Evaluation of galling resistance for some selected combinations of tool steels / stainless steel sheet materials/ lubricants using pin-on-disc testing

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Abstract
Stainless steels are well known to be prone to cold welding and material transfer in sliding contacts and therefore difficult to cold form unless certain precautions as discussed in this paper are taken. In the present study different combinations of tool steels/stainless steels/lubricants has been evaluated with respect to their galling resistance using pin-on-disc testing. The results show that a high galling resistance is favored by a high stainless steel sheet hardness and a blasted stainless steel sheet surface topography. The effect of type of lubricant was found to be more complex. For example, the chlorinated lubricants failed to prevent metal-to-metal contact on a brushed sheet surface but succeeded on a blasted sheet surface of the same stainless steel material. This is believed to be due to a protective tribofilm which is able to form on the blasted surface, but not on the brushed surface.

Key words: galling, stainless steels, cold work tool steels, lubricants

1. Introduction

Stainless steel sheet can be cold formed by any of the conventional processes, e.g., bending, blanking, deep drawing, roll forming, hydro forming, etc. but from a tribological point of view, stainless steels are more difficult to form than carbon steels since these steel grades are prone to cold welding and show low heat conductivity increasing the severity of the tribological contact. As a result high demands are put on the forming tool, i.e. the tool materials used must show a combination of high hardness, toughness, polish ability, galling resistance, etc. Also, the increasing strength of the stainless steels together with the demands for more environmental friendly lubricants have lead to tougher forming conditions and increasing risks for galling resulting in an unacceptable surface finish of the sheet after cold forming.

There are many parameters influencing the sheet metal forming operation and it is today not clearly understood how these parameters interact and which parameter and/or combination of parameters that is most critical for the galling initiation. Besides the chemical composition (including passive film composition), mechanical properties and physical properties of a stainless steel grade and also the surface finish of the stainless steel sheet will influence the galling tendency [1, 2]. For example, Nilsson et al have shown that electrochemical etching of a 2B stainless steel surface significantly improved the tribological performance [2]. Besides the most widely used surface finish 2B (i.e. a cold rolled, heat treated, pickled and temper rolled) stainless steel sheet can be produced in a number of surface finish conditions such as cold rolled and brushed, cold rolled and blasted, cold rolled and pickled, cold rolled and grinded, cold rolled and polished, etc.

Also, the properties of the tool steel, e.g. chemical composition, microstructure, mechanical properties, have a big impact on the tribological performance in a sheet metal forming applications. Recent studies have shown that a family of new high nitrogen alloyed powder metallurgy (PM) tool steel grades with unique property combinations of hardness, wear resistance and low friction properties display very promising anti-galling properties in the forming of stainless steels [3-5]. However, a high surface finish of the forming tool, i.e. R_a < 100 nm or better, is a pre-requisite in order to avoid or decrease the risk for galling.

Due to the severe tribological contact conditions in cold forming of stainless steel sheet the lubrication requirements are most critical and high performance lubricants such as chlorinated oils or waxes have been the lubricants generally used when cold forming stainless steels. Many studies have shown the outstanding performance of chlorinated lubricants which mainly is due to their ability to chemically react under the influence of high pressure and form a tribofilm on the surface, thus preventing cold welding [3, 6-9]. However, the chlorinated lubricants are harmful both to human and nature and today there is an ambition to only use environmentally friendly lubricants.

The aim of the present study is to evaluate the galling resistance of a number of stainless steel sheet materials, tool steels and lubricants by pin-on-disc testing and increase the understanding for which parameters that are the most critical in order to prevent galling under lubricated conditions.

2. Experimental

2.1 Materials

Four different stainless steel grades, one austenitic grade (1.4301), one ferritic grade (1.4509), one metastable austenitic grade in temper rolled condition (HyTens 1000) and one duplex grade (LDX 2101) were included in the present study, see Tables 1 and 2. Besides, the influence of steel sheet surface topography was investigated by studying the duplex grade, LDX 2101 with two different surface conditions, one brushed (LDX 2101 2E) and one blasted (LDX 2101 VKS), respectively, see Fig. 1. Three different PM cold work tool steels were included in the investigation, see Table 3. The microstructures of the tool steel grades in the hardened and tempered condition consist of a martensitic matrix with an evenly distributed hard phase. The size of the hard phase particles are around 1 µm for the carbides and around 0.7 µm for the nitrides. Finally, four different commercial lubricants, including both chlorinated and non-chlorinated, were included in the study, see Table 4. All lubricants contain EP-additives for improved performance. The viscosity of the lubricants ranges between 70 – 200 mm^2/s. One of the lubricants, Castrol Iloform FST 8, is not considered to be environmentally hazardous.

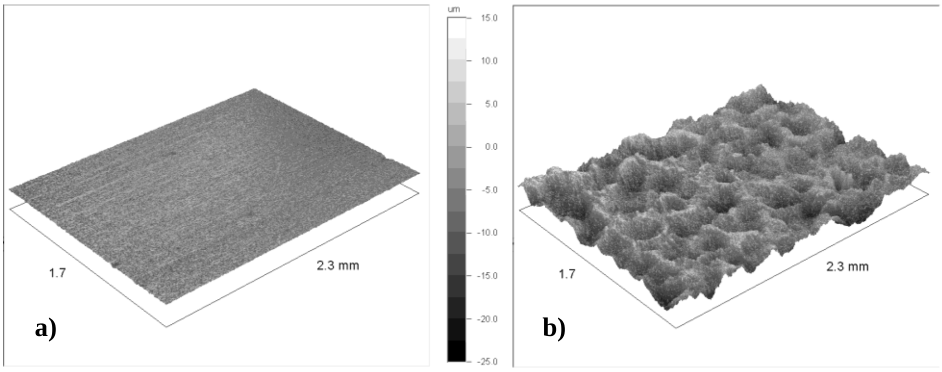


Figure 1. Light inference microscopy images of surface topography of a) LDX 2101 2E brushed surface (S_a = 0.3 µm, b) LDX 2101 VKS blasted surface (S_a = 4 µm).

Table 1. Chemical composition of the stainless steel grades investigated

Steel grade	C [wt%]	N [wt%]	Cr [wt%]	Ni [wt%]	Mo [wt%]	Others [wt%]
1.4301	0.04	-	18.1	8.3	-	-
1.4509	0.025	-	18.0	-	-	0.6 Ti+Nb
HyTens 1000	0.10	-	17	7	-	-
LDX 2101	0.03	0.22	21	1.5	0.3	5 Mn

Table 2. Properties of the stainless steel grades investigated

Steel grade	R_m [MPa]	S_a [µm]	Surface condition	Surface hardness [HV0.05]	Thermal conductivity [W/mK]
1.4301	600	~0.2	2B (cold rolled, heat treated, pickled and skin passed)	190 ± 10	15
1.4509	520	~0.3	2B	220 ± 30	25
HyTens 1000	1000-1150	~0.4	2H (temper rolled with deco rolls to produce a matte finish)	370 ± 50	15
LDX 2101	800	2E: ~0.3 VKS: ~4	2E (Cold rolled, heat treated, mechanical descaling by brushing, pickled) VKS*	280 ± 40 360 ± 30	15

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

Table 3. Chemical composition and properties of the tool steels investigated

Steel grade	C [wt%]	Si [wt%]	Mn [wt%]	Cr [wt%]	Mo [wt%]	W [wt%]	N [wt%]	V [wt%]	Hard phase content [volume-%]	E [GPa]
Vanadis 6	2.1	1.0	0.4	6.8	1.5	-	-	5.4	9% MC 6% M_7C_3	225
Vanadis 10	2.9	0.5	0.5	8.0	1.5	-	-	9.8	16% MC 7% M_7C_3	220
Vancron 40	1.10	0.50	0.40	4.50	3.20	3.70	1.80	8.50	5% M_6C 14% MN	236

Table 4. Properties of the lubricants investigated

Lubricant	Viscosity at 40° C [mm^2/s]	Chlorinated	EP-additive	Environmentally hazardous
Castrol Ilofrom FST 8	200	No	Yes	No
Rhenus Rform 150	150	No	Yes	Yes
Castrol Iloform TDN 81	120	Yes	Yes	Yes
Castrol Iloform PN 226	70	Yes	Yes	Yes

2.2 Experimental procedure

The galling tendency of the selected combinations of stainless steel sheet, tool steel and lubricant was evaluated by pin-on-disc testing using a commercial CSM Tribometer. In the tests, a pin with a diameter of 10 mm and a polished (R_a value in the range of 50-100 nm) 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. The tribological testing was performed under lubricated conditions in ambient air (21-22 °C, 25-26 % RH) using a normal load of 20 N and a relative sliding speed of 0.2 m/s. A lubricant amount of 1 g/m^2 corresponding to a film thickness of approximately 1 µm was applied onto the stainless steel sheet panels. The tests were run for 600 m sliding distance or until the friction coefficient exceeded 0.2 corresponding to galling. During testing the friction coefficient was continuously recorded. All tests were repeated three times, but at different radii, 5, 7 and 9 mm, respectively. It should be noted that with the configuration used the pin is sliding in the same wear track resulting in a repeated contact between the mating surfaces during testing. The different surfaces were investigated both before and after testing using scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX) and light interference microscopy.

3. Results

Figure 2 gives an example of typical friction curves obtained for Vanadis 10 in lubricated sliding contact against the different stainless steel sheets using the Castrol Iloform FST 8 lubricant. As can be seen the stainless steel grades display a significant difference in galling resistance, the austenitic and ferritic grades showing a very low galling resistance while the metastable austenitic grade, being the hardest, shows a relatively high galling resistance. The duplex grade shows a somewhat intermediate behaviour, the blasted surface condition showing the best performance. The duplex grade is also the only one showing a gradual increase in friction coefficient with increasing sliding distance, the other steel sheets show a sudden and very rapid increase in friction coefficient from a low and stable level of µ = 0.15 to a high and unstable level due to cold welding.

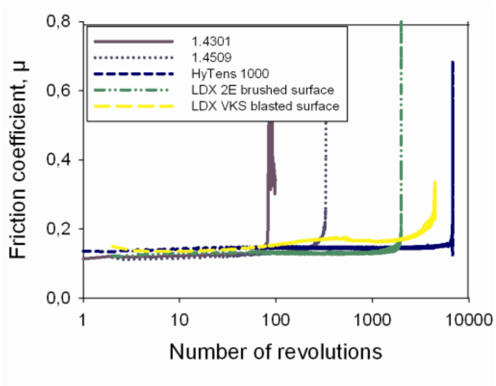


Figure 2. Friction characteristics of the stainless steel grades in lubricated sliding contact with Vanadis 10 using FST 8 as lubricant.

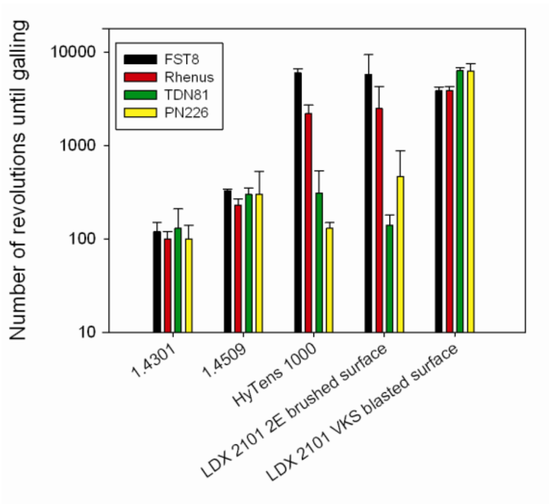


Figure 3. Galling resistance for the different stainless steel grades and lubricants after lubricated sliding contact with Vanadis 10

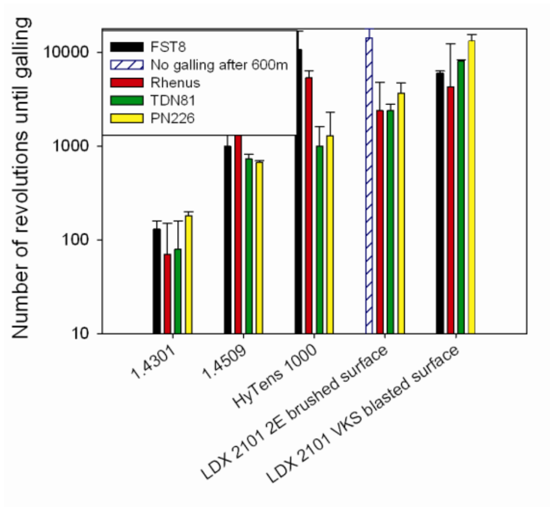


Figure 4. Galling resistance for the different stainless steel grades and lubricants after lubricated sliding contact with Vancron 40.

Figure 3 summarizes the results from the pin-on-disc tests with the Vanadis 10 tool steel. The data presented is the mean value based on the three tests with the standard deviation marked in the figure. Again the austenitic and ferritic grades show a very low galling resistance. For the metastable austenitic and the duplex grades the results are less clear although the blasted surface shows significantly better performance as compared with the brushed surface in the case of the duplex grade. The former steel sheet surface topography also results in a significantly lower scatter for all lubricants investigated. The galling characteristics of Vanadis 6 are very similar to those displayed by Vanadis 10, i.e. no significant differences in galling resistance can be distinguished when comparing these two tool steels.

Figure 4 summarizes the results from the pin-on-disc tests with the Vancron 40 tool steel. When comparing Figs. 3 and 4 it can be seen that Vancron 40 generally performs significantly better than Vanadis 10 and Vanadis 6 (not shown) and that one of the combinations evaluated, (LDX 2E with FST 8) did not resulted in any galling during the 600 m sliding distance.

As was the case for the Vanadis 6 and Vanadis 10 tool steels the influence of type of lubricant is difficult to interpret also in this case.

4. Discussion

Of the stainless steel grades investigated the austenitic (1.4301) and ferritic (1.4509) grades show the lowest resistance to galling. This is most probably due to a low hardness (shear strength at the sliding interface) which promotes superficial plastic flow, fracture and material transfer to the mating tool material surface and thus a stainless steel/stainless steel sliding contact and subsequent galling. For the harder grades the results are more complex although it can be seen that the blasted LDX 2101 steel sheet show the overall best galling resistance. The reason for this is most probably due to the rougher blasted surface which is believed to contain reservoirs keeping the lubricant at the sliding interface promoting necessary lubrication.

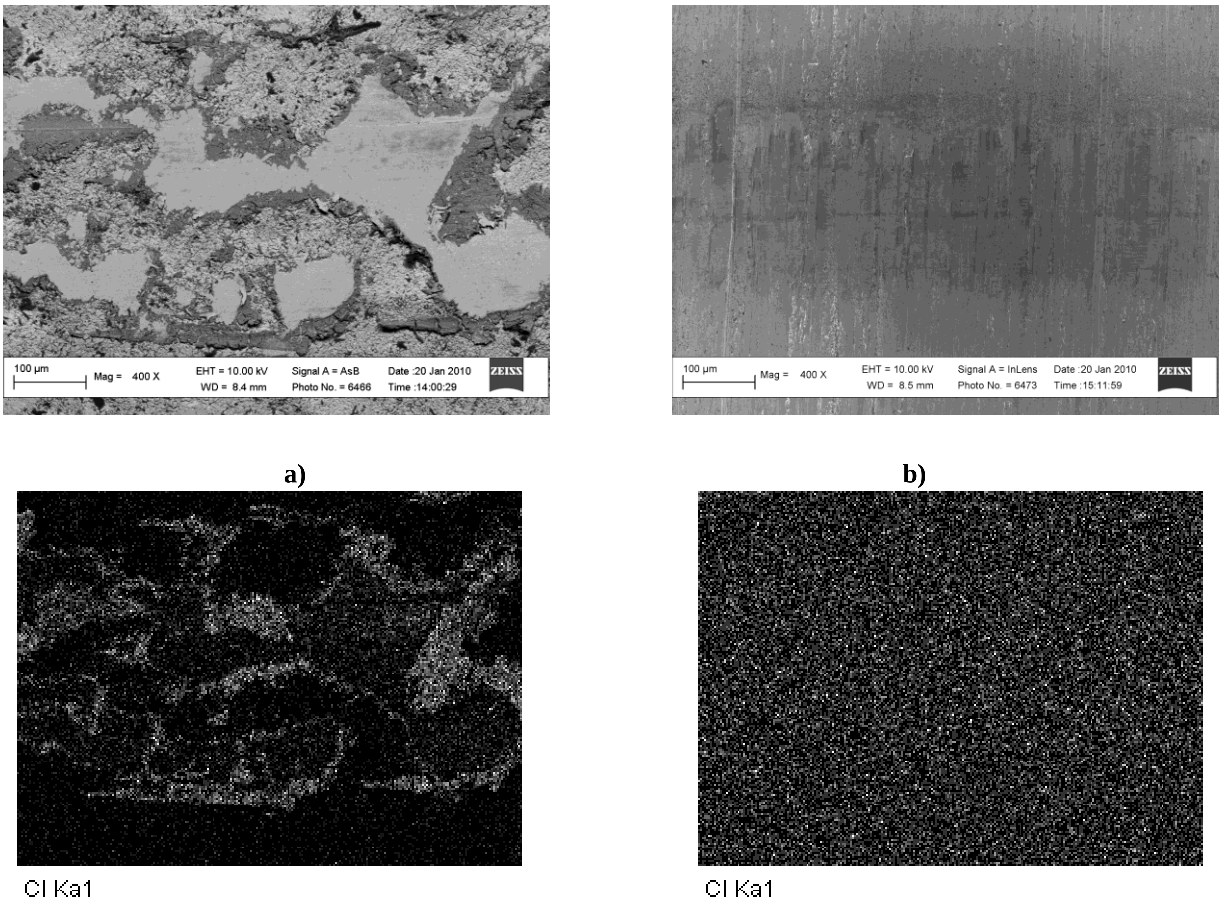
When comparing the different tool steel grades Vancron 40 shows the overall best galling resistance. The Vancron 40 grade also shows a lower scatter and a more robust appearance when comparing the performance of the different lubricants. These results are in good agreement with earlier studies were it has been proposed that the high galling resistance of Vancron 40 is due the well defined microstructure of Vancron 40 with 19 vol.% well distributed sub-micrometer carbide and nitride particles which in a fine-polished surface condition will protrude from the matrix thus inhibit the tendency to metal-metal contact thus preventing cold welding and transfer layer formation. Besides, the low friction properties of VN and V_2O_5 may contribute to this positive effect [10, 11].

When comparing the different lubricants, it is clear that none of the lubricants can provide a sustainable lubricant film for the two stainless steels with lowest surface hardness, i.e. 1.4301 and 1.4509, where extensive cold welding occurs after only a short sliding distance which leads to a rapid increase in friction. The reason for this is most probably due to a more pronounced plastic deformation of the steel sheet surface resulting in a larger nominal contact area (wider wear track) preventing the necessary lubricity at the sliding interface due to the flattening out of lubricant pockets. Although the results indicate that lubricants showing a high viscosity display a higher galling resistance, the results show a disturbingly high scatter which makes the interpretation of the ranking of the lubricants difficult. For example, the two chlorinated lubricants TDN 81 and PN 226 have in other studies proven to be superior compared to other mineral oils [6-8] something which cannot be clearly be seen in the present study. Contamination of the lubricant is one possible explanation for the big scatter.

In order to try to explain the somewhat stochastic behaviour (high scatter) in some of the tests complementary studies were performed in order to evaluate the presence of surface defects (fine scratches) on the steel sheet surface and the tool steel surface on the galling resistance. These tests were performed for the combination HyTens 1000, Vanadis 10 and FST 8 as lubricant using the same test parameters as in the previous tests. The results of these tests show that the presence of fine scratches on the steel sheet surface have no influence on the resulting galling resistance. In contrast, the presence of scratches on the tool steel surface have a significant impact on the galling resistance, i.e. a tool steel surface with a S_a-value of 50-100 nm, 220 nm and 390 nm gives a critical number of revolutions until galling of 7500 ± 1200, 90 ± 30 and 20 ± 1, respectively.

Finally, additional tests where the amount of FST 8 lubricant was increased from 1 to 10 g/m^2 using Vanadis 10 and steel sheet samples of 1.4301, 1.4509 and HyTens 1000 were performed in order to evaluate if a too limited amount of applied lubricant could be the reason for the high scatter for some of the material combinations investigated. The results of these tests showed that the critical number of revolutions until galling increases with approximately 60% but that the scatter, i.e. the standard deviation, remained in the same range. Thus, the reason for the scatter shown in Figures 3 and 4 is most probably due to the presence of surface defects on the tool steel surface. Although the tool steel pins were fine polished using 1 µm diamond in the last step the presence of small surface defects may act as initiation points for pick-up of stainless steel counter material increasing the risk for further material transfer and galling.The fact that the mean values used in the bar charts are based on values at three different radii is also a source of error but it should not affect the results to the extent that it affects the ranking of the different materials.

For the blasted stainless steel sheet the performance of the two lubricants with chlorinated EP-additives is better than the performance of the non chlorinated lubricants. To investigate the reason for this, complementary pin-on-disc tests, using Vanadis 10, the TDN 81 lubricant and the two different types of LDX 2101 steel sheets were performed in which the sliding distance was limited to about ¾ of the critical number of revolutions until galling, i.e. when a friction coefficient of 0.2 was reached. Post-test examination of the two different steel sheet samples using SEM and EDX showed significant differences in chemical composition within the generated wear tracks, see Figure 5. As can be seen, the darker areas within wear track on LDX 2101 VKS steel sheet display a significant amount of Cl which is not the case in the wear track on the LDX 2101 2E steel sheet where the intensity of Cl corresponds to the noise level. Thus, it is belived that the rougher surface topography of the blasted LDX 2101 VKS steel sheet containing a significant amount of lubricant pockets helps supporting the generation of a tribofilm based on the EP-additives of the TDN 81 lubricant which helps preventing a metal-metal contact at the sliding interface. Also, the rougher surface surface topography resulting in smaller contact spots on the steel sheet helps activate the EP-additives of the lubricant and thus tribofilm formation. In contrast, the smoother brushed LDX 2101 2E steel sheet, showing a lower tendency to generate this kind of tribofilm, display a lower galling resistance.



c) d)

Figure 5. a) SEM micrographs of the wear track on LDX 2101 VKS (a) and LDX 2101 2E (b) after lubricated sliding contact against Vanadis 10 using the chlorinated TDN81 lubricant. The EDX maps in Figs c) and d) show the distribution of chlorine within the same areas.

Conclusions

Based on the results in the present study the following conclusions can be made;

A low tool surface topography, Ra < 100 nm or better, is of outmost importance in order to obtain a high galling resistance.

The nitrogen alloyed PM tool steel Vancron 40 show a higher galling resistance as compared with the PM tool steels Vanadis 6 and Vanadis 10.

A high surface hardness of the stainless steel sheet improves the galling resistance.

The surface topography of the stainless steel sheet influences the performance of the lubricant and the generation of galling inhibiting tribofilms.

For the lubricants without any chlorinated EP additives, the lubricant with highest viscosity is the slightly better performing lubricant.

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