Influence of tool steel surface topography on galling during hot forming of Al-Si coated ultra high-strength steels

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Abstract

Galling is a severe form of adhesive wear encountered in metal forming operations. In hot stamping, an Al-Si coating is normally applied onto the ultra high strength steels (UHSS) to prevent decarburisation and improve the corrosion resistance of the steel. Material transfer occurring from the coated UHSS to the tool surface has been identified as major issue in hot stamping. It is a known problem as this transferred material impairs the quality of the produced parts as well as increases the costs of maintenance of the tools. The present work focuses on the understanding of surface topography parameter and their effect on galling. Surface roughness level and orientation of the roughness marks (lay) on tool surface have been studied. The results showed that a single parameter of the surface topography is not enough to describe the resistance to galling. Parameters such as Rp, Rv and Rsk are also important to consider in order to rank the galling resistance of the surface. The sliding direction with respect to the surface lay also had a significant influence on galling; sliding in the direction parallel to it resulted in substantially reduced material transfer.

Keywords: material transfer; Al-Si; ultra high strength steel; high temperature, surface roughness.

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1. INTRODUCTION

Galling has been identified as a crucial problem during hot forming of Al-Si coated ultra high strength steels (UHSS). Material transfer from the work-piece to the tool is known to occur during forming of the Al-Si coated UHSS sheets. Material transfer occurs from the coated Al-Si steel blank to the tool steel surface where big lumps of transferred material can form and impair the quality of the work-piece. The exposure to high temperature of Al-Si coating on the work-piece gives rise to the formation of intermetallics with iron from the substrate [1, 2]. These intermetallics have high hardness which means that the lumps developed on the tool surface contain hard constituents. These intermetallic constituents can therefore induce severe wear not only on the tool but also on the formed components and cause geometrical variations beyond the specifications. Another common problem associated with galling is that there is an increase in down time for refurbishing and maintenance of the tools and this has an adverse effect on the overall economy of the stamping process.

Surface roughness is known to influence the galling behaviour both in dry and lubricated contacts. In his study [3], Schedin observed that galling has a big tendency to initiate at the irregularities on the surface and larger lumps develop during the forming operations. He states that the action of surface irregularities as initiation sites for galling does not depend on material combinations or lubrication. He suggests that due to the nature of how galling initiates, material transfer cannot be completely avoided and only the growth rate of the transferred layer may be controlled.

In the forming process, not only irregularities of the surface can act as initiation sites for material transfer. Die corners are regions where temperature and normal contact pressures are high and these tend to be the sites where galling initiates. Hou [4] suggests that high local temperature and normal contact pressure can be of great importance in the occurrence of galling.

In a study done by Podgornik and Hogmark [5], they observed that polishing of the tools reduces the severity of galling. However, they suggest that surface engineering can bring some benefits but it needs to be well controlled. They proposed a solution for providing good galling properties where surface modification of the tools should include plasma nitriding, post polishing after plasma nitriding and finally a deposition of a hard low friction coating.
The authors have previously studied the initiation mechanisms of galling in hot sheet metal forming [6]. It was observed that accumulation and compaction of debris are key features in terms of the severity of material transfer. Mild galling was observed on polished and milled specimens as accumulation of debris did not occur as easily as for ground surfaces.

The occurrence of galling at high temperatures is extremely important but only a few studies have been done to understand galling and to explore ways to overcome this problem. Yanagida et al. [7] have studied the performance of different lubricants for hot stamping of UHSS. They found that lubricants help in decreasing the stamping load and the die wear. However, it is not clear whether the use of such lubricants has a beneficial effect in reducing galling during forming of Al-Si coatings. Kondratiuk et al. [8] have studied the wear behaviour of coated tool steels sliding against Al-Si UHSS. They observed that the use of coatings applied to the tool steel had a negative effect on wear of the work-piece and resulted in more severe galling than with uncoated tool steels. They suggested that a way to reduce galling could be to increase the temperature during the austenitisation stage.

This work is aimed at evaluating the impact of surface roughness on the occurrence of galling during tool/work-piece interaction at elevated temperatures. The influence of different surface topography parameters and the surface lay orientation in relation to sliding direction on the galling tendency has been studied.

2. EXPERIMENTAL

In this work tribological experiments have been carried with untreated tool steel and different surfaces were produced by grinding. Three different grit sizes of SiC abrasive papers were used. As a reference, the surface roughness that is normally achieved after refurbishing an actual hot stamping tool was used. The different surfaces were characterised and the effect of the parameters on galling resistance was evaluated. The influence of the orientation of the surface lay, relative to the sliding direction, was also studied. Tribological tests were done with sliding parallel and perpendicular to the tool surface lay.

2.1 Test Materials and Specimens

The specimens used for the tribological tests were an upper pin of Ø2 mm made from a hot work tool steel. The chemical composition of the hot work tool steel was the same for all the cases. A similar composition is normally used for tools in the actual hot stamping process. The lower disc (Ø16 mm and 1.7 mm height) was made from Al–Si-coated UHSS which was welded onto a steel backing plate of Ø24 mm and 6.3 mm height. The properties of the Al-Si coated UHSS have been described in [1].

The tool steel pin specimen surfaces were prepared by grinding with SiC abrasive paper. Different grit sizes, #60, #120 and #240 of SiC abrasive papers were used. Grinding was done in a single direction with a view to produce a surface lay with a well defined orientation. This will be referred to as mild grinding. The surface related to the refurbished tools will be referred to as coarse grinding. Table 1 shows the surface topography values that correspond to each test specimen.

Commonly, the average surface roughness Sa/Ra is used for describing surfaces, but this type of parameter does not provide spatial structure information and does not differentiate between peaks and valleys. Ra is the average surface roughness in 2D and Sa is the equivalent average surface roughness in 3D. To evaluate the impact of the information that is not provided by the surface roughness Sa, additional parameters were used. The measurements were done using a 3D optical surface profiler and the data was obtained in 2D in the x-direction, which was perpendicular to the surface lay of the pin surface.

Rpv and Rv were used as these parameters directly give information about the peak height and valley depth and Rt is the added value of Rpv and Rv. Rsk (skewness) and Rku (kurtosis) were also used as they describe the symmetry of the surface distribution. The sign of the Rsk will tell if the farther points are proportionally above (positive) or below (negative) the mean surface level. Thus, it will tell if a surface has predominance of peaks/spikes or the predominance of holes/valleys. Rku on the other hand gives information about the randomness or repetitiveness of a surface. Similar to Sa, the above mentioned parameters do not provide information about the spatial structure. To account for this, Sm was used as it describes the mean spacing between profile peaks.

Figure 1 shows the surface images of different pin specimens taken with a 3D optical profilometer. The surface shown in Figure 1 (a) corresponds to a typical surface achieved after coarse grinding of an actual hot stamping tool. Figure 1 (b), (c) and (d) correspond to surfaces obtained after grinding with SiC abrasive papers of grit #60, #120 and #240 respectively. Only specimens with a surface topography corresponding to that shown in Figure 1 (a) were used for the studies pertaining to the surface lay.
Table 1. Surface topography values of the ground pin specimens.

<table>
<thead>
<tr>
<th>Grinding</th>
<th>Sa (µm)</th>
<th>Rp (µm)</th>
<th>Rv (µm)</th>
<th>Sm (µm)</th>
<th>Rt</th>
<th>Rsk</th>
<th>Rku</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse grinding</td>
<td>1.20~2.74</td>
<td>2.884±</td>
<td>-3.008±</td>
<td>127.2±</td>
<td>7.892</td>
<td>0.929</td>
<td>4.354</td>
</tr>
<tr>
<td>Mild grinding,</td>
<td>0.65~0.822</td>
<td>1.824±</td>
<td>-1.904±</td>
<td>99.461±</td>
<td>3.728</td>
<td>0.117</td>
<td>2.653</td>
</tr>
<tr>
<td>grit 60</td>
<td>0.205</td>
<td>0.285</td>
<td>14.024</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild grinding,</td>
<td>0.47~0.49</td>
<td>0.787±</td>
<td>-1.391±</td>
<td>78.426±</td>
<td>2.178</td>
<td>-0.655</td>
<td>4.64</td>
</tr>
<tr>
<td>grit 120</td>
<td>0.124</td>
<td>0.338</td>
<td>11.995</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild grinding,</td>
<td>0.34~0.39</td>
<td>0.440±</td>
<td>-0.643±</td>
<td>90.59±</td>
<td>1.083</td>
<td>-0.600</td>
<td>3.225</td>
</tr>
<tr>
<td>grit 240</td>
<td>0.167</td>
<td>0.163</td>
<td>36.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. 3D Optical surface profiler images of pin specimen surfaces after: a) coarse grinding and mild grinding with abrasive paper of grit: b) #60 c) #120 and d) #240.

2.2 Test Equipment and Procedure

The tribological tests were carried out by using an Optimol SRV high-temperature reciprocating friction and wear tester, a more detailed description of the tribometer can be found in [6]. Before the tests all specimens were cleaned with ethanol. The upper pin specimen was kept separated from the lower disc during heating and the holding time.

The lower specimen was then heated. This was done with a view to closely simulate the actual process, in which the work-piece is first heated up and then it comes into contact with the cooler tool. Once the desired temperature was reached (900°C), the lower (work-piece) specimen was retained at that temperature for 4 minutes to allow sufficient time for the diffusion of the Al-Si coating while still separated from the upper (tool) specimen. When a time of 4 minutes had elapsed, the pin was loaded against the disc and the test was started. The holding time was determined in the laboratory through trial tests. This was done in order to simulate the microstructural evolution of the coating in the actual stamping process. On completion of the test, the specimens were left to cool in air and then removed and analysed.

For the study concerning the influence of surface roughness parameters, the tribological tests were carried out with sliding perpendicular to the direction of the grinding marks of the pin specimen. The experiments to study the impact of the surface lay were done with sliding parallel and perpendicular to the grinding marks of the pin surface.
The test conditions used for the tests carried out in this work are presented in Table 2.

Table 2. Test parameters

<table>
<thead>
<tr>
<th>Test parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Load</td>
<td>31 N</td>
</tr>
<tr>
<td>Nominal contact pressures</td>
<td>10 MPa</td>
</tr>
<tr>
<td>Temperature</td>
<td>900°C</td>
</tr>
<tr>
<td>Stroke length</td>
<td>4 mm</td>
</tr>
<tr>
<td>Frequency</td>
<td>12.5 Hz</td>
</tr>
<tr>
<td>Duration</td>
<td>30 s</td>
</tr>
</tbody>
</table>

3. RESULTS

3.1 Influence of Surface Roughness

Figure 2 shows a comparison of the four different ground surfaces after the tribological tests. The dark zones correspond to the transferred material from the Al-Si coating. As can be observed, the coarse ground specimen showed severe material transfer and most of the pin surface was covered by transferred material. Surprisingly though, in case of the mild ground specimens, regardless of the grit size, very little galling occurred. All of the specimen showed features of abrasive wear and also presence of randomly distributed islands of adhered material. The appearance of the surfaces ground with abrasive paper was seemingly equal; only for the case of the coarse ground specimen, a thicker transferred layer could be observed.

3.2 Influence of Surface Lay Orientation

Figure 3 shows the results from the tests involving different orientation of surface lay. The specimens used for these experiments were coarse ground.

The micrographs show a considerable difference between the two specimens despite having the same Sa value (~2 µm). Severe material transfer was observed on the one that slid perpendicular to the surface lay (Figure 3 (a)). On the specimen that slid parallel to the surface lay, mild galling occurred at the centre of the specimen (Figure 3 (b)) and the presence of dark zones was almost negligible. However, at the edge a larger presence of dark zones was observed and wear debris were accumulated outside the area of contact (Figure 3 (c)).

3.3 Wear of Lower Disc Specimens.

Sliding against an untreated pin specimen seemed to have a similar effect on the UHSS discs regardless of the surface roughness of the pin specimens (Figure 4). For most cases, the Al-Si coating on the disc specimen did not undergo severe wear. Flattening of the surface occurred but most evident was the presence of oxide layers (glaze layers).

![Figure 2. SEM images of the tool steel specimens after the tests: a) coarse ground, b) mild ground grit #60, c) mild ground grit #120 and d) mild ground grit #240. Contact pressure: 10 MPa; Sliding direction: left to right.](image-url)
Only the disc that slid against the coarsely ground pin showed slightly more wear than the others. Furthermore, abrasive wear was observed on this specimen only. The specimen that slid parallel to the surface lay developed glaze layers and no abrasive wear was observed.

EDS analysis of the surfaces revealed presence of oxygen which suggests that the compacted glaze layers are formed from oxidised debris coming from wear of the upper pin specimens.

3.4 Friction Behaviour

The frictional behaviour is shown in Figure 5. Slight differences, depending on the surface roughness were observed. For the case of the coarse ground specimens the friction coefficient started at around 0.6 and then gradually increased up to 0.8. The same behaviour was observed when sliding was done perpendicular and when it was done parallel to the surface lay. This suggests that the occurrence of galling is not directly related to a sudden increment in friction coefficient, as the specimens that slid perpendicular to the surface lay showed considerably more galled material than the one sliding parallel.

In the case of the surface ground with abrasive paper, the friction coefficient remained stable for the whole duration of the test. In Figure 5, the curve belongs to the pin ground with grit #60; however a similar behaviour was encountered for all the other specimens ground with abrasive paper.

Table 3 shows the surface topography values of the pin specimens developed after the tribological tests. Overall, the roughness of the specimens increased after the tribological tests.

4. DISCUSSION

From the results, it is clear that surface roughness (Sa) alone, is not a clear indicative of the resistance to galling of the pin specimens. By intuition, a high Sa value would suggest a poor galling resistance, however, there is no clear limit as to what can be considered as a high value. The specimens ground with abrasive paper have clear differences in terms of surface roughness, but in terms of galling all of them showed good galling resistance.
In a study done by Podgornik and Jerina [9] they suggested that Rsk and Rku roughness parameters can be used to classify the galling resistance of austenitic stainless steel against a cold work tool steel. They proposed that with a more negative Rsk value and a high Rku value, a better galling resistance is observed and their importance is magnified when lubricants are used.

In the present work however, there is no clear relation of these two parameters with the resistance to galling. The specimens with lower Rsk value showed less material transfer but the Rku does not correlate as well. For instance, the coarse ground specimen had an Rku value of 4.35 which is higher than the specimen ground with #60 abrasive paper (2.653) and its galling resistance was entirely opposite. It is important to note however, that the study in [9] was done at lower temperatures and with different materials, thus different mechanisms are encountered.

The high material transfer on the coarse ground specimen can be due to several factors. The surface not only posses a high Sa value but also a high Rv (maximum profile valley depth) and a high Sm (mean spacing of peaks). The presence of deep valleys allows the accumulation of wear debris which can compact and develop as thick lumps on the surface. A mechanism for the occurrence of galling was proposed by the authors in [8]. It was suggested that the occurrence of severe galling occurs by entrapment and compaction of the wear debris. When this is not possible, the severity of galling is reduced and occurs by direct adhesion of the Al-Si coating. The results obtained from the mild ground specimens (Figure 4 (b)-(d)) resemble those obtained from a milled or polished specimen shown in [8].

Wear of the asperities of both surfaces occur during sliding and this results in the generation of wear debris and a new surface is formed on the pin. In case of the mild ground specimens, the asperities are worn fast due to its low Rsk value. This effect, combined with the fact that the surface has a low Rv and Sm results in lesser number of sites where debris can be accumulated and compacted during sliding.

Considering the results from the worn lower disc specimens, it is possible to see that sliding at high temperature helps in forming a protective glaze layer on the Al-Si coated disc. This glaze layer is formed primarily from oxides from the pin specimen, thus suggesting that there are two effects occurring.

### Table 3. Surface topography values of the ground pin specimens after tribotests.

<table>
<thead>
<tr>
<th>Grinding</th>
<th>Ra ((\mu m))</th>
<th>Rp ((\mu m))</th>
<th>Rv ((\mu m))</th>
<th>Sm ((\mu m))</th>
<th>Rt</th>
<th>Rsk</th>
<th>Rku</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse ground</td>
<td>2.22</td>
<td>4.920 ± 0.618</td>
<td>-5.627 ± 0.849</td>
<td>125.24 ± 35.877</td>
<td>10.546</td>
<td>-0.327</td>
<td>2.501</td>
</tr>
<tr>
<td>parallel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse ground</td>
<td>2.56</td>
<td>6.422 ± 1.66</td>
<td>-6.461 ± 0.880</td>
<td>96.54 ± 25.82</td>
<td>12.883</td>
<td>0.016</td>
<td>2.305</td>
</tr>
<tr>
<td>perpendicular</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild grinding, #60</td>
<td>1.76</td>
<td>4.027 ± 0.724</td>
<td>-4.789 ± 1.080</td>
<td>95.055 ± 19.032</td>
<td>8.816</td>
<td>-0.085</td>
<td>2.774</td>
</tr>
<tr>
<td>Mild grinding, #120</td>
<td>1.83</td>
<td>3.646 ± 0.541</td>
<td>-5.115 ± 1.213</td>
<td>130.25 ± 44.812</td>
<td>8.762</td>
<td>-0.623</td>
<td>2.722</td>
</tr>
<tr>
<td>Mild grinding, #240</td>
<td>1.96</td>
<td>2.880 ± 0.541</td>
<td>-4.40 ± 1.213</td>
<td>95.37 ± 7.279</td>
<td>7.279</td>
<td>-0.462</td>
<td>2.866</td>
</tr>
</tbody>
</table>
simultaneously. On one hand it is the accumulation and compaction of the wear debris on the pin (which occurs easily on the coarse ground specimen) and on the other hand the formation of the protective glaze layer on the disc.

In the case of the mild ground specimens, the glaze layer could be responsible for the limited amount of adhered material on the pin surface. In the case of the coarse ground specimen however, it seems that when the transferred material on the pin surface interacts with the glaze layer on the disc, the protective layer is damaged, thus generating a more severe wear on the coated disc and enhancing the severity of galling.

The different behaviour of the two lay orientations can also be explained in terms of the entrapment of debris. It is clear that severe material transfer does not occur when the sliding is parallel to the surface lay orientation. Under these conditions it is very likely that the reciprocating sliding allows the loose debris to escape the contact through the valleys of the surface, in a channel-like effect. On the contrary, during sliding in a direction perpendicular to the surface lay pattern, the severity of wear and the entrapment of wear debris give rise to build-up of material and increased tendency of galling.

In Table 3, it was shown that the specimens ground with abrasive paper also developed a rough surface with high Rv and considerably high Sm value. The fact that these rough surfaces developed during sliding do not generate severe galling or further accumulation and compaction can be explained by two factors. Firstly, a protective glaze layer is formed on the surface of the Al-Si coated disc and secondly, similar to the case of the specimen that was slid parallel to the surface lay, any debris formed can be transported out of the surface through the valleys.

5. CONCLUSIONS

- The surface roughness obtained by grinding the tool steel specimens using different grit size of SiC abrasive papers does not have a significant influence on the occurrence of galling.

- The orientation of surface roughness marks (lay) with respect to the sliding direction does influence the galling tendency significantly. Parallel sliding with respect to the surface lay tends to reduce material transfer and the galling tendency.

- Combined use of parameters such as Sa, Rv, Sm and Rsk are important when describing the resistance to galling of the Al-Si coating onto the tool steel specimen.

- Formation of protective glaze layers on the Al-Si coating significantly reduces the severity of material transfer and the wear of the Al-coating.

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6. REFERENCES.


