FAILURE ANALYSIS OF STEEL MILL CHOCK BOLTS

EXAMPLE REPORT

OVERVIEW & OUTCOME

A steel mill had experienced repetitive bolt failures on their rolling stands, each failure resulting in unplanned downtime. Although careful installation had been ensured, failures continued to occur. The mill decided to further investigate the root cause of failure.

Analysis found that the bolts had failed due to abnormally high loading. Therefore, the bolt failures were not the problem yet symptoms of another condition which had resulted in abnormal loading on these parts. It was recommended the mill further investigate the cause of the abnormally high loading.

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FAILURE ANALYSIS OF STEEL MILL CHOCK BOLTS

SUMMARY

The chock bolts had failed by low cycle fatigue due to having experienced abnormal, excessive cyclic loading well above what the bolts could sustain. As the chock design was not intended for the bolts to experience significant loading, bolt failure was a symptom of an issue elsewhere. It is recommended that Mill further investigate the cause of the increased loading applied onto the locking key segments and bolts of these chocks.

1.0 INTRODUCTION

A Steel Mill submitted three chock bolts that had failed during service, each resulting in forced downtime. Each of the 1” diameter socket screw cap bolts had been used to fasten locking key segments onto different chocks apart of rolling stands, intended to prevent the lock rings from rotating loose. Figure 1 displays photographs provided by the Mill of a locking key segment and its bolt failure. For reference, a new, un-used bolt was also submitted.

The bolts had a minimum tensile strength requirement of 170ksi. Each chock has a locking key segment which is held by a single bolt. Discussion with the Mill had included that the locking key segment and its associated bolt should not sustain significant loading during service.

Steel Image was requested to determine the nature and details of bolt failure.

2.0 EXAMINATION

2.1 Examination and Fractography of the Failed Bolts

Figure 2 displays the four submitted bolts. Each of the three failed bolts had been pre-marked by #1, #2 and #3 according to their chock. Within this report, the bolts were referenced as Bolts #1, #2 and #3 accordingly.

All three failed bolts had sustained failure approximately one inch from the bolt end. Bolt #1 had also sustained a second failure at the end of its threads, immediately adjacent its shank. Of the two fractures on Bolt #1, it was assumed that the fracture near the bolt end had occurred first (referred to as Fracture A).

The fracture surface of Bolt #1, Fracture A exhibited low cycle fatigue features (Figures 3a and 5). Four different stages were observed, each with a slightly different orientation of crack growth and loading. The first stage exhibited multi-origin fatigue initiation along one side of the bolt. The next two stages exhibited multi-origin fatigue re-initiation. The final stage corresponded to final failure (ductile overload). The variation in loading directionality between stages suggested that the bolt had rotated, changing the
loading on it. Although it was possible that the bolt had not been tightly installed, from other observations it seemed more likely that the bolt had been overloaded during service and subsequent deformation had removed its preload, allowing the bolt to rotate.

Bolts #2 and #3 had failed by low cycle fatigue due to gross overloading (Figures 4, 6 and 7). Bolt #2 exhibited multi-origin fatigue initiation on one side of the bolt. Once the crack had grown through approximately half the bolt cross-section, the remaining ligament had failed by ductile overload.

Two fatigue cracks had formed on either side of Bolt #3. Once these cracks had accounted for approximately 30% of the cross-sectional area, the final 70% had failed by ductile overload. The relatively large sizes of the final failure zones on Bolts #2 and #3 indicated the bolts had sustained gross overloading.

The threads on all three failed bolts exhibited damage along the lengths corresponding to the lock ring. A portion of a thread on Bolt #1 had formed fatigue cracks due to side/angled loading assumed to have been applied from the lock ring (Figure 8). As the lock ring (or anything) should not be applying asymmetric side loading on this portion of the bolt, it supported that something abnormal with the chock assembly had resulted in irregular loading conditions.

2.2 Bolt Material Testing

Chemical analysis of Bolt #3 was conducted in accordance with ASTM E1019, E1097 and E1479. Table 1 lists the obtained results. The bolt conformed to the compositional requirements of 4140 low alloy steel which is a commonly used grade for such bolt applications.

<table>
<thead>
<tr>
<th>Sample</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Mo</th>
<th>Cr</th>
<th>Ni</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt #3</td>
<td>0.39</td>
<td>0.80</td>
<td>0.18</td>
<td>0.011</td>
<td>0.010</td>
<td>0.15</td>
<td>1.10</td>
<td>0.02</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*Chemical analysis was performed in accordance with ASTM E1019, E1097 and E1479.

Tensile testing of material taken from Bolt #3 was conducted in accordance with ASTM A370. Table 2 lists the obtained results. The bolt conformed to the drawing tensile requirements.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield Strength (ksi)</th>
<th>UTS (ksi)</th>
<th>Elongation (%)</th>
<th>Reduction of Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Req.</td>
<td></td>
<td>170 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bolt #3</td>
<td>179</td>
<td>195</td>
<td>12</td>
<td>48</td>
</tr>
</tbody>
</table>

*Tensile testing was performed in accordance with ASTM A370.
Rockwell hardness testing was conducted upon Bolt #1 in accordance with ASTM E18. Table 3 lists the obtained results. The core hardness was within the range expected for high strength bolts.

Table 3: Rockwell Hardness Test Results*

<table>
<thead>
<tr>
<th>Sample</th>
<th>Measurements (HRC)</th>
<th>Avg. Hardness (HRC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolt #1</td>
<td>40.0, 41.0, 41.0</td>
<td>41.0</td>
</tr>
</tbody>
</table>

*Rockwell hardness testing conducted in accordance with ASTM E18.

A longitudinal cross-section was taken through the end of Bolt #1 and prepared for metallographic evaluation in accordance with ASTM E3. Optical examination found the core structure to comprise of tempered martensite expected for high strength bolts (Figure 9). No significant quality issues were observed with the core bolt material.

In summary, all testing completed found the bolts to be of sound metallurgical quality.

3.0 DISCUSSION

Bolts #1, #2 and #3 had failed by low cycle fatigue due to having experienced excessive, cyclic loading. The level of loading on Bolts #2 and #3 (and likely #1) was well above what the bolt material could sustain. Therefore, bolt failure was attributed to an abnormal condition which applied excessive loading onto the bolts.

Regarding whether the bolts had been correctly installed or not, the level of loading on Bolts #2 and #3 was high enough that they would have failed even if they had been properly preloaded during installation.

Chemical testing, tensile testing, hardness testing and optical microscopy were conducted to assess the bolt material condition. Assuming the bolts were representative of one another, the bolts were found to be of sound quality. Bolt #3, which exhibited the highest level of relative loading, conformed to the drawing tensile requirements. Ultimately, failure was not attributed to a quality issue with the bolts.

Bolt failure had occurred by low cycle fatigue. The majority of the cross-sectional areas of Bolts #2 and #3 had failed by ductile overload indicating excessively high loading. Although the details of the bolt design were not available, the level of loading was assumed to be well above what the bolts were rated for. Also note that the bolts had sustained damage along the their sides due to irregular loading applied along regions corresponding to the lock ring. As such, the bolt failures were deemed to be a symptom of problems elsewhere with the chock assemblies.

Discussion with the Mill had included that neither the locking key segments nor these bolts should experience significant loading during service. Therefore, bolt failure from excessive loading indicated an issue with the chock assemblies, resulting in abnormal
loading be applied onto the bolts and locking key segments. It is recommended that the Mill further investigate what conditions could apply increased loading onto the locking key segment and bolt.

4.0 CONCLUSIONS

The reoccurring bolt failures were symptoms of problems elsewhere with the chock assemblies. Bolts #1, #2 and #3 had failed by low cycle fatigue due to having experienced abnormal, excessive cyclic loading. The majority of Bolts #2 and #3 cross-sections had failed by ductile overload. This indicated that the level of loading was well above what the bolt material was rated for. Therefore, bolt failure was attributed to abnormal loading conditions which applied excessive loading onto the bolts.

It is recommended that the Mill further investigate the cause of the increased loading sustained by the locking key segments and bolts.

The bolts were found to be of sound quality. Failure was not due to a bolt deficiency. Failure was not consistent with a bolt installation issue.
Figure 1: Photographs provided by the Steel Mill displaying the chock, locking segment and an example of a fractured bolt.
Figure 2: Photographs displaying the three fractured bolts and the reference bolt. Each of the three failed bolts had been installed on different chocks.
Figure 3: Macrographs of Chock Bolt #1 displaying (a) Fracture A and (b) Fracture B. The features of Fracture A matched that of the other two bolt failures and it was assumed to have formed first. Fracture A displayed numerous stages of crack growth and crack re-initiation. The variation in crack directions and features between stages suggested that the bolt had rotated loose, changing the orientation of sustained loading.
Figure 4: Macrographs displaying the fracture surfaces of Chock Bolts #2 and #3. (a) Bolt #2 exhibited low cycle fatigue crack features. Final failure accounted for half the bolt cross-section. (b) Bolt #3 exhibited two fatigue cracks having started on either side of the bolt. Final failure accounted for approximately 70% of the bolt cross-section. The relatively large sizes of the final failure zones on both bolts indicated they had been grossly overloaded.
Figure 5: SEM images displaying Chock #1 fracture surface A. This crack was assumed to have started first. Failure had initiated by fatigue. The relatively large striation spacing close to the initiation region indicated that the loading on the bolt had been extremely high. SE1, 15kV.
Figure 6: SEM images displaying Chock Bolt #1 fracture surface B. On this fracture, crack initiation and growth through ~70% of the cross-section had occurred by fatigue. The final region had failed over several cycles which were well above the yield strength of the steel, forming microvoid coalescence features. SE1, 15kV.
Figure 7: SEM images displaying the fracture surface of Chock #2. The bolt had sustained high cyclic loading which caused fatigue cracking to initiate and grow through half the bolt cross-section. The remaining half failed by ductile overload. The size of the final failure zone indicated this bolt had been grossly overloaded. SE1, 15kV.
Figure 8: Macrographs displaying Chock Bolt #1 to have sustained side loading from the lock ring. This had caused fatigue cracking on the side of one tooth. Additional fatigue cracks within the thread roots were observed within the vicinity of the primary fracture, also formed by the excessive tensile loading.
Figure 9: Micrographs displaying the core structure of Bolt #1. As expected for such high strength bolts, the core material comprised of tempered martensite. No significant metallurgical deficiencies were observed. Etched using 3% nital.