The early stage of galling

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Abstract

In sheet metal forming (SMF) of materials such as stainless steels there is a major problem with transfer and accumulation of sheet material to the metal forming tool surface. The problem is known as galling; a kind of severe adhesive wear, which results in severe scratching of produced parts. In this thesis, galling observed in contacts between tool steels and stainless steel sheets under lubricated sliding conditions was studied, focusing on the early stage of galling. It was found that changes in friction cannot be used as galling indicator in the early stage of galling because transfer and accumulation of sheet material happens even though friction is low and stable. The progression of galling is influenced by tool steel damage occurring around the tool steel hard phases caused by sheet material flow, which results in formation of wear-induced galling initiation sites. A correlation between the critical contact pressure to galling and sheet material proof stress was found. Galling happened at lower pressures for sheet material with lower proof stress possibly due to easier sheet material flow, resulting in quicker tool damage. Material transfer and tool steel damage were delayed for tool steels comprising homogenously distributed, small and high hard phases. Additionally, the galling resistance was higher for tool steels with higher hardness due to decreased tool steel damage. In a comparison between observations of the worn tool surfaces after wear tests and calculations in FEM it was found that material transfer did not take place at regions with highest contact pressures but at regions with highest plastic strains. The results obtained in this thesis indicate that tool steel damage and sheet material flow occurring in the contact during sliding are important factors influencing galling.
List of papers

I. Galling resistance and wear mechanisms for cold-work tool steels in lubricated sliding against high strength stainless steel sheets
P. Karlsson, A. Gåård, P. Krakhmalev, J. Bergström
Wear 286-287 (2012) 92-97

II. Galling resistance evaluation of tool steels by two different laboratory test methods for sheet metal forming
P. Karlsson, J. Eriksson, A. Gåård, P. Krakhmalev, M. Olsson, J. Bergström
Lubrication science 24 (2012) 263-272

III. Influence of work material proof stress and tool steel microstructure on galling initiation and critical contact pressure
P. Karlsson, P. Krakhmalev, A. Gåård, J. Bergström
Accepted for publication in Tribology International

IV. Influence of size and distribution of hard phases in tool steels on the early stage of galling
P. Karlsson, A. Gåård, P. Krakhmalev, J. Bergström
Proceedings of the 9th International tooling conference, September 11-14 2012, Leoben, Austria
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Paper I  Major part of planning, experimental work, evaluation and writing

Paper II  Part of planning, experimental work, evaluation and major part of writing

Paper III  Major part of planning, experimental work, evaluation and writing

Paper IV  Major part of planning, experimental work, evaluation and writing
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1 Introduction

Friction and wear are two factors of high importance to control in a mechanical design. Both are studied in tribology; the science and technology of surfaces in relative motion, which also involves lubrication, or lubrication science. Tribology is an interdisciplinary field and many of the tribological theories and models have been developed by researchers in different areas. In the history of tribology, laws of friction were developed and wear was sorted into different wear mechanisms after empirical studies with different laboratory equipments. Nowadays, different types of tribometers are used for wear testing. The tribometers often simulate parts of the otherwise complex tribological system found in real applications. In manufacturing, sheet metal forming (SMF) is an example of a complex tribological system.

The SMF operation is an open tribological system, which means that the same surface on the forming tool slides repeatedly in contact with a fresh sheet surface. Forming the sheet into the desirable shape includes plastic deformation, often under lubricated conditions. SMF can be performed in many ways like deep drawing and stretching. For both deep drawing and stretching, the sheet is clamped between a blank holder and a die and forming of the sheet is made by a punch. However, in stretching, the sheet is not allowed to slide in the blank holder area, which is the case in deep drawing.

A contact between surfaces in relative motion often results in wear of one of the surfaces or both. Depending on different parameters such as sliding speed and contact pressure, the wear is classified into different wear modes. In SMF, two typical wear modes are dominating, namely abrasive and adhesive wear. Abrasive wear is characterized by removal of material by scratching. Scratches may occur due to hard surface protrusions or work-hardened debris particles caught between the surfaces in contact [1-3].

Adhesive wear takes place when material is transferred from one surface to another. The transferred material adheres by adhesive forces and may stick to the countersurface temporarily or permanently. During the sliding, the adhered material may also be work-hardened and thereby cause abrasive wear on the counterbody. Adhesive wear originates at contacting asperities where adhesive bonds may form and during sliding the bonds are torn apart. If the separation takes place in a volume of one of the materials instead of separation at the interface, material transfer can happen. Both adhesive and abrasive wear can be
reduced by proper material selection or separation of the contacting surfaces by lubricants. In SMF, the surfaces are often separated by a lubricant film. However, due to high contact pressures in forming operations, micro contacts between surfaces asperities occur and thus both wear modes described are possible [1-3].

1.1 A brief history of galling investigations

In SMF operations, there is a major problem with transfer and accumulation of sheet material to the tool surface. The problem is known as galling, a kind of severe adhesive wear, which results in high and unstable friction and severe scratching of produced parts, Figure 1. Obviously, this is not acceptable and in order to predict and reduce galling for different tribopairs, further understanding of the galling mechanisms is of high importance for the SMF industry.

![Figure 1. Scratches on a formed product caused by galling.](image)

1.1.1 Galling as a deformation process

Galling has been observed for a long time, but the details are not well understood and generally it is believed that strong adhesion, bonding between surfaces, is required for galling to occur. However, in literature it has been
reported that the material transfer is caused by continuous plastic deformation, adhesion or both [4-6]. For example, in the earlier investigations of galling, Cocks and Antler [7-10] observed the formation and growth of transferred material to a hemispherical ended copper rider sliding against a rotating copper drum, Figure 2. With applied tangential force $F$, surface deformation occurred and with increasing sliding distance a lump, called wedge by Cocks, of transferred material from the drum to the rider. This wedge separated the surfaces and grew in size with increasing sliding distance. Occasionally the wedge broke away but a new wedge was quickly formed and Cocks suggested that strong adhesion was not required for the process of formation and growth of the wedge to occur. Instead, Cocks proposed mechanical interlocking as the reason for the initial surface deformation and material transfer. Further growth of the wedge happened due to accumulation of drum material in front of the wedge in the shearing process and continuous plastic deformation process between the wedge and the drum.

![Diagram](image.png)

Figure 2. The wedge formation according to Cocks [8]. In (a) a force is applied and sliding begins, (b) leads to surface deformation and (c) wedge growth.

Antler [9,10] observed that the formation and growth of the wedge was a result of transfer and build up of counter body material to the rider but also stated that both mechanisms, surface damage observed by Cocks and accumulation of transferred material occurred at the same time. Antler also observed that the wedge occasionally broke off the rider but was quickly formed again with
further sliding. He suggested that the deformation of the wedge was a result of welding of the wedge to the counter body or collision to a high asperity. MacDonald [11] showed that wedges similar to the one Cocks and Antler observed were easily detached from the surface and no sign of adhesion or welding was observed. In later work Schedin [12] proposed that galling is a result of tool surface defects such as scratches caused by hard counter body fragments during sliding or grinding marks from tool surface preparation prior to testing. The tool surface defects acted as galling initiation sites at which fragments of counter body material were transferred and accumulated. Both MacDonald and Schedin proposed the mechanism of interlocking of microscopic asperities to be a possible reason for accumulation of material to the tool surface. Similar to Cocks and Antler, Schedin also observed that fragments of accumulated material on the tool surface were occasionally back-transferred to the surface of the counter body. Depending on authors, the piece of the transferred material has different names such as wedge, prow and lump or whatever name is given to the shape, its formation seems to be of fundamental importance for the galling process.

1.1.2 Galling as an adhesion process

So far the galling process has been described as a deformation process with little or no focus on adhesion. However, it was previously mentioned that adhesion is believed to be an important factor in the galling process. From the adhesion theory of friction and wear, Tabor developed a model of junction deformation [13]. This model has been the base for many authors’ contribution and development of the understanding of the influence of adhesion on galling [3,13,14]. The model is based on the fact that when two solids are pressed against each other, the contact does not take place over the whole area, but at a few local regions (junctions) i.e., interacting surface asperities. Tabor showed that by applying normal and tangential stresses, the real area of contact increases and the growth of this area is a function of the interface friction coefficient. Junction growth continues until slip happens at the interface or fracture occurs and material transfer is initiated and typical pattern of adhesive wear can be observed. In Tabors model it can be seen that the severity of the interface friction depends on the size of the transferred material.

Experiments with extensive focus on the deformation mechanism of junction interaction was performed both prior to the development of Tabors model and
after that. Greenwood and Tabor \[15\] for example studied machined junctions and Green \[16,17\] used plasticine to study the deformation process. The results from asperity interactions in these models, observed by optical microscopy, were used for theoretical calculations and development of the weld-junction theory of friction \[18\]. In studies of asperity interaction of austenitic stainless steel, Kayaba and Kato \[19\] found two kinds of adhesive transfers which they named slip tongue and wedge transfer. The latter was observed behind the junction and slip tongue in front.

1.1.3 The definition of galling and recent galling studies

With time, the theories for galling based on adhesion and deformation began to interconnect and the definition of galling formulated in ASTM G40 standard was defined. The ASTM G40 defines galling as a form of surface damage arising between sliding solids, distinguished by macroscopic, usually localized, roughening and creation of protrusion above the original surface; it often includes material transfer, or plastic flow, or both \[20\]. Today, the scientific tools such as scanning electron microscope and transmission electron microscope can reach much higher resolution compared to the microscopes used in times of Cocks and Antler, which enables analysis of galling at micro and nano scales. Other advanced instruments for surface characterization like atomic force microscope allows for surface analysis with nanoscale resolution. This has resulted in further understanding and development of surface asperity interaction models \[21-31\].

The early studies of galling were performed on pure metals. In the modern industry, however, the materials are more advanced as for example high alloyed steels. The new materials have more complicated microstructure and higher properties compared to the pure metals. This makes galling studies more complex and it is, therefore, not certain if the old models and theories of galling apply for materials other than pure metals.

In recent years, great effort has been put into the development and evaluation of new tool materials, tool design and tool surface preparation to reduce problems associated with galling \[31-38\]. Among recently developed tool steels, nitrogen alloyed powder metallurgy (PM) tool steels attracted interest due to enhanced galling resistance \[37,39\]. However, the initiation of galling for these new and more advanced materials is not thoroughly understood and different
initiation mechanisms related to adhesion, surface defects, tool steel microstructure, efficiency of lubricant and temperature have been proposed [12,37,40-47]. Thus, further tests must be performed for the new and more advanced material in order to evolve the knowledge of galling and mechanisms involved in galling initiation.

2 Materials

2.1 Tool steels

There are many requirements on the tools used in SMF today. The tools must have high wear resistance and resist failure due to chipping, cracking or plastic deformation. The introduction of high strength sheet materials and additional requirements to use less lubricant in SMF further increase the demands on the tool steels. Therefore, new tool steels with higher wear resistance under tougher conditions must be developed.

In the American Iron and Steel Institute (AISI) classification system, tool steels are arranged into groups based on application, alloying elements and heat treatments [48,49]. Cold-work tool steels used for SMF operations include ingot cast and forged steels. These tool steels are divided into three categories, oil-hardening (O), air-hardening medium-alloy (A) and high-carbon, high-chromium (D) cold-work tool steels. All three types of cold-work tool steels were developed to provide high wear resistance, hardness and fracture toughness. These properties are provided by primary carbides and a tempered high-carbon martensite. Typical heat treatment is hardening and repeated tempering to remove retained austenite and reach required hardness-toughness combination. Additionally, the high alloy content in the steels provides high hardenability.

New and more advanced tool steels are the powder metallurgy (PM) tool steels. These steels comprise much finer and homogenously distributed hard phases compared to the conventional ingot cast cold-work tool steels. Additionally, some PM tool steels have enhanced adhesive wear resistance and, therefore, these steels are very promising tool materials for SMF operations. However, the adhesive wear resistance or galling resistance for the PM tool steels is not thoroughly investigated yet. Also, the influence of the finer tool microstructure on the PM steels wear resistance, compared to conventional ingot cast tool
steels, on galling is not clear. It is, therefore, of high interest for the SMF industry to evaluate the galling resistance of the PM steels in comparison with conventional ingot cast tool steels using work materials which are prone to galling, such as stainless steels.

In order to investigate the influence of tool microstructural features such as size and distribution of hard phases on galling, three different tool steels were chosen for galling evaluation in this thesis work. The materials were an ingot cast AISI D2 type tool steel, commercially available as Sverker 21, and two types of nitrogen alloyed PM tool steels P1 and Vancron 40, Figure 3 and Table 1-2. P1 is still in development stages and Vancron 40 is commercially available as Uddeholm Vancron 40. In Sverker 21, M7C3 carbides of approximately 5-20 µm in length often form elongated clusters. P1 comprises small and homogenously distributed M(C,N) carbonitrides of approximately 2-4 µm in diameter. Additionally to the carbonitrides, the Vancron 40 tool steel contains M6C carbides of similar size, Figure 3. Austenitizing temperature of approximately 1050°C and 1020°C with holding time of 30 min and tempering at 525°C for 2x2 h and 560°C for 3x1 h were used to achieve the hardness of the Sverker 21 and PM tool steels, respectively. Prior to wear tests, the tool materials were ground and then polished to a surface roughness of approximately R, 0.05 µm, Table 2.
Figure 3. Microstructure of tool steel P1 (a), Vancron 40 (b) and Sverker 21 (c).

Table 1. Chemical composition of the tested tool steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>Chemical composition [wt %]</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>N</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td></td>
<td>1.1</td>
<td>4.5</td>
<td>3.2</td>
<td>0.6</td>
<td>2.6</td>
<td>12</td>
</tr>
<tr>
<td>Vancron 40</td>
<td></td>
<td>1.1</td>
<td>4.5</td>
<td>3.2</td>
<td>3.7</td>
<td>1.8</td>
<td>8.5</td>
</tr>
<tr>
<td>Sverker 21</td>
<td></td>
<td>1.5</td>
<td>12</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 2. Material properties of the tested tool steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>Hard phase [Vol. %]</th>
<th>Hardness [HRC]</th>
<th>Rₐ [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>19% M(C,N)</td>
<td>64 HRC</td>
<td>0.05</td>
</tr>
<tr>
<td>Vancron 40</td>
<td>5% M₆C, 14% M(C,N)</td>
<td>61 and 65 HRC</td>
<td>0.05</td>
</tr>
<tr>
<td>Sverker 21</td>
<td>13% M₆C₃</td>
<td>60 HRC</td>
<td>0.05</td>
</tr>
</tbody>
</table>
2.2 Sheet material

In SMF, there are several typical classes of sheet materials or work materials such as carbon steels, titanium alloys and stainless steels. The choice of sheet material depends on the application area of the final product. Stainless steel is often used in applications where the material must have high corrosion resistance, high strength and good formability. These material properties are wanted in a large variety of application areas and the nowadays stainless steel products can be used in kitchen sinks, washing machines, watches, automotive parts, chemical and medical tools etc. In the automotive industry stainless steels are a promising material for crash bumpers due to the good combination of strength and ductility. However, stainless steels are prone to galling. Therefore, it is of high importance to the SMF industry to gain more knowledge of galling mechanisms for different stainless steel types in order to prevent galling in SMF operations.

By definition, stainless steel has high corrosion resistance. The resistance to corrosion is provided by the high content of chromium in the material, at least 12 wt\%, which allows for a passive film of chromium oxide to form on the surface. Although this film is very thin, only a few nanometers in thickness, it effectively protects and passivates the steel in corrosive environments [49,50]. There are four major types of stainless steels; austenitic, ferritic, duplex and martensitic.

The austenitic stainless steels are non-magnetic and have an fcc crystal structure. The steel contains typical fcc-stabilizing alloy elements such as nickel and manganese. This group has excellent weldability, impact strength and high work-hardening capability. The majority of stainless steel used in applications today is austenitic stainless steels and typical application areas are kitchen sinks, chemical tanks, food processing equipment etc [49-51].

The ferritic stainless steels are magnetic and have a bcc crystal structure. Compared to the austenitic grades, the ferritic stainless steels have slightly higher strength and thermal conductivity but less weldability and corrosion resistance. Additionally, the ferritic types are not susceptible to stress corrosion cracking. Even though chromium is the main alloy element, molybdenum and niobium is sometimes added to improve the corrosion resistance and weldability of the steel. The ferritic stainless steels are often used in application
areas like catering and appliances, vehicle exhausts, fuel lines, architectural trim and household electrical devices [51,52].

Duplex stainless steel contains two phases, austenite and ferrite and thus combines the material properties of the austenitic and ferritic steels. However, the strength of the duplex types is higher than the strength of ferritic and austenitic stainless steels. Application areas of duplex stainless steels are for example building and construction, heat exchangers, marine applications and chemical and petrochemical plants [49,50,52].

Martensitic stainless steels are stronger, through martensitic hardening, than the other types of stainless steels. However, martensitic structures have low ductility and, additionally, the corrosion resistance and weldability are lower for martensitic stainless steels compared to other stainless steel types. Application areas of martensitic stainless steels are for example knife blades, springs, shafts, fasteners and surgical instruments [50-52].

As described, there are several stainless steel types, each of them with different physical and mechanical properties. The influence of these material properties on galling is not clear and, therefore, it is important to include the major stainless steel types in the galling studies. This was performed in this study and the tested sheet materials were stainless steel type EN 1.4301 (austenitic), EN 1.4509 (ferritic), EN 1.4162 (duplex) and EN 1.4310 C1000 (metastable austenitic), Table 3-4. The austenitic and the ferritic sheet materials had a 2B surface finishing (cold rolled, pickled and skin passed). The surface finishing of the duplex and the metastable austenitic stainless steel sheets were 2E (cold rolled, pickled and mechanical descaling by brushing) and 2H (temper rolled) surface respectively, Figure 4. Prior to wear tests, the sheet materials were cleaned with degreasing agent and ethanol before 5 g/m² of Castrol FST-8 lubricant was applied. In the wear tests, sliding occurred parallel to the rolling texture of the sheets, Figure 4.
Table 3. Chemical composition of the tested steel sheets

<table>
<thead>
<tr>
<th>Steel</th>
<th>Chemical composition [wt %]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 1.4301</td>
<td>0.04 18 - - 8.1 -</td>
</tr>
<tr>
<td>EN 1.4509</td>
<td>0.02 18 - - - NbTi</td>
</tr>
<tr>
<td>EN 1.4162</td>
<td>0.03 21.5 0.3 0.22 1.5 5 Mn</td>
</tr>
<tr>
<td>EN 1.4319 C1000</td>
<td>0.10 17 - - 7 -</td>
</tr>
</tbody>
</table>

Table 4. Material properties of the tested steel sheets

<table>
<thead>
<tr>
<th>Steel</th>
<th>Structure</th>
<th>Rp_{0.2} [MPa]</th>
<th>Hardness [HV0.05]</th>
<th>R_s [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 1.4301</td>
<td>Austenitic</td>
<td>300</td>
<td>170±10 HV0.05</td>
<td>0.2</td>
</tr>
<tr>
<td>EN 1.4509</td>
<td>Ferritic</td>
<td>360</td>
<td>180±5 HV0.05</td>
<td>0.2</td>
</tr>
<tr>
<td>EN 1.4162</td>
<td>Duplex</td>
<td>600</td>
<td>270±30 HV0.05</td>
<td>0.3</td>
</tr>
<tr>
<td>EN 1.4310 C1000</td>
<td>Metastable austenitic</td>
<td>900</td>
<td>360±30 HV0.05</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 4. Surface finish of the austenitic (a), ferritic (b), metastable austenitic (c) and duplex (d) steel sheet. The arrows indicate the direction of the cold rolling surface texture from the manufacturing process.
3 Galling tests

There are several ways to test the galling resistance of materials. Since it is not economical to run full scale industrial tests, laboratory galling tests are performed. In laboratory tests, tribometers are used to simulate the contact situation in real applications such as sheet metal forming operations. The laboratory tests are simplified versions of real applications but the wear mechanisms occurring in the contact during tests should be the same as in real forming operations. The advantages with the laboratory tests are that they, generally, are fast and cheap and process parameters such as load, sliding velocity and contact geometry can be varied in a controlled manner. Other than the process parameters, the tribometers also represent different tribosystems such as open and closed systems. In closed tribosystems, the same surfaces are in contact throughout the tests. In real applications, this contact system is found in for instance camshafts in car engines. In open tribosystems, at least one surface is always in contact with a fresh counterbody surface, similar to the contact situation in SMF operations [52].

3.1 Slider-On-Flat-Surface (SOFS)

The SOFS tribometer represents an open tribosystem where the tool is slid against a fresh sheet surface. The tribometer is used to simulate wear in SMF and it is possible to test the galling performance of different material combinations at different operation parameters. In the tribometer, a double-curved disc made of tool steel is fixed to prevent rotation and thereafter the disc is pressed and slid against a real sheet surface. The disc is slid up to 1 m stroke length in one direction and at the end of the sheet the disc is released from the sheet surface and moved back to the point of origin. After a small shift perpendicular to the sliding direction, the disc sliding movement is reiterated against a fresh sheet surface, Figure 5. One km sliding distance can be reached on 1 m² sheet surface and the progression of wear can be analyzed in the reiterated slides on the sheet surface. The range of applicable sliding speeds and normal loads are 0.01-1 m/s and 5-800 N respectively.
3.2 Pin-On-Disc (POD)

Other tribometers that are commonly used in galling tests are for example POD [53]. For POD testing, a pin with a hemispherical shaped end is loaded against a rotating disc, Figure 6. In galling tests using POD, the pin is made of tool steel and the disc is cut out from a sheet. The pin slides in the same wear track during wear tests and the test configuration in POD results in a repeated contact between the mating surfaces. Thus, the POD represents a closed tribosystem. Normal loads are controlled by dead-weights and the pin can be configured to slide against the disc at different radius, but then the sliding velocity will be different. The range of applicable normal loads and sliding speeds are 0.1-60 N and 0.3-1600 rpm respectively. Galling tests can be performed with a controlled amount of lubricant, applied to the disc prior to test, or both the pin and the disc can be completely submerged in lubricant. Additionally, the disc can be heated up to approximately 1000°C during or prior to tests.
3.3 Comparison of two tribosystems (Paper II)

Galling investigations were done using both open and closed tribosystems. In order to investigate the influence of the type of tribosystem on galling, two different tribosystems were used for the evaluation of the galling resistance of two types of tool steels sliding against a ferritic stainless steel type EN 1.4509 under lubricated sliding condition [53]. The tested tool steels were Sverker 21 and Vancron 40 tested with hardness 61 HRC and 65 HRC.

In the study, the SOFS and POD tribometer represented an open and closed tribosystem respectively [53]. The latter resulted in a quick friction rise when material transfer from the sheet to the tool occurred, Figure 7. Additionally, galling occurred at lower contact pressures and shorter sliding distances in the closed system compared to the open system, Figure 8. The differences observed between the two different wear tests regarding sliding distance to galling and friction characteristics may be related to the fact that SOFS and POD are different types of tribosystem. The POD is a closed system where the tool slides in the same wear track during the whole wear test. In this type of tribosystem work hardening of the worn sheet surface occurred.
Figure 7. Typical friction diagram for the closed (POD) and open (SOFS) tribosystem.

It is possible that the amount of lubricant applied prior to the wear test decreased or was pushed away from the contact zone by the tool during wear tests. In such a tribosystem the friction would change rapidly when the lubricant layer is broken. Therefore, the possibly decreased amount of lubrication in the contact zone probably triggered the onset of galling, which was observed as a sudden change in friction for POD, Figure 7.

The SOFS is an open tribosystem, where the tool always meets a fresh sheet surface. Thus, the amount of lubricant is more or less constant during the tests. Therefore, the progressively increased friction during wear tests is probably best explained by a well lubricated contact zone and gradually transferred sheet material to the tool surface. Similar behavior was observed in galling tests with other materials [54-56].

The results show that galling happen at higher contact pressures and a longer sliding distance in the SOFS compared to the POD tester for the same material combinations and parameters, Figure 8. Even though there are differences in critical sliding distance to galling, both equipments provided the same ranking of the tested steels. The PM tool steel Vancron 40, treated to hardness of 65 HRC showed better galling resistance comparing to the other tool steels. It has
been shown that scratches and other surface damages might act as initiation sites for galling [57]. Thus, a possible explanation to the better performance of the harder PM tool steel could be less damage to the tool steel surface due to enhanced resistance to scratching with higher tool steel hardness [56]. The cause for scattering in wear test data is believed to be due to tool surface defects such as fine scratches. With a smaller contact area, the POD system was more influenced by surface defects than the SOFS system which resulted in higher scattering of wear test data.

![Figure 8. Wear test results for the two different tribosystems.](image)

The two different laboratory test equipments provided a good base for quick ranking of tool materials in terms of galling resistance under lubricated conditions. Similar results of the tested tool steels have been observed by others and factors like hardness, carbide distribution etc. are believed to influence the galling resistance [35,46,56,58]. The SOFS test resembles a sheet metal forming operation better than the POD test since it is an open system were the tool continuously meets fresh sheet material, which is the case for most cold forming operations. On the other hand, the SOFS test requires larger amounts of test material compared to the POD test. Nevertheless, both methods are possible alternatives for investigations of whether a selected combination of sheet- and tool material or lubricant will work well in a real sheet metal forming application with respect to galling. Additionally, both methods are much faster and economical than performing semi-industrial forming test.
4 Finite element (FE) modeling

FEM is often used to calculate parameters like contact pressure, plastic strain and springback in SMF. In SMF, highest contact pressures are generally developed at the die radius. However, as has been shown in [59-61], the pressure varies along the die radius with two characteristic maxima. Therefore, the contact conditions are rather complex since different wear mechanisms might occur at different locations of the tool due to different contact pressures. In [62,63], FEM has been used to calculate contact pressures for several real forming applications. The range of pressures reported was 0.6-1.3 GPa.

The contact situation in FEM is usually simplified compared to the complex situation in real forming operations and parameters such as surface roughness are often neglected or simplified. Nevertheless, FEM is a valuable tool to estimate the contact pressure in correlation to factors like the mechanical properties of the materials and the geometry of the tool. The contact area, and thus contact pressure, is influenced by the mechanical properties of the sheet material during plastic deformation. Therefore, contact pressure is a more suitable parameter compared to load when several materials with different mechanical properties are to be tested and compared.

4.1 FE- modeling of the contact between the tool and sheet in SOFS (Paper II-IV)

Contact pressures in SOFS were calculated using a 3D finite element model with loading in the z-direction, Figure 9. In the model, the tools were regarded as elastic and the sheets as elastic-plastic von Mises materials with strain hardening according to tensile test data supplied by the producer. The sheet and the tool were modeled with symmetry according to Figure 9 (a), using 10-node modified quadratic tetrahedron (C3D10M) elements with hourglass control and refined mesh in the contact area, Figure 9 (b). Based on experimental data before the onset of galling, a coefficient of friction of 0.1 was used in the model.
The FE-model was also used to investigate the influence of sliding under static load on the contact pressure and plastic strains, Figure 10. The disc representing the tool was pressed and slid against the sheet material and the FEM calculations were correlated to experimental results [64].

Figure 9. FE-model (a-b) and a typical contact pressure contour plot (c).

Figure 10. FE-model with sliding motion included. Overview of the model (a) and close-up of the mesh in the contact area (b).
As seen in Figure 11 (b), highest pressures in SOFS are developed in the centre of the contact. However, highest plastic strains are found in the periphery of the contact, Figure 11 (a). From SEM observations of the tool surface after interrupted tests in SOFS, Figure 11 (c), it is seen that sheet material is initially transferred and accumulated at the outer part of the contact zone.

The importance of contact pressure on galling has been discussed many times in literature and a criterion of critical contact pressure for galling initiation has been suggested [62,63]. Nevertheless, in this investigation it was found that material transfer initiates not in areas of highest contact pressure but in areas of highest plastic strain in the sheet. The present results, therefore, indicate that contact pressure is not the only factor controlling material transfer and the galling problem should be reconsidered taking into account factors of plastic strains of sheet material.

Figure 11. Plastic strain (a) and contact pressure (b) results from the FEM calculations. Top view and cross sectional view of the sheet is presented in (a) and top view only in (b). Transferred material to the tool surface after tests in SOFS is presented in (c). Arrows indicate the sliding direction of the tool.
5 Galling mechanisms and typical stages of galling

5.1 Typical stages of galling (Paper I-III)

During wear tests in SOFS, friction is continuously recorded. Figure 12 illustrates a typical friction diagram for the Sverker 21 and the Vancron 40 tool steels after tests under lubricated sliding against the duplex stainless steel sheet at 500 N normal load [56]. The diagram shows three different typical frictional stages observed for all materials at lubricated sliding at all selected pressures. The first stage was characterized by stable friction. Subsequently, friction started to increase at stage two. Further sliding led to the onset of stage three, with high and unstable friction.

The changes in friction correlated to different tribological behavior in each stage, Figure 13. In addition to friction data, the correlation was revealed by analysis of the contact areas of the sheet and tool discs in SEM after the wear tests. In stage I, early material transfer resulted in an adhered thin layer of sheet material on the disc surface, Figure 13 (a). On the counter-surface, sheet surface flattening was observed, Figure 14 (b). The transfer layer did not cause any changes in friction, because as it has been suggested in [12,40] the initial thin layer of adhered sheet material on the tool surface might be unstable and could, therefore, be back-transferred from the disc to the sheet.
Further sliding led to a transition of wear mechanisms and the transferred material formed microscopic lumps on the tool steel surface, Figure 13 (b). The lumps caused scratching or microscopic plowing of the sheet surface, which was indicated by an increase of the coefficient of friction. In the present study, this mechanism was observed for tests against stainless steels as work material, but similar mechanisms have been reported for other tool steels and sheet materials [40,56,65]. The scratches on the sheet in this stage, Figure 14 (c), were beyond industrial acceptance and, therefore, the beginning of this stage was used as indication of galling. An increase of the coefficient of friction by 0.05 from the initial value was used as galling indication in the wear tests.

Figure 13. Typical stages of transfer and accumulation of sheet material on the disc surface. Arrows indicate the sliding direction of the disc.

At stage III, a typical pattern for severe adhesive wear was observed on the sheet surface, Figure 14 (d). In this stage, complete coverage of the disc contact area by transferred and adhered sheet material in the shape of a macroscopic wedge was observed, Figure 13 (c), resulting in high and unstable friction, Figure 12. This situation corresponds to the standard definition of galling ASTM G40 [20], which has been observed for other wear tests [20,53,66]. In this stage, the microstructural features of the tool steel hardly influence the galling. Therefore, the wear mechanisms at stage I and II and the
transformation between them are of high interest for understanding of the influence of tool steel microstructure on galling origination.

Figure 14. 2D depth profile (a) and 3D surfaces (b-d) of the track surface at the typical stages of galling. Arrows indicate the sliding direction of the tool.
5.2 Influence of the tool steel microstructure on galling origination (Paper I-IV)

As described, transfer of sheet material to the disc surface occurs already in stage I. In tests against the ferritic stainless steel, for example, the transferred layer was observed after 2 m and 50 m sliding distance for the Sverker 21 and Vancron 40 tool steel respectively, Figure 15 [64]. The thin layer was observed on the hard phases and matrix for both tested tool steels. Additionally, scratching of the matrix was observed for the Sverker 21 tool steel.

![Figure 15. Worn surface of the Sverker 21 steel (a) after 2 m sliding distance and 50 m sliding distance for the Vancron 40 steel (b). Arrows indicate the sliding direction of the tool.](image)

After sliding distances of 5 m and 70 m for the Sverker 21 and Vancron 40 tool steels respectively, analysis of the disc surfaces showed that the surfaces was damaged. The tool steel matrix was worn around the hard phases resulting in formation of wear-induced galling initiation sites located around carbides. The typical damaged areas are shown in Figure 16 for the tested tool steels after interrupted tests [67]. As seen in Figure 16 (a-b), the damage was more pronounced for the Sverker 21 steel, which had slid for only 5 m while the PM material Vancron 40 had slid for 70 m.
Although the damaged matrix areas were observed for both tested tool steels, the disc surface damage was observed after longer sliding distance for the Vancron 40 steel. Better performance can be a result of the difference in hard phase size and distribution. Similar trend has been reported for other tool steels in [46,56,68]. In [68] for example, tool steels with higher carbide content and shorter average distance between the carbides, displayed an enhanced adhesive wear resistance of the tool in sliding wear tests against an austenitic stainless steel. It was assumed that the adhesion to the tool matrix was the dominating mechanism in galling initiation [68]. The increased adhesive wear resistance of the tool steels with higher carbide content was thus explained by less contact between the matrix and the work material with shorter distance between the tool steel carbides. Additionally, in [68] the tool steels with highest carbide content and carbides in clusters showed a decreased adhesive wear resistance of the tool. Thus, not only carbide content but also a fine size and homogeneous distribution of the carbides enhanced the adhesive wear resistance of the tool steel.

Figure 16. Tool surface damage caused by sheet material flow, resulting in wear-induced galling initiation sites for the Sverker 21 (a)-(b) and Vancron 40 (c) tool steels. Arrows indicate the sliding direction of the tool. The sliding distance was 5 m for the Sverker 21 steel and 70 m for the PM steel Vancron 40.
In the present study, the Vancron 40 material comprises small and homogeneously distributed $M_6C$ carbides and $M(C,N)$ carbonitrides, each of them of approximately 2-4 µm in size. The Sverker 21 steel comprises clusters of elongated $M_7C_3$ carbides of approximately 5-20 µm in length. The size and distribution of hard phase in Sverker 21 results in a longer average distance between the carbides compared to Vancron 40, Figure 3. Therefore, the Sverker 21 tool steel with more open matrix areas is susceptible to scratching and material transfer due to adhesion. It was observed that for Sverker 21, Figure 15 (a) and Figure 16 (a-b), wear to the matrix was more pronounced. In the PM tool steel Vancron 40, only moderate disc surface damage was observed. Thus, transfer and accumulation of sheet material was probably accelerated at the damaged areas of the Sverker 21 tool steel and therefore galling starts earlier due to the bigger size and inhomogeneous distribution of carbides.

Surface analysis by atomic force microscopy (AFM) of the Sverker 21 and Vancron 40 steels showed that the microstructure of the materials not only differed in size and distribution, but also in height of the hard phases [64]. Even for very fine polished specimens, the hard phase of Sverker 21 was lower than the hard phases of Vancron 40, Figure 17-18.

![AFM height scan of the Sverker 21 (a) and Vancron 40 (b) tool steel.](image)

Figure 17. AFM height scan of the Sverker 21 (a) and Vancron 40 (b) tool steel.

It was found that the average height of the hard phase in the Sverker 21 steel was approximately 7 nm, Figure 18 (a). In the Vancron 40 steel, the peak value of hard phase heights was approximately 15-20 nm, Figure 18 (b). However, the height distribution for the Vancron 40 steel was broader and more asymmetric.
which indicate a larger scatter in hard phase heights in the Vancron 40 steel compared to the Sverker 21 steel. These results were obtained using AFM height scans in tool surface areas of approximately 30 μm², and the results are in good agreement with AFM data presented in [46,69].

Differences in height of hard phases may influence on the work material transfer. For the PM steel Vancron 40, the transferred material was more pronounced on the M(C,N) carbonitrides, Figure 15 (b). Possible explanations to this experimental observation are differences in heights or adhesion to stainless steel for the two different hard phases in the PM tool steel. If the M(C,N) carbonitrides are higher or have higher adhesion to stainless steel compared to the M₆C carbides, the sheet material would, to a larger extent, cover the M(C,N) carbonitrides as was observed, Figure 15 (b). In addition to the size and distribution of hard phases, it is possible that the higher hard phase particles in Vancron 40 prevented the contact between the sheet and the tool matrix and thus delayed galling. It has been shown that the damaged areas of the tool matrix as a result of scratching act as galling initiation sites where the transferred sheet material accumulates [12]. Experimental observations in Figure 15 (a) and Figure 16 (a-b), showed that scratching of the tool steel matrix was more pronounced for the Sverker 21 steel and the material transfer was probably accelerated at these damaged areas, which resulted in coverage of matrix and hard phases at shorter sliding distance compared to Vancron 40.

Figure 18. Hard phase height distribution of the Sverker 21 (a) and Vancron 40 (b) tool steel from AFM height scans.
In addition to the factors mentioned so far, hardness of the tool material also influenced the galling resistance of the tool steel [53]. In tests against the duplex stainless steel sheet, for example, the PM tool steel Vancron 40 with higher hardness showed better performance, Figure 19 [56].

![Figure 19. Sliding distance to galling diagram.](image)

From SEM analysis of the worn disc surfaces it was concluded that tool damages occurred by scratching of the tool surface and transfer of sheet material to the tool surface due to adhesive wear of the sheet. A possible explanation to the increased galling resistance of the harder Vancron 40 steel is an increased resistance to the tool steel matrix damage with higher tool steel hardness.

5.3 The influence of sheet material proof stress on the critical contact pressure to galling (Paper III)

Galling is associated with material transfer, or plastic flow, or both and, therefore, mechanical properties of the sheet materials are of importance since they influence galling. In order to study the influence of sheet material strength on the critical contact pressure to galling, the Sverker 21 and Vancron 40 tool steels were tested against four different types of stainless steel sheets under lubricated sliding conditions [67]. The tested sheet types were austenitic, ferritic, duplex and metastable austenitic. Results of the wear tests are summarized in Figure 20. In Figure 20 (a), the finite element calculated contact pressures are plotted against the total sliding distance to galling. The tests were started at a high contact pressure and if galling was detected within the selected sliding distance of 200 m, the pressure was decreased and tests were run again. This
procedure was repeated until galling did not occur before 200 m sliding distance. The highest contact pressure at which galling was not detected was defined as $P_{cr}$, the critical contact pressure. The critical pressure values are marked with open markers in Figure 20 (a) and are used in the diagram in Figure 20 (b).

To correlate tribological performance to mechanical properties of the sheet materials, critical contact pressures for each tool-sheet pair were plotted versus proof stress of sheet materials, Figure 20 (b). The trend for both tool steels was the same; the critical contact pressure increases with increasing proof stress of the sheet materials. The trend lines in Figure 20 (b) can be interpreted as the border between safe and unsafe test conditions. If the contact pressure in a selected tribo-couple overcomes the critical value, galling occurs within 200 m sliding distance, otherwise galling is not detected.

![Figure 20. Wear test results as a sliding distance to galling diagram (a) and critical contact pressure diagram (b).](image)

It has been suggested that critical pressure or galling threshold pressure may be used to assess metal forming operations and predict galling [62,63]. The performance of Uddeholm Vancron 40 tool in forming of austenitic stainless and carbon steel has been summarized and shown that galling occurs if contact pressure in forming operations overcomes a critical value. Additionally, a linear dependence between the work material’s yield strength and the critical contact pressure for galling has been reported [62,63]. Unfortunately, wear mechanisms have not been investigated and the origin of the transition has not been
explained. Similar linear-type dependence between the sheet steel proof stress and critical contact pressure was displayed in the present study for the two different tool steels and four different stainless steels, Figure 20 (b).

In the tests run at overcritical contact pressures, a stage of unstable friction and formation of a macroscopic lump was observed for all tested material pairs in 200 m distance. Analysis of cross sections made through the lump and disc showed that the tools were worn, Figure 21.

Figure 21. Cross section of the Sverker 21 tool steel after tests against the ferritic sheet (a-b) at 200 N and at 700N against the duplex sheet (c). The arrow indicates the sliding direction of the tool.

In literature it was found that the tool wears by the sheet material if the tool to the sheet hardness ratio is less than 2 [70]. Microhardness measurement showed that the adhered sheet material is harder compared to non-deformed sheet steel and, therefore, hardness ratio may approach and decrease below the critical value of 2 so that the sheet material may scratch the tool surface. For wear tests performed at contact pressures below the critical value, only minor damage to the matrix of the tool steel surface was observed for both tool steel types tested. Also, the coefficient of friction was stable about 0.07, indicating that after 200 m sliding distance, stage I with minor material transfer and sheet surface flattening is still not passed.
The obtained results allow developing a concept interconnecting contact pressure and proof stress of the sheet steel with galling initiation mechanisms for evaluation of tool-sheet steel couples’ performance. The concept may be formulated in terms of critical contact pressure, $P_{cr}$, and governing critical tool wear within the selected sliding distance for each selected couple of tool and sheet steel. At $P < P_{cr}$, due to plastic flow of sheet material, the tool is worn moderately but not enough to initiate formation of microscopic lumps on the surface. At $P > P_{cr}$, the tool is damaged substantially and wear-induced matrix damage causes quick formation of the lump.

For selected $P_{cr}$, sheet material with lower proof stress is extensively plasticized and causes significant tool surface damage initiating galling. Steels with higher proof stress will initiate this damage, and thus galling, at higher pressures. This concept is visualized by plotting critical pressure values for each steels couple versus the sheet proof stress and it is seen that easy plasticized low strength steels had lower critical contact pressure. This dependence has a linear character and determines safe and unsafe regions for 200 m sliding distance, Figure 20 (b).

Obviously, sliding distance is a key parameter to identify the critical contact pressure, and for longer safe sliding distances lower critical pressures will be observed. In the present research, the maximum sliding distance was selected to be 200 m, but simple analysis of Figure 20 (b) shows that the same trend would be observed for 50 m or 100 m sliding distances. This concept also provides a simple tool for comparison of galling resistance of tool and sheet steels in different combinations and selection of a proper tool material for a given sheet steel may be easily done.

6 Summary and future work

Galling in contacts between tool steels and stainless steel sheets under lubricated sliding conditions was studied, focusing on the early stage of galling. In conventional tests, a stage of unstable friction and severe adhesive wear is used to determine galling. At this stage, however, the contact area of the tool steel surface was completely covered with transferred and adhered sheet material. Even though it is convenient to use this last stage as criterion for galling due to quick galling resistance ranking of different materials, it is difficult
to conclude the origin of galling from these tests. In order to learn more about factors influencing galling and galling initiation it is, therefore, important to study wear mechanisms typical for the stages prior to the final galling.

In tests with focus on the early stage of galling it was found that already after short sliding distances sheet material was transferred and accumulated as a thin layer to the tool surface, without any changes in friction. Additionally, the tool steels matrices were worn around the hard phases by sheet material flow, creating wear-induced galling initiation sites. For sheet material with lower proof stress, galling happened at lower pressures possibly due to easier sheet material flow, resulting in quicker tool surface damage. It was observed in SEM and proven by FEM that sheet material transfer and accumulation occurred not at regions with highest contact pressures but at regions with highest plastic strains. Thus, sheet material flow causing tool steel damage seems to be an important factor influencing galling origination.

Compared to the conventional ingot cast Sverker 21 tool steel, both material transfer and the tool surface damage was delayed in the tests with the PM tool steel Vancron 40. The better performance of the PM tool steel was attributed to the refined tool steels microstructure. In the Sverker 21 steel elongated clusters of the larger hard phase results in large open areas of matrix, vulnerable to damage by sheet material flow. The microstructure of the Vancron 40 steel comprises small and homogenously distributed hard phases. Because of the fine size and homogeneous distribution of hard phases in the PM tool steel Vancron 40, this steel better prevents the contact between the sheet material and the tool matrix compared to the coarse microstructure of the ingot cast Sverker 21 steel. Thus, damage to the tool matrix is decreased and galling is delayed as was observed for the PM tool steel. In tests with PM tool steel Vancron 40 tested at different hardness, the harder tool steel showed best performance. The damage of the tool steel surface previously described was less for the harder Vancron 40 steel and galling was, therefore, delayed. Additionally it was observed that the hard phases in the Sverker 21 and Vancron 40 steel not only differed in size and distribution of, but also in height. The height of the hard phases in the Vancron 40 steel was approximately 15-20 nm and height values of approximately 7 nm was observed for the Sverker 21 tool steel. In addition to size and distribution of hard phases, the higher hard phases in the PM tool steel Vancron 40 probably contributed in the better prevention of the contact
between sheet material and the tool steel matrix. This will result in a delay in material transfer and accumulation of sheet material to the tool surface.

To further conclude the influence of these microstructural features on the origin of galling, more effort on this subject is needed in future work. The height of the hard phases, for example, could be considered in future galling studies in order to conclude the effects on the galling origination. In this study it was shown that the hard phases differed in height even though the same surface preparation was performed to the tool steels prior to wear tests. To investigate the influence of surface preparation method on the hard phase height and thus possibly the galling resistance of the tool, would be a valuable contribution of knowledge to the sheet metal forming industry. The influence of the chemical composition of the tool steel hard phases on galling has been discussed in recent publications but no conclusions have been reached yet. It is possible that adhesion forces against stainless steel are different for different hard phases, which might influence the galling resistance of the tool steel. Further tool steel surface analysis with reliable adhesion measurements might, therefore, be interesting for future work.

More studies on the transfer and accumulated thin film on the tool surface in the early stage of galling might also be interesting to include in future work. The stability of this layer is not clear and the effect on galling origination is, therefore, difficult to estimate. To better understand the galling initiation it is important in future work to further analyze the thin film.