FAILURE ANALYSIS OF AN ELECTRIC ARC FURNACE LADLE U-LUG

EXAMPLE REPORT

OVERVIEW & OUTCOME

A U-lug on a ladle failed during a maintenance lift. Its failure was deemed both an operational concern and a safety hazard. To ensure repeat failures don’t occur, failure analysis was used to diagnose the cause of failure.

The analysis found that the U-lug had failed due to very high loading applied from the crane hook. This was due to the combination of (a) abnormally large hooks being used and (b) the hooks having been inserted through the U-lug in the opposite orientation as usual. This resulted in the hook having become wedged between the ladle and U-lug, applying abnormally high loading on the U-lugs and causing failure.

Therefore, it was recommended that the Operator review (a) their tilting procedures and (b) assess the ideal hook size for these ladles/U-lugs.
FAILURE ANALYSIS OF AN ELECTRIC ARC FURNACE
LADLE U-LUG

SUMMARY

Failure of a U-lug on an electric arc furnace ladle was due to elevated loading from (a) the inserted crane hook having been positioned in the reverse, inside-out orientation and (b) an oversized hook having been used. The oversized hook had become wedged between the lug and the ladle body, applying elevated, pulsed loading onto the U-lug. This resulted in brittle failure. It is recommended that the Operator review the procedure for tilting of the ladles, in particular assessing the ideal orientation of hooking through the lugs and the ideal hook size to be used.

Although minor issues with the U-lug material had been observed, the failure was attributed predominantly to the elevated loading conditions experienced.

1.0 INTRODUCTION

A steelmaker experienced failure of a corner U-lug on a ladle used for their electric arc furnace. Failure occurred during tilting of the ladle at a maintenance station. Upon failure, the U-lug had been thrown, hitting the building wall. Its failure was recognized as a safety concern as well as an operational issue.

The failed lug was one of four additional corner U-lugs installed on the ladle in the early 1990s. The drawing specified the U-lugs were to be made of ASTM A36 and they were reported to have been welded onto the ladle using weld filler E10018. Note that the original U-lugs of the ladles from the 1970s comprised of AISI 1020 and had been welded using weld filler E7018.

Typically during tilting, the crane hooks are inserted into the lugs from the outside-in. During the specific tilting operation which caused failure, the hooks had been inserted in the reverse orientation, inside-out. Also note that (a) the size of the hooks used were larger than usual for this station and (b) the U-lugs on the failed side are never used in furnace operation and seldom used during ladle maintenance.
2.0 EXAMINATION

2.1 On-Site Examination

S. Turcott visited on-site to pick-up the available sample and examine the fractures remaining on the ladle. Figure 1 displays the U-lug remnants on the ladle and Figure 2 displays the fracture surfaces. Fracture had occurred adjacent the welds. Combined with in-lab analysis, it was shown that the top segment had failed first. Crack initiation occurred adjacent the weld which also exhibited some solidified ladle spillage (Figure 2a). From the location of initiation and direction of crack propagation, the top segment had experienced an element of side loading.

On the ladle, adjacent the top segment fracture, was a heavy contact pattern from the crane hook (Figure 3). By the size and severity of the contact pattern, and that later found on the U-lug body, the crane hook had become wedged between the lug and ladle, applying extremely high loading.

After the top segment had fractured, the bottom segment experienced vertical, downwards bending loading (Figure 2b). Failure occurred during two, rapid loading pulses.

For the ease of reference, the fractured segments are referred to as Fractures #1 and #2, listed in the order of failure.

While on-site, representatives of the Operator provided a demonstration of the ladle tilting operation with the hooks connected (a) in the typical orientation, outside-in and (b) the reverse orientation which failure had occurred from. In the typical orientation, the tilting operation went smoothly with no resistance/restraint of the hook movement. In the reverse orientation, the hooks became wedge between the U-lugs and the ladle. Creaking noises occurred when the hooks suddenly shifted positions. Figure 4 displays the hooks inserted in the reverse, inside-out orientation which failure had occurred. This demonstration left a notable contact pattern on the side of the ladle adjacent one U-lug.

2.2 In-Lab Examination

Figure 5 displays the (a) U-lug body and (b) portions of the fracture surfaces cut from the ladle. As cutting was restricted to low-temperature methods, the Operator reported difficulties in removing the intended geometry of the ladle side fractures. As a result, neither of these two ladle-side pieces contained the crack initiation regions.

The U-lug body exhibited a significant contact pattern from the crane hook adjacent Fracture #1. Figure 6 illustrates the contact pattern which corresponded to the loading responsible for failure of Fracture #1.

Figure 7 displays the fracture surfaces of the U-lug body. Both fractures were fresh, shiny and neither exhibited deformation within the failure vicinity. SEM examination confirmed both fractures had occurred in a brittle fashion. As illustrated in Figure 8,
Cleavage fracture features were observed at all locations, including crack initiation. At the initiation site of Fracture #1, a small minority of the fracture exhibited microvoid coalescence yet overall, fracture had occurred in a brittle fashion (Figure 8b,c).

Fracture #2 had initiated at two neighbouring locations adjacent the weld, one occurring at a weld flaw. The weld flaw had been benign until the fracture. As (a) Fracture #2 occurred second and (b) crack initiation had also occurred at a location without a flaw, the weld flaw was not deemed as a significant contributor to failure. Figure 9 displays the micro-fracture features of Fracture #2.

SEM examination of Fracture #2 found the entirety of Fracture #2 to exhibit cleavage fracture features, typical of brittle overload.

2.3 Chemical Analysis

The Operator had performed chemical analysis of the core material of the U-lug. Table 1 lists the results provided. The carbon content was marginally above that listed in ASTM A36 yet, allowing for the permitted variance of 0.04wt% provided in ASTM A6, the U-lug composition did conform to ASTM A36 compositional requirements. Table 2 summarizes the compositional requirements of ASTM A36.

Discussion with the Operator had included that, based upon the steel chemistry they did not believe that this steel had been produced at their facility.

Table 1: Chemical Results Provided

<table>
<thead>
<tr>
<th>Composition (wt%)</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>Si</th>
<th>Cr</th>
<th>V</th>
<th>Mo</th>
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<tr>
<td></td>
<td>0.31</td>
<td>0.85</td>
<td>0.006</td>
<td>0.18</td>
<td>0.27</td>
<td>0.06</td>
<td>0.059</td>
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<tr>
<td>Ni</td>
<td>Cu</td>
<td>Al</td>
<td>Sn</td>
<td>Ti</td>
<td>Nb</td>
<td>B</td>
<td>Ca</td>
</tr>
<tr>
<td>0.06</td>
<td>0.09</td>
<td>0.004</td>
<td>0.006</td>
<td>0.003</td>
<td>0.002</td>
<td>0.0004</td>
<td>13ppm</td>
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</table>

Table 2: Comparison to ASTM A36

<table>
<thead>
<tr>
<th>Composition (wt%)</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM A36</td>
<td>0.28 max*</td>
<td>0.60-0.80</td>
<td>0.40 max</td>
<td>0.05</td>
<td>0.04</td>
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<tr>
<td>U-Lug</td>
<td>0.31</td>
<td>0.85</td>
<td>0.27</td>
<td>0.018</td>
<td>0.006</td>
</tr>
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</table>

*As listed per ASTM A36. ASTM A36 Section 7.2 allows for product composition variance in accordance with ASTM A6. This grants a maximum carbon content of 0.32wt%.

2.4 Optical Examination

Cross-sections were taken through (a) a remote location of the U-lug, (b) through a weld and (c) through the Fracture #1 initiation region. Samples were prepared for metallographic evaluation in accordance with ASTM E3. Optical examination of the core structure revealed a ferritic and pearlitic structure typical of an as-forged ASTM A36 material. Figure 10 displays the core structure of the U-lug.
Crack initiation had occurred within the heat affected zone of the weld. At the initiation location, the heat affected zone (HAZ) comprised of acicular ferrite. Mild decarburization was present. No detrimental phases, such as tempered martensite, were observed. Figure 11 displays the microstructure at the crack initiation region. The heat affected zone was consistent with the heat affected zone at remote locations (Figure 12).

2.5 Hardness Testing

Rockwell hardness testing was conducted upon the core U-lug material in accordance with ASTM E18. Table 3 lists the obtained hardness values. The hardness was slightly above that expected for ASTM A36 material. Note that ASTM A36 does not include hardness requirements.

Table 3: Rockwell Hardness Results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Measurements (HRB)</th>
<th>Avg. Hardness (HRB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-Lug Core</td>
<td>92.0, 90.5, 93.0, 91.5, 92.5</td>
<td>92</td>
</tr>
</tbody>
</table>

3.0 DISCUSSION

The U-lug had failed due to elevated, pulsed loading applied from the crane hook during the tilting operation. Although minor issues with the U-lug material/manufacture had been observed, the failure was attributed predominantly to the loading conditions.

The loading responsible for failure had occurred from inserting the hook through the lug in the reverse, inside-out orientation. In this configuration, the crane hook had become wedged between the U-lug and the ladle body, applying elevated loading onto the U-lug. As indicated by the noises emitted, the hook would periodically, rapidly adjust positions. This had likely created pulses of sudden, increased loading on the U-Lug. These elevated pulses were the specific loading events responsible for failure.

Crack initiation had occurred adjacent the weld and within the weld heat affected zone. No detrimental or abnormal phases were observed within the HAZ structure at the location of failure. The weld would act as a restraining/rigid point and, under bending loading, be a natural location for crack initiation.

The contact pattern from the hook on the failed U-lug and the adjacent ladle were more severe than on other U-lugs. This indicated that the failed U-lug had experienced additional loading during the latest tilting operation than other lugs used for the same operation. Subtle variations in the location and angle of the U-lug may impact the loading it experiences from the hook. Also, since (a) this lug was seldom used and only used during ladle maintenance, (b) the hook size was larger than that generally used for ladle maintenance and (c) the orientation of the crane hook was opposite of that typically used, the loading conditions applied on this particular lug may have been unique since its installation.
Failure had occurred during a single tilting operation rather than fatigue accumulated from numerous operations. Therefore, no cracks would have been present during the latest annual NDE inspection.

ASTM A36 is typically considered a ductile material and, based upon its microstructure and hardness, would have behaved as such under low strain rate conditions (ie. slow loading). Yet brittle fracture indicated the loading responsible had been from sudden, high strain rate loading. Had the U-lug not experienced these elevated pulses, this U-lug would likely have experienced a typical service life without issue.

The U-lug chemistry conformed to the ASTM A36 requirements including the permitted variation tolerances. The hardness was slightly above the expected value, likely from being at the upper limits of the carbon content. Based upon the composition and hardness values, the U-lug impact properties would be expected be within the bottom portion of the distribution for ASTM A36 material. If deemed necessary for further investigation, tensile testing and charpy impact testing could be completed. However, with the primary cause of failure having been identified as the loading condition from hook wedging, further testing of the U-lug material was not deemed critical.

The Operator may wish to review the procedure used to tilt the ladles. This may include assessing the optimum/safest hook size and/or hook orientation used for the tilting operation.

4.0 CONCLUSIONS

Failure of the U-lug on electric arc furnace ladle was due to elevated loading due to (a) the crane hook having been inserted through the lug in the reverse, inside-out orientation and (b) an oversized hook having been used. In this configuration, the hook had become wedged between the lug and the ladle body, applying elevated/pulsed loading onto the U-lug which caused brittle failure.

Although minor issues with the U-lug material/manufacture had been observed, the failure was attributed predominantly to the elevated loading conditions experienced.

It is recommended that the Operator review its procedure during tilting of the ladles, in particular assessing (a) the ideal orientation of hooking the lugs and (b) the ideal hook size to be used.
Figure 1: Photograph displaying the fractured U-lug remnants on the ladle.
Figure 2: Photographs displaying the fractures. Further analysis would support that the top failure had occurred first, followed by the bottom ligament. For the ease of reference, the fractures are identified as Fractures #1 and #2 as marked.
Figure 3: Photograph displaying notable contact patterns on the ladle. These contact patterns had likely been formed during the lifting operation responsible for failure. The vicinity of the second corner U-lug on this side exhibited a much lighter contact pattern.

Figure 4: Typically, the crane hooks are connected from the outside-in. Yet at the time of failure, the hooks were reversed, having been inserted into the U-lugs from the inside position (as illustrated). The Operator provided a demonstration of tilting the ladle with the hooks in the reverse orientation. During the demonstration, loud banging noises indicated sharp, sudden movements of the hooks within the lugs. These sudden movements had applied rapid load increases onto the lugs, causing failure on one lug.
Figure 5: Photographs displaying the fractured U-lug remnants submitted for analysis. The remnants cut from the ladle did not comprise of the crack initiation regions.
Figure 6: Photograph displaying a heavy, fresh contact pattern along the U-Lug from contacting against the crane hook. As this U-Lug was very seldom used, this contact pattern was generated during the single tilting operation which had resulted in failure. The severity of the contact pattern indicated extremely high loading having been applied from the hook.

Figure 7: Photographs of the fracture surfaces.
Figure 8: SEM images displaying the micro-fracture features present on Fracture #1. (b,c) The initiation region comprised predominantly of cleavage, brittle fracture features with a minority of ductile fracture features. (d,e) The remainder of the fracture surface exhibited cleavage, brittle fracture features.
Figure 9: Macrograph and SEM images displaying the details of failure of the Fracture #2. This fracture had occurred after Fracture #1. Crack initiation occurred at two neighbouring locations, one comprising of a weld flaw. The brittle crack progressed through half the lug thickness during one loading pulse and fractured from a second pulse.
Figure 10: Micrographs displaying the core structure of the U-Lug (remote the welds and failures). The core structure comprised of ferrite and pearlite. The core structure was typical of ASTM A36 after forging.
Figure 11: Micrographs displaying crack initiation on Fracture #1 to have occurred within the weld heat affected zone. Etched using 3% nital.

Figure 12: Micrographs displaying the weld heat affected zone at the U-lug surface at a remote location. Etched using 3% nital.