OVERVIEW & OUTCOME

After years of service, and only days after recent maintenance, a shaft connecting to a gearbox had failed. The replacement shaft failed days later. Due to significant downtime and the associated losses, an investigation was conducted to understand the cause of the failures.

The shaft failures were due to misalignment introduced during recent maintenance. In particular, misalignment between the meshing gears on the failed end of the shaft. Prevention of future failures would require ensuring proper alignment within the gearbox and this connecting shaft.
FAILURE ANALYSIS OF GEARBOX SHAFTS

SUMMARY
Both shafts had failed due to misalignment between the shaft/gear and meshing gear. Gear misalignment had caused bending loading during each revolution, resulting in fatigue cracking and failure.

1.0 INTRODUCTION
A Tube Mill submitted two failed shafts for examination. Both shafts were from a cut off carriage gear box. Shaft #1, which had been used for many years of service, failed three days after maintenance on the gearbox. Shaft #2, the replacement shaft, had failed after three days of service. The shafts comprised of ASTM A193 B7 (4140) hardened steel.

Steel Image was requested to determine the details of failure.

2.0 EXAMINATION

2.1 Visual / Macroscopic Examination

Figure 1 displays a photograph provided by the Mill of an intact shaft while Figure 2 displays the failed shafts. Both shafts had failed at the same shoulder radius location. This failure site corresponded to the first rigid point/diameter increase from the keyed shaft end.

Figure 3 displays the fracture surfaces of the two shafts. The fracture surface of Shaft #2 was more preserved than Shaft #1 which exhibited some post-fracture damage. However, examination would show that both shafts displayed similar fracture surfaces. On both shafts, the cracks had first started by multi-origin fatigue crack initiation at one side of the shoulder radius. As the cracks progressed through the shafts, numerous more initiation sites formed around the perimeters of the shoulder radii.

After initiation, the cracks progressed through the shafts by fatigue crack growth. The crack paths are illustrated in Figures 4 and 5. Due to the shoulder radius acting as a stress concentrator, the fatigue cracks propagated around the periphery of the shafts faster than within the center. This created concave crack arrest marks, inverted from the typical, classically perceived convex crack arrest marks.

The crack progressed until the last few cycles overcame the final ligament. This final failure zone was located just inwards of the shaft edge. Both shafts exhibited a similar size of this final failure zone which was estimated to be approximately 5% of the shaft cross-section.
The cracks having initiated on one side of the shaft and having progressed across to the other indicated the shafts had experienced repetitive, asymmetric bending loading. This indicated misalignment between shafts/mating gears and the meshing gears. Misalignment had caused bending loading during each revolution.

2.2 SEM Fractography

The fracture surfaces of both shafts were cut from the bulk shaft and prepared for examination under a scanning electron microscope (SEM). Examination of Shaft #1 at the initiation region found the edge of the fracture to exhibit post-fracture damage. Although macro-fracture features were present, the first intact micro-fracture features were located 1mm from the shaft edge. These features comprised of fatigue features. At this stage, no fatigue striations were resolvable (Figure 6b,c).

As the fatigue crack progressed through the shaft, the crack growth accelerated. Secondary cracking had formed just beneath the initiation region (Figure 6d,e). By mid-shaft thickness, individual fatigue striations were apparent (Figure 6f,g). Final failure occurred in a ductile fashion indicated by the microvoid fracture features (Figure 6h,i).

Shaft #2 exhibited nearly identical micro-fracture features. The initiation region also exhibited damage and the first region exhibiting resolvable micro-features comprised of secondary cracks typical of fatigue crack growth. At mid-shaft, fatigue striations from each cycle had formed. Final failure occurred by ductile overload. Figure 7 displays the micro-fracture features at various locations of the fracture surface on Shaft #2.

2.3 Chemical Analysis

Chemical analysis of the shaft was conducted in accordance with ASTM E1019, E1097(mod) and E1479. Table 1 lists the obtained results which conformed to the compositional requirements for ASTM A193 B7 steel.

<table>
<thead>
<tr>
<th>Composition (wt%)</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Mo</th>
<th>Cr</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM A193 B7</td>
<td>0.37-0.49</td>
<td>0.65-1.10</td>
<td>0.15-0.35</td>
<td>0.040 max</td>
<td>0.035 max</td>
<td>0.15-0.25</td>
<td>0.75-1.20</td>
<td>-</td>
</tr>
<tr>
<td>Failed Shaft</td>
<td>0.43</td>
<td>0.89</td>
<td>0.24</td>
<td>0.030</td>
<td>0.01</td>
<td>0.21</td>
<td>1.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>
2.4 Optical Microscopy

A cross-section through the crack initiation region of Shaft #1 was taken and prepared for metallographic evaluation in accordance with ASTM E3. Optical examination found the core shaft structure to be typical of a hardened ASTM A193 B7 steel. The microstructure comprised of tempered martensite (Figure 8).

Examination of the crack initiation region found the crack to have initiated and propagated in a transgranular fashion typical of fatigue cracking. The mechanical damage having occurred after fracture, observed during fractography, appeared as a work hardened layer (white). Figure 9 displays the initiation region. No material flaws or any evidence of pre-crack damage was observed.

2.5 Hardness Testing

ASTM E18 Rockwell hardness testing was conducted on material from adjacent the failure and at a remote location. Testing adjacent the failure was completed at the same shaft radius as the corner of crack initiation. Table 2 lists the obtained results which satisfied the ASTM A193 B7 hardness requirements.

Table 2: Hardness Test Results

<table>
<thead>
<tr>
<th>Location</th>
<th>Measurements (HRC)</th>
<th>Avg. Hardness (HRC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM A193 B7</td>
<td></td>
<td>35 max</td>
</tr>
<tr>
<td>Remote</td>
<td>30.5, 29.5, 30</td>
<td>30</td>
</tr>
<tr>
<td>Adj. Failure</td>
<td>31.0, 31.5, 30.5</td>
<td>31</td>
</tr>
</tbody>
</table>

3.0 CONCLUSIONS

The shaft failures were the result of misalignment between the shafts/coupled gears and the meshing gears. As a result of the misalignment, the shafts experienced bending loading during each revolution, causing high cycle fatigue failure. The shaft/gear misalignment had most likely been introduced during recent maintenance of the gearbox.

The shaft material exhibited typical composition, hardness and microstructure for ASTM A193 B7 (4140) steel. No material or manufacturing concerns were observed. Failure was not attributed to a quality issue with the shafts.
Figure 1: Photograph provided of an intact shaft. The location of the failures is indicated.

Figure 2: Photograph displaying the submitted, failed shafts. Both shafts had failed at the same shoulder radius location.
Figure 3: Photographs displaying the fracture surfaces of the two shafts. The fractures appeared nearly identical to one another.
Figure 4: Photograph of Shaft #1 with the progression of fracture marked. Multi-origin fatigue crack initiation occurred on one side of the shaft. The crack grew by fatigue through the majority of the shaft. The final region to fail is marked as the “final failure” zone.
Figure 5: Photographs of Shaft #2 with the progression of fracture marked. Multi-origin fatigue crack initiation occurred on one side of the shaft. The crack grew by fatigue through the majority of the shaft until the final ligament failed by overload. The features and progression of fracture matched closely with Shaft #1.
Figure 6: SEM Images of Shaft #1 displaying the (b,c) fracture features at the initiation region and (d,e) features approximately 5mm from the initiation region. Continued on next page. SE1, 20kV.
Figure 6 (Continued): SEM images of Shaft #1 (f,g) at mid-fracture and (h,i) within the final failure region. SE1, 20kV.
Figure 7: SEM images of Shaft #2 displaying (b,c,d) fatigue fracture features through the majority of the shaft. (e) The final fracture region comprised of ductile overload features. SE1, 20kV.
Figure 8: Micrographs displaying the core structure of Shaft #1. The shaft microstructure was typical of a hardened, quenched and tempered steel. Etched using 3% nital.

Figure 9: Micrographs displaying the initiation region of Shaft #1. The fracture had occurred in an intergranular fashion typical of fatigue failure. The work hardened layer (white zone) was from damage occurring after fracture. No material issues were observed. Etched using 3% nital.