Influence of surface texture on the galling characteristics of lean duplex and austenitic stainless steels

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Abstract Two simulative test methods were used to study galling in sheet forming of two types of stainless steel sheet: austenitic (EN 1.4301) and lean duplex LDX 2101 (EN 1.4162) in different surface conditions. The pin-on-disc test was used to analyse the galling resistance of different combinations of sheet materials and lubricants. The strip reduction test, a severe sheet forming tribology test was used to simulate the conditions during ironing. This investigation shows that the risk of galling is highly dependent on the surface texture of the duplex steel. Trials were also performed in an industrial tool used for high volume production of pump components, to compare forming of LDX 2101 and austenitic stainless steel with equal thickness. The forming forces, the geometry and the strains in the sheet material were compared for the same component.
It was found that LDX steels can be formed to high strain levels in tools normally applied for forming of austenitic steels, but tool adaptations are needed to comply with the higher strength and springback of the material.

1 Introduction
This study was performed to study the effect on galling on the forming tool when replacing austenitic steels (EN 1.4301) with low-Ni duplex steels (EN 1.4162) in various types of sheet metal forming processes.

The increased use of high strength steels has accentuated the interest in tooling solutions capable of sustaining higher forming pressures. In the last decades, a number of accelerated test methods have been developed for prediction of tool life during high-volume production [1-6]. The methods vary from semi-industrial testing, where the sheet deformation mode equals industrial forming, to standardized wear tests, where the tribological contact between sheet, tool surface and lubricant is the main issue. To optimize time and cost, often a combination of test methods are used, together with numerical prediction of the contact pressures during forming [7-9].

This study includes three methods to investigate the need of new tooling solutions for forming of lean duplex steel in different surface conditions. Pin-on-disc is a relatively fast standardized wear test using small amounts of sheet material, which facilitates testing of a large number of sheet surfaces. This method differs from industrial sheet forming in that the tool repeatedly slides in the same wear track on the sheet, and that no bulk deformation of the sheet is present.

The second laboratory test used here, the strip reduction test, was originally developed to rank the efficiency of different types of lubricants [10]. It simulates industrial forming in that the sheet sample is deformed plastically by an ironing process, and that resulting scratches on the sheet are used as indication of galling. As the temperature during lubricated forming affects the galling process, the tools are preheated in some of the tests. Although the tool temperature increases rapidly during strip reduction, it has been shown that the initial temperature affects the galling resistance [1].

The third test was an industrial case-study, where a chosen die was used with different sheet materials, without changing the sheet thickness, die geometry or die surface condition.
2 Materials

Two different stainless steel grades, one austenitic grade (1.4301) and one duplex grade (1.4162, LDX 2101®) were included in the present study, see Table 1. The influence of steel sheet surface topography on the galling tendency was investigated by studying the austenitic grade in the as-received 2B condition and in a wet grinded condition (using 1000 mesh grinding paper). The duplex grade was studied in three different surface conditions: one brushed condition (LDX 2101 2E), one blasted condition (LDX 2101 VKS) and one wet grinded condition (using 1000 mesh grinding paper). The tools used in the investigation were produced from a nitrogen alloyed PM cold work tool steel (Vancron 40) that was hardened and manually polished, see Table 2.

Three different commercial lubricants were included in the study: Rhenus Rform 150 without chlorinated EP additives and a viscosity of 150 mm²/s at 40 °C, Rhenus LA722-017 with 135 cSt viscosity at 40°C, and Castrol Iloform TDN 81 with chlorinated EP additives and a viscosity of 120 mm²/s at 40 °C.

Table 1. Properties of the stainless steel grades investigated

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Composition</th>
<th>Sheet surface condition</th>
<th>Sa [µm]</th>
<th>Surface hardness [HV0.05]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4301</td>
<td>C:N:Cr:Ni:Mo:Oth. [wt%]</td>
<td>2B (cold rolled, heat treated, pickled and skin passed)</td>
<td>~0.2</td>
<td>190 ± 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet grinded 2B with 1000 mesh</td>
<td>~0.1</td>
<td>230 ± 30</td>
</tr>
<tr>
<td>1.4162-LDX 2101®</td>
<td>0.03:0.22:21:1.5:0.3:5Mn</td>
<td>2E (Cold rolled, heat treated, mechanical descaling by brushing, pickled)</td>
<td>~0.3</td>
<td>280 ± 40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VKS*</td>
<td>~4</td>
<td>360 ± 30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet grinded 2E with 1000 mesh</td>
<td>~0.1</td>
<td>270 ± 30</td>
</tr>
</tbody>
</table>

* Outokumpu special product – a hot coil product that is lightly cold reduced and then shot blasted before descaling. The result is a surface with a finish between hot rolled and cold rolled.

Table 2. Tool materials and surfaces in the study

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Tool surface condition</th>
<th>Sa [µm]</th>
<th>Tool hardness [HRC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vancron 40</td>
<td>SRT pins – industrial best practice polishing using 6 µm diamond in the last step</td>
<td>~0.05</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>Pin-on disc pins – manual polishing using 3 µm diamond in the last step</td>
<td>~0.1</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 3. Test matrix showing included sheet materials with respect to chemistry (alloy), mechanical properties (surface hardness), and surface topography (Sa value). PIN denotes pin on disk tests, SRT strip reduction tests.

<table>
<thead>
<tr>
<th>Sheet material</th>
<th>Topography: Sa-value [µm] and major surface preparation stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4301</td>
<td>190 PIN SRT</td>
</tr>
<tr>
<td></td>
<td>230 PIN</td>
</tr>
<tr>
<td>LDX 2101</td>
<td>270 PIN</td>
</tr>
<tr>
<td>1.4162</td>
<td>280 PIN</td>
</tr>
<tr>
<td></td>
<td>360 PIN</td>
</tr>
</tbody>
</table>


3 Experimental testing

3.1 Pin-on-disc testing

The pin-on-disc testing was performed using a commercial CSM Tribometer. In the tests, a pin with a diameter of 10 mm and a polished hemispherical shaped end surface (radius 5 mm) made of the tool steel is loaded against a rotating disc punched out from a stainless steel sheet panel, in this study of thickness 1.5 to 3 mm. The tool pins were polished to a surface roughness of $S_a \sim 0.1 \mu m$. The tribological testing was performed under lubricated conditions in ambient air (21-22 °C, 25-26 % relative humidity). The normal load was set to 20 N and the relative sliding speed to 200 mm/s. A lubricant amount of 2 g/m$^2$ was applied onto the stainless steel sheet panels before testing, using either Rform 150 or TDN 81. During testing, the friction coefficient was continuously recorded. The tests were run for a fixed number of revolutions: i.e. 20 000 or until the friction coefficient exceeded 0.2, which was set as the galling criterion. All tests were repeated three times, but at different track radii: 5, 7, and 9 mm, respectively. It should be noted that the pin is sliding in the same wear track resulting in a repeated contact between the mating surfaces during testing.

3.2 Strip reduction testing

The strip reduction test was used to evaluate the galling resistance of the different sheet materials. It is a severe sheet forming tribology test simulating the conditions in ironing. Figure 1 shows the schematic outline of the test [10]. A 15 mm diameter non-rotating tool pin is applied as one of the tools, the other one being a supporting tool plate. The set-up allows four tests with the same tool pin before repolishing, by turning the tool pin 90° after each test. Galling is quantified by surface roughness measurements on the tested sheet strip, using scratches deeper than 2 \( \mu m \) as galling criterion. The tools were preheated in some of the tests, and 60 °C was chosen to represent the temperature of a run-in production tool.

The strip sliding velocity was 80 mm/s, and sheet thickness reductions of 30 % were obtained, starting from thickness 0.7 and 0.8 mm. The sheet samples were extensively lubricated on both sides prior to the test. The duplex sheet material with a brushed 2E surface was drawn along (-L) and perpendicular (-T) to its brushing and rolling direction. The 2B surface of the austenitic material was drawn perpendicular to its rolling direction. Each sheet-tool combination was tested in five duplicates, with different initial tool temperatures and lubricants, using Rform 150 as the standard lubricant, and the lubricant LA722-017 in the RT tests.

The temperature development during strip reduction of the different sheet materials was measured using surface coated tools equipped with thermocouples. To reduce the heating effect from galling, lower reduction values and the lubricant TDN 81 containing EP-additives were used.

![Fig.1. Strip reduction test set-up, and schematic drawing of tool pins with holes for mounting of thermocouples, from [10].](image-url)
3.3 Industrial case study

The industrial tests were performed in a production tool normally used for an austenitic 1.4401 pump component. The die had a surface roughness of 0.06 µm Ra and was surface coated with TiAlN. The component is produced in a 2500 kN four cylinder hydraulic press. The process involves automatic blank-feeding and lubrication of circular blanks of 1.5 mm thickness, deep-drawing, punching of a center hole, final drawing and calibration of the upper flanges and sealing surfaces. A final cutting operation was not included in this study. Tests were performed with 1.5 mm LDX 2101 blanks that were lubricated with TDN 81 and introduced manually in the press. Reference samples of 1.4301 and 1.4401 were also formed at this occasion.

Interrupted tests were used to follow the sheet metal flow in the tool, see Figure 2. Three samples were formed from each stage and 34 samples from the final stage. The blanks were marked with square grids to compare the strain levels of different materials. The geometry after forming was recorded with an optical system (GOM Athos) and was compared to the product CAD.

The original process conditions (900 kN main cylinder force, 55 mm/s forming speed) were used in the first interrupted stage, but the main cylinder force was increased to 1100 kN when forming LDX to final geometry.

4 Results and discussion

4.1 Pin-on-disc testing

Figure 3 summarizes the results from the pin-on-disc experiments. In the box plots presented the line within the box represents the median value while the box boundaries represent the minimum and maximum values, and thus the scatter, of the three tests performed.
Fig. 3. Number of pin-on-disc revolutions until galling for the investigated combinations: a) results for lubricant Rhenus Rform 150 and b) results for lubricant TDN81. The line within the box represents the median value while the box boundaries represent the minimum and maximum values. Note that for the LDX VKS grade galling does not take place within 20 000 revolutions and no box plot is therefore shown.

Figure 3 shows that stainless steel grade 1.4301 tested in the as-received 2B condition performs poorly for both lubricants, only managing about 100 revolutions before galling occurs. When testing 1.4301 in the grinded condition the performance clearly improves for both lubricants, about 10 000 revolutions are obtained before galling occurs. This improvement in performance is likely due to a more favorable surface morphology of the grinded surface compared to the 2B surface which facilitates the maintenance of a lubricant film separating the sheet and tool surface and thus prevents cold welding. The improvement could also be due to deformation hardening of the grinded surface, making it less prone to cold welding.

Comparison of the grinded 1.4301 with the grinded LDX, i.e. two stainless steels with similar surface topography but different chemical composition, shows that 1.4301 performs better than LDX for both lubricants.

When comparing the grinded LDX surface with the LDX 2E surface it can be seen that the 2E surface performs better than the grinded surface. This is the case for all tests (except for one single test for one of the lubricants). This could be explained by the grinding process changing the surface topography to a smoother surface with less lubricant reservoirs, resulting in a poor performance.

The LDX surface with highest galling resistance in these pin-on-disc tests is the blasted surface (LDX VKS). For the Rhenus lubricant the blasted LDX surface manages about 10 000 revolutions before galling occurs and for the TDN81 lubricant galling does not take place within 20 000 revolutions. This is the only combination for which galling does not take place in this test. This good performance is likely due to a combination of high surface hardness and a favorable surface topography with many lubricant reservoirs.

When comparing the results for the 1.4301 grade with a 2B surface, the 1.4301 grade with the grinded surface and the LDX grade with a grinded surface the median values are similar for the two lubricants.

For the brushed LDX 2E surface and the blasted LDX VKS surface, TDN81 is clearly the best performing lubricant. TDN81 gives at least 10 000 revolutions more than the Rhenus oil before galling occurs, and as regards the LDX VKS surface the difference is even higher as all samples survived the stipulated test range.
4.2 Strip reduction testing

Figure 4 shows the critical distance for galling initiation for the strips drawn to 30% thickness reduction in the SRT test. The large reduction gives high tool pressures that results in early galling, even though the lubricant amount is considerably larger than in industrial forming. The summarized data shows that the LDX 2E surface sliding along its brushed direction (2E-L) resulted in early galling, while LDX 2E sliding transverse to its brushing direction (LDX 2E-T) obtained equivalent or higher galling resistance than the austenitic material 1.4301.

![Graph showing SRT results](image)

**Fig. 4.** Results from 30 % strip reduction measurements using the lubricant Rform 150. The graph shows mean value and standard deviation (error bars) of length until galling occurs, as defined by 2 µm deep scratches on the sheet material. A sliding direction parallel to the brushing direction decreased the galling resistance of LDX.

The strip reduction test gives a higher degree of directionality as a result of the plane strain deformation with no strip width deformation. This may explain the large effect of the brushing direction of the 2E sheet surface. When studying the sheet surfaces after testing (Figure 5), some surface texture remains even after 30 % reduction. Thus, when the sliding direction is parallel to the brushing direction the lubricant is left free to escape through the valleys made by brushing, whereas sliding in transverse direction ensures retention of the lubricant during the strip reduction.

![Brushed sheet surface images](image)

**Fig. 5.** Brushed sheet surface LDX 2E after strip reduction, confocal microscopy images in reflection mode. The sharp horizontal grooves are scratches from the tool sliding, that are measured and used as indication to galling. The sheet surface texture (fine roughness) is still present after 30 % ironing.

The temperature during strip reduction testing at 15 % thickness reduction was compared for the two sheet materials, again testing the LDX 2E material in the longitudinal as well as the transverse brushing direction. Figure 6 shows the temperature measured by a thermocouple mounted 1 mm below the tool surface. The tool/work piece interface temperature is 10-15°C above these measured temperatures [11]. The LDX sheet surfaces produce more heating than 1.4301 during forming, partly
from larger adiabatic heating effects due to the higher flow stress. A significant temperature increase is noticed when testing LDX 2E-L as compared to LDX 2E-T. This is due to increased friction, and eventually, galling of LDX 2E-L. The surfaces LDX 2E-T and 1.4301 2B did not result in galling during 15 % reduction.

![Graph showing temperature increase](image)

**Fig. 6.** Temperature in the tool during 15 % strip reduction of different sheet surfaces, measured 1 mm from the tool pin surface. LDX 2E-L produced higher temperatures when galling was obtained.

### 4.3 Industrial case study

The component shown in figure 2 could be formed in LDX of equal thickness as the original austenitic material using the original press program and tools, but increased press forces. It was noticed that forming of LDX with brushed 2E surface produced higher tool temperatures than 1.4301 with 2B surface. TDN81 that was used as lubricant showed darkening on the LDX parts, indicating that the degradation temperature was reached, see Figure 7. Some galling marks were observed on the LDX samples, but no influence from the brushing direction of the sheet surface was observed. A few of the galling marks originated from a small scar on the die surface.

![Photo of pressed components](image)

**Fig. 7.** Photo of pressed components in LDX from interrupted tests. Darkened lubricant and galling marks are observed already after a few pressed components. The etched pattern is aligned with the rolling direction of the blank, horizontal in this photo.
The LDX material required a 20 % higher forming force than 1.4301, and 30 % higher springback was noticed in the upper wall parts of the LDX samples compared to 1.4301, see Figure 8. The LDX samples had a 1.5 mm smaller central hole diameter than the austenitic samples, and tool modifications would be needed to accomplish the required tolerances of the final part.

![Fig. 8. Side view (upper part) of tested component (a), and deviation from product CAD in formed components of 1.4301 (b) and LDX (c).](image)

### 5 Discussions

The studied sheet surfaces differ in relation to three aspects, that all have a clear influence on the galling resistance: topography, mechanical properties, and chemistry, as shown in Table 3. The contact pressure and speed of the tests vary considerably, and galling occurs within 330 mm sliding length for strip reduction, compared to 1130 mm for pin-on-disc. The test matrix for the strip reduction tests was decided by the current availability of materials in suitable thickness ranges, and only two surfaces were tested with both laboratory tests: 1.4301 2B and LDX 2E, with Rform 150 as lubricant. If the optimal sliding direction 2E-T for the LDX material is used for comparison, the results from the strip reduction and the pin-on-disc tests correlate in that LDX 2E performs better than 1.4301 2B, but the results are contradictory if comparing to strip reduction along the brushed LDX 2E surface. These experimental results indicate how the sheet surface influences galling in stainless forming, but more work is needed to give a thorough explanation. The results are discussed in relation to the different aspects in the following sections.

![Fig. 9. The studied surface textures of LDX, interference microscopy images with 627x471 µm area.](image)
5.1 Surface topography

Both laboratory tests show that a surface texture able to accommodate a lubricant film trapping the lubricant in hydrostatic valleys between the surface asperities during the forming operation, results in high galling resistance. For the high strength material LDX, the galling resistance increased with increased surface roughness, when studying the pin-on-disc results. The best material VKS, had a tenfold increase in $S_a$-values and a different texture geometry compared to the other sheet surfaces, see Figure 9. The strip reduction tests also proved a beneficial influence of the increased surface roughness of the 2E material, but only if used transversely to the drawing direction. This effect is, however, not relevant to most 3D forming operations, see for example the circular blanks used in the industrial case study.

5.2 Mechanical properties

A harder sheet surface is less prone to plastic deformation, which is one onset to adhesive bonding, and earlier studies have shown a relation between sheet metal yield strength and high galling resistance [12-13].

Comparing the commercial surfaces of this study, the heavily workhardened LDX surfaces produced by scratch brushing and shot blasting proved better performance than the softer surfaces in the pin-on-disc tests, and also in strip reduction tests when brushing were perpendicular to drawing direction. However, for the manually grinded surfaces, the effect of initial material yield strength, and measured hardness was inverse to the above results, i.e. the originally softer material was better.

The industrial tests showed that LDX can be formed to a high degree of deformation using tools designed for austenitic steels. To obtain equivalent product geometry, tool adaptations are needed to comply with the higher strength and springback of the LDX material. Replacing 1.4301 with LDX of equal thickness will result in increased die surface pressure. However, most applications where high strength duplex grades are introduced are associated with a gauge reduction that in its turn decreases the surface pressure. Thus, the risk of galling when introducing LDX will partly depend on the amount of gauge reduction.

5.2 Chemistry

The possibility for sheet and tools to react with the lubricant film is essentially a chemical property. The better performance of the lubricant TDN81 compared to Rhenus Rform 150 is due to the fact that the protective tribofilm consisting of chlorine is much more efficient than the tribofilm formed by the Rhenus lubricant, [14]. This difference between the two lubricants is only seen for the surfaces with the rougher surface topography (LDX 2E and LDX VKS).

For the steel sheets with smoother surfaces (1.4301 with a 2B surface, 1.4301 with a grinded surface and LDX with a grinded surface) TDN81 does not have a better performance. In this case the viscosity of the lubricant might be more important in order for the lubricant to adhere to the sheet surface. The Rhenus lubricant has a slightly higher viscosity which may explain why TDN81 does not perform better than the Rhenus lubricant in these cases.

6 Conclusions

Pin-on-disc tests and strip reduction tests show that high surface hardness and increased surface roughness of the stainless steel sheet improves the performance of the lubricant and postpones pick-up and galling.

The risk of galling is dependent on the surface texture of the lean duplex steels, proving higher surface roughness to be advantageous regarding lower friction and postponement of pick-up and galling.
The texture orientation of the LDX 2E surface was of high importance for the galling resistance in the strip reduction tests, showing transverse texturing with respect to the sliding direction to be advantageous.
Tool adaptations are needed when replacing austenitic steel with high strength LDX of equivalent thickness.

7 References