OVERVIEW & OUTCOME

The screws on two pumps, as part of a large shipment, were found cracked upon opening the sea containers after their voyage across the Pacific. The conducted failure analysis had found that the screws had failed by hydrogen embrittlement as a result of their plating process. Due to the risk of additional failures, the screws were manually replaced on the full lot of pumps.

Further investigation by the pump manufacturer found that the screw supplier had not taken the proper precautions to prevent hydrogen embrittlement during plating. The pump manufacturer switched to another screw provider.

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FAILURE ANALYSIS OF A FRACTURED SCREW

SUMMARY

The screw had failed due to hydrogen embrittlement. The presence of hydrogen within the screw caused cracking several hours/days after installation. Hydrogen was introduced during manufacture, likely through the plating process.

1.0 INTRODUCTION

A fractured screw used to hold together a plastic motor housing was submitted. The plastic housing had been assembled in Canada and shipped to Japan where the screw had been found fractured upon arrival. Steel Image was requested to determine the nature of the failure.

The screw was zinc plated and comprised of an EJOT thread. The governing material specification included the minimum strength, chemistry and hardness range (320-380 HV_{10kg}).

In addition to the fractured screw, new/un-used screws from three additional batches had been submitted for examination. Note that these screws were not tracked and it was unknown as to which batch the fractured screw had been from.

2.0 EXAMINATION

2.1 Visual / Macroscopic Examination

Figure 1 displays the submitted samples and Figure 2 displays the fractured screw within the plastic housing. The fracture had occurred along the transverse orientation, approximately one turn beneath the screw head. Figure 3 displays the fracture after removal from the housing (photograph taken after SEM fractography). No significant deformation had occurred within the vicinity of the fracture to indicate installation overload.

2.2 SEM Fractography

The plastic housing segment containing the fractured screw was cut and the screw/plastic segment was prepared for examination using a scanning electron microscope (SEM). Examination of the fracture surface found the outer perimeter to comprise of different fracture features than the fracture center. The fracture surface at the initiation region, and around the perimeter of the fracture, comprised of intergranular fracture features. Figures 4 and 5b,d display these features. Intergranular fracture features are indicative of several forms of embrittlement yet, combined with the background information, in this particular case indicated that failure had occurred by hydrogen embrittlement.
The fracture center comprised of microvoid coalescence fracture features exhibiting minimal ductility. This indicated that after sufficient crack growth by hydrogen embrittlement, final failure occurred by ‘ductile’ overload.

### 2.3 Optical Examination

Longitudinal cross-sections of screws from Batches #1, #2 and #3 were prepared for metallographic evaluation in accordance with ASTM E3. Optical examination found the core structures of the screws from each batch to comprise of a lightly tempered martensitic structure. This structure was typical of a hardened, quenched and tempered screw. **Figure 6** displays the core structure from the three batches.

Examination found the screw threads and roots to comprise of forming flaws (**Figure 7a,b**). These flaws had not contributed to failure and were considered benign. Considering the extent of material displacement required to roll-form these threads, such flaws are likely unavoidable.

All screws were zinc plated. The plating thickness was within the order of 6-7µm. **Figure 7c** displays an example of the plating.

### 2.4 Hardness Testing

Microhardness testing of the core screw material was conducted in accordance with ASTM E384 using a 1kg load. **Table 1** presents the hardness values obtained. Note that the hardness results were significantly above the allowable hardness of 380 HV and therefore, did not conform to specification hardness.

**Table 1:** Hardness Results

<table>
<thead>
<tr>
<th>Screw Batch</th>
<th>Hardness Measurements (HV&lt;sub&gt;1000gf&lt;/sub&gt;)</th>
<th>Avg. Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>HV&lt;sub&gt;1000gf&lt;/sub&gt;</td>
</tr>
<tr>
<td>Standard Req.</td>
<td></td>
<td>320-380</td>
</tr>
<tr>
<td>#1</td>
<td>453, 451, 456, 470, 455</td>
<td>457</td>
</tr>
<tr>
<td>#2</td>
<td>467, 474, 469, 479, 467</td>
<td>471</td>
</tr>
<tr>
<td>#3</td>
<td>434, 430, 453, 447, 456</td>
<td>444</td>
</tr>
</tbody>
</table>
3.0 CONCLUSIONS

The screw had failed due to hydrogen embrittlement. Hydrogen embrittlement is caused by hydrogen being present within the steel and results in delayed cracking under static loading. In simplification, the presence of hydrogen within the screws caused cracking several hours/days after installation.

Determination of hydrogen embrittlement as the failure mode was made based upon (1) the intergranular fracture features and (2) the background information. Intergranular fracture features are indicative of numerous forms of embrittlement. However, knowledge that cracking occurred in a delayed manner after the last known loading event (screw installation), indicated that failure had indeed occurred via hydrogen embrittlement.

The source of hydrogen responsible for embrittlement was likely from the manufacturing process. The two most common processes responsible for introducing hydrogen are (a) pickling and, more likely in this case, (b) electro-plating. Inhibitors can be applied to both processes to eliminate/minimize the hydrogen produced. For critical applications and/or to ensure hydrogen removal, baking at 190ºC is generally required.

Testing to determine whether a component or material has suffered from hydrogen embrittlement is generally conducted by static loading at 75-90% of the material tensile strength for 24 to 96 hours. The customer may consider performing testing which includes installing screws into a fixture, applying torque to achieve 75-90% of the minimum tensile strength and monitoring whether the screw fails over time. Screw failure would indicate hydrogen embrittlement. Several samples per lot should be performed in order to gain statistical confidence. Further reference to ASTM Standards F519 and F1624 could be used to help develop testing procedures and quality monitoring.

The core hardness values of the screws from Batches #1, #2 and #3 were found to be significantly higher than the specified hardness limit. The higher the hardness, the more susceptible the screw is to hydrogen embrittlement. However, hydrogen embrittlement occurs based on many variables including (a) susceptible material, (b) high hardness, (c) hydrogen content and (d) stress levels. Although it is recommended the screws be produced to meet the governing specification, this alone will not reliably prevent hydrogen embrittlement. Screws with hardness values within the acceptable limit may still be susceptible to hydrogen embrittlement failure. Prevention/removal of the hydrogen before installation is the only way to ensure the integrity of the screws.
Figure 1: Photograph displaying the submitted samples.
Figure 2: Photographs displaying fractured screw within the plastic housing.
Figure 3: Photograph displaying the fractured screw after removal and comparing it to a new, un-used screw. Note that the head of the fractured screw was not provided.
**Figure 4:** SEM images displaying crack initiation to have occurred by intergranular fracture typical of hydrogen embrittlement. SE1, 20kV.
Outer Perimeter, Intergranular Fracture Features

Center, Microvoid Coalescence (ductile overload)

Microvoid Coalescence

Figure 5: SEM images displaying (b,d) additional images of the outer perimeter comprising of intergranular fracture features. (c,e) The fracture center comprising of microvoid coalescence typical of ductile overload. SE1, 20kV.
**Figure 6:** Micrographs displaying the martensitic core structures of screws from (a,b) Batch #1, (c,d) Batch #2 and (e,f) Batch #3. Etched using 3% nital.
Figure 7: Micrographs displaying examples of (a.b) forming flaws and (c) the plating on a screw from Batch #1. Note that the presence of these flaws had not contributed to failure and likely are unavoidable considering the extent of material displacement needed to form these threads. As-polished condition.