – 400X Intergranular Fracture Sample 1

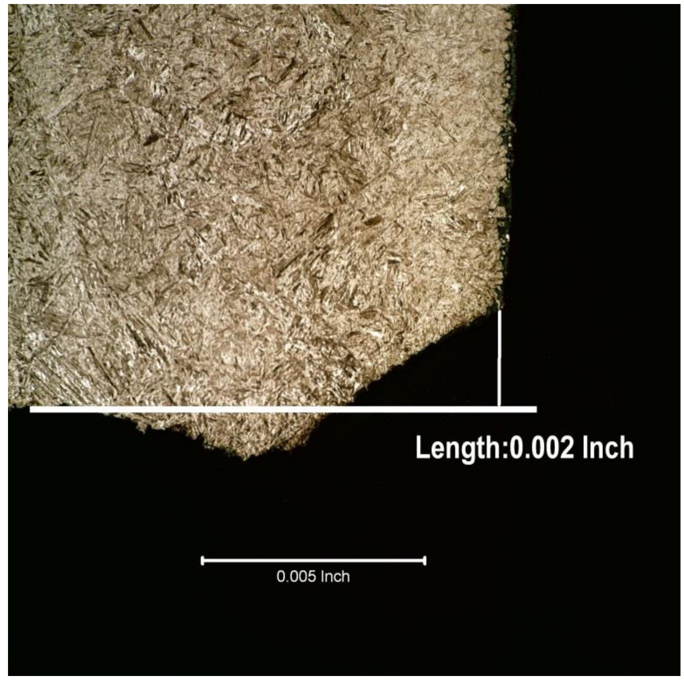

Figure 6 – 400X Shear Lip Sample 1

Figure 6 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 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.

Sample 2 was cut from the flat fracture area shown in Figure 3. The presence of intergranular fracture, Figure 7, of the tempered martensite indicated very brittle steel. The presence of Bainite and pearlite, Figure 8, indicated that the quench rate was not high enough to produce a 100% martensitic microstructure, but, considering the overall size of the shaft, this was not unusual. The small area of Bainite and pearlite had little to no effect on the strength of the shaft.

Figure 7 – 400X Intergranular Fracture Sample 2

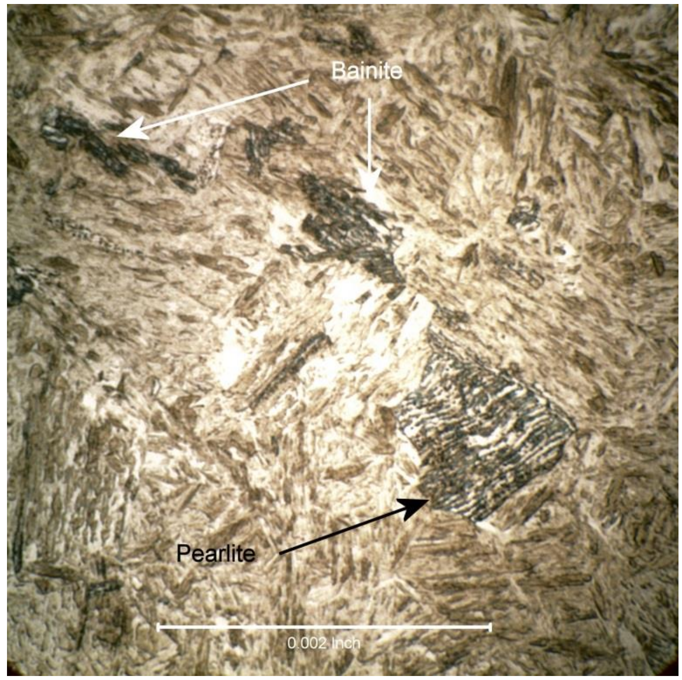

Figure 8 – 1500X Bainite and Pearlite Sample 2

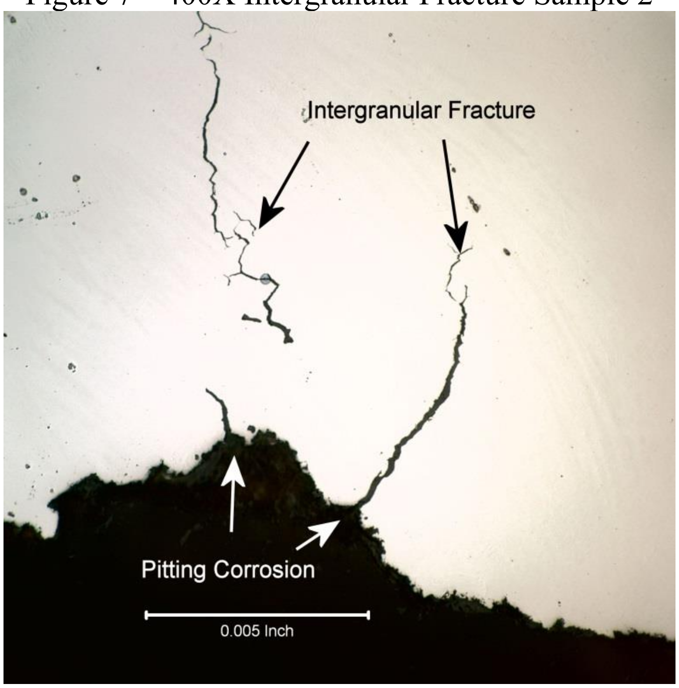

Figure 9 – 400X Pitting Corrosion and Intergranular Fracture Sample 3

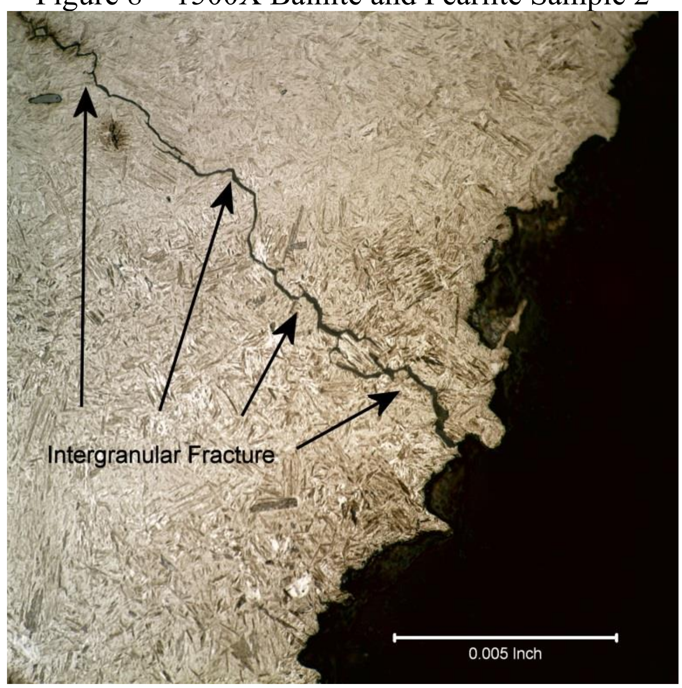

Figure 10 – 400X Intergranular Fracture Sample 3

Sample 3 was taken near the fracture origin shown in Figures 1 and 2. Figure 9 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 9 and 10 were secondary cracks.

Discussion

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

Conclusions

1) The 3 Inch Drive Shafts were unusable as heat treated because they had insufficient fracture toughness for their intended application.

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

Recommendations

1) Re-tempering 3 Inch Drive Shafts at 800º F. and re-inspecting shafts for dimensions, straightness, and roundness. Scrapping shafts that were not within tolerance.

2) Changing the hardness of the drive shaft to 360 Brinell.

NOTE: SAE/AISI 4340 low alloy steel was heat treated wrong. I have run across this situation a number of times where 4340 alloy steel shafts or parts end up being heat treated to its maximum hardness and very quickly fail in service. As far as I know the remaining drive shafts in this lot were salvaged and those shafts that were heat treated to 360 Brinell had a normal or longer life expectancy.