The influence of tool steel microstructure on 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 sort of severe adhesive wear, which results in severe scratching of produced parts. In this thesis, the overall aim was to gain knowledge of the influence of tool steel microstructure on galling initiation under sliding conditions. It was discovered that material transfer and tool steel damage caused by sheet material flow creating wear-induced galling initiation sites occurred in the early stage of galling. The galling resistance was higher for tool steels with higher matrix hardness due to better resistance to tool steel damage. Initial friction and critical contact pressure to galling was influenced by the strength of the sheet material. Material transfer happened at low pressures and the friction value was high in a case of sheet materials with lower proof strength, possibly due to the sheet contact against the tool steel matrix resulting in high adhesion and quicker tool damage. It was demonstrated that, in addition to hardness of the tool steel matrix and sheet material proof strength, tool steel microstructural features like size, shape, distribution and height of hard phases are important parameters influencing galling. Tool steels comprising homogeneously distributed, small and high hard phases better prevented the contact between sheet material and the tool steel matrix. Thus, a metal to metal contact with high friction was more efficiently avoided, which resulted in better tool performance.
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
Tribology International 60 (2013) 104-110

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
Peer reviewed proceedings of the 9th International tooling conference, September 11-14 2012, Leoben, Austria

V
Influence of tool steel microstructure on friction and initial material transfer
P. Karlsson, A. Gåård, P. Krakhmalev
Submitted to Wear 2014

VI
Influence of tool steel hard phase orientation and shape on galling
P. Karlsson, A. Gåård, P. Krakhmalev, J. Berhe-Larsson
Peer reviewed proceedings of the 6th International conference on tribology in manufacturing processes & joining by plastic deformation, June 22-24 2014, Darmstadt, Germany
Other publications

A
The early stage of galling
P. Karlsson
Licentiate thesis, Karlstad University studies, 2012

B
Galling investigations and test methods – A literature review
P. Karlsson
Literature review, Karlstad University studies, 2014
The author’s contribution to the papers

**Paper I**  Major part of planning, experimental work, evaluation and writing

**Paper II**  Major part of writing and part of planning, experimental work and evaluation

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

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

**Paper V**  Major part of planning, experimental work, evaluation and writing

**Paper VI**  Major part of evaluation and writing and part of planning and experimental work
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1 Introduction

Friction and wear are two factors of high importance in mechanical design. Both are studied in tribology; the science and technology of surfaces in relative motion, which also involves lubrication or lubrication science [1-3]. Tribology is an interdisciplinary field and many of the tribological theories and models have been developed by researchers in different areas. Generally, laws of friction and wear have been developed based on empirical results using different laboratory tribometers. The tribometers simulate parts of the otherwise complex tribological system found in manufacturing processes such as sheet metal forming (SMF). 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. SMF can be performed in many ways and one example is deep drawing, Figure 1. In this forming operation the sheet is clamped between a die and a blank holder and a punch subsequently deforms the sheet into a predetermined shape.

![Figure 1](image-url)

Figure 1. The deep drawing process (a) at which the sheet is clamped between a die and a blank holder (b) and formed by a punch (c) into a specified shape (d).
When surfaces are in contact and moved relative to each other, wear occurs. Depending on different parameters such as contact pressure and sliding speed, the wear is categorized into different wear modes. Two common modes of wear in mechanical devices are abrasive wear and adhesive wear. Abrasive wear is characterized by removal of material by scratching and adhesive wear takes place when material is transferred from one surface to another. In SMF operations, materials such as stainless steels are difficult to form because the sheet material tends to stick to the surface of the metal forming tool. Hence, material transfer and buildup of sheet material to the tool surface occurs, which is a major problem since it results in high and unstable friction and scratching of produced parts, Figure 2. The phenomenon is known as galling, which is a sort of severe adhesive wear [4-6].

![Figure 2. Scratches on a formed product caused by galling.](image)

Wear and galling can be reduced by lubricants. However, in SMF lubricants are applied that leads to boundary lubrication conditions with micro-contacts between surface asperities and, thus, wear related problems such as galling. New environmental requirements on SMF industries result in higher demands of the tool steels because the industries are required to reduce the amount of lubricants and also use more environmentally friendly lubricants. Therefore, new tool steels capable of working under tougher conditions are needed.
Galling has been investigated for quite some time, but the details about the microscopic mechanisms of galling initiation are not well understood. In some of the earliest investigations of galling the formation and growth of transferred material between material couples was studied by for instance Cocks and Antler [7-9]. From experimental results, the concept of galling was formulated in the ASTM G40 standard 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” [6]. The early studies of galling were performed on pure metals. In the modern industry, however, the materials are more advanced and have a complex microstructure compared to the pure metals, which makes galling studies more complex.

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 [10-17]. Among recently developed tool steels, nitrogen alloyed powder metallurgy (PM) tool steels have attracted interest due to enhanced galling resistance [16,18]. 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 [16,19-26]. Thus, further galling investigations of new and more advanced materials with more complicated microstructure are of high importance in order to evolve the knowledge of important parameters influencing galling and the mechanisms involved in galling initiation. It will support the development of new steel grades with high anti-galling characteristics.

The objective of this thesis was to gain knowledge of galling under sliding conditions and the influence of tool steel microstructure on galling initiation. Tool steels and sheet materials with different microstructures were evaluated under lubricated and dry sliding in a Slider-On-Flat-Surface (SOFS) tribometer. The tool steels ranged from conventional ingot cast steels to new and more advanced nitrogen alloyed powder metallurgy steels. The sheet materials included in this thesis were mainly stainless steels but some high strength carbon steels were also tested.
2 Materials

2.1 Tool steels

Tool steels are used in applications such as stamping and forming because of material properties like high wear resistance, strength and toughness. There are many ways to classify tool materials and in the American Iron and Steel Institute (AISI) classification system for instance, tool steels are arranged into groups based on application, alloying elements and heat treatments [27,28]. Cold-work tool steels used for SMF operations usually are ingot cast and forged steels. These tool materials 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 martensitic matrix. Typical heat treatment is hardening and repeated tempering to remove retained austenite and reach a required hardness-toughness combination. Additionally, the high alloy content in the steels provides high hardenability.

New and more advanced tool materials are the powder metallurgy (PM) tool steels. These steels comprise much finer and homogenously distributed hard phases compared to the conventional ingot cast and forged cold-work tool steels. However, the influence of tool steel microstructural features such as size and distribution and height of hard phases on galling are not clear. It is, therefore, important to investigate the influence of microstructure on galling for tool materials with different microstructures as in PM and conventional tool steels.

2.1.1 Tool materials in this study

In order to investigate the influence of tool steel microstructural features like size and distribution of hard phases on galling, four different tool steels were chosen for evaluation in this thesis work. The materials were a conventional ingot cast and forged AISI D2 type tool steel, commercially available as Sverker 21, and three types of PM tool materials; PM1, PM2 and Vancron 40, Table 1. PM1 and PM2 are in development stages and Vancron 40 is commercially available as Uddeholm Vancron 40. Prior to the wear tests, the tool steels were ground and polished to a surface roughness of approximately $R_a = 0.05 \mu m$, Table 1.
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 required in a large variety of application areas and stainless steel are used in kitchen sinks, washing machines, watches, automotive parts, chemical and medical tools etc. [28-30]. In the automotive industry stainless steels are a promising material for crash bumpers due to the good combination of strength and ductility. However, some stainless steel types are prone to galling and it is of high importance to the SMF industry to gain more knowledge of galling mechanisms for different stainless steel grades.

2.2.1 Sheet materials in this study

There are several stainless steel grades and each of them have different mechanical properties depending on the microstructure. However, the influence of these material properties on galling is not clear. This study included the four major types of stainless steel used in the industry, EN 1.4301 (austenitic), EN 1.4509 (ferritic), EN 1.4162 (duplex) and EN 1.4310 C1000 (metastable austenitic), Table 1.

Two different hot rolled, high strength, cold forming steel sheet materials were also included in galling tests to investigate the influence of the sheet mechanical properties on galling for other sheet material types than stainless steels. The materials were high strength low alloyed steels EN 10149-2, S 355 MC (DX355) and S 700 MC (DX700) and the main phase in these steels was ferrite, Table 1. These materials were included in galling tests under dry conditions and the steels were polished to a surface roughness of approximately $R_a$ 0.05 µm prior to testing.
Table 1. Properties of the investigated materials.

<table>
<thead>
<tr>
<th>Steel</th>
<th>Chemical composition [Wt%]</th>
<th>Hard phase content [Vol. %]</th>
<th>Structure</th>
<th>Rp_{0.2} [MPa]</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM1</td>
<td>1.1C, 4.5Cr, 3.2Mo, 0.6W, 2.6N, 12V</td>
<td>19% M(C,N)</td>
<td>-</td>
<td>-</td>
<td>64 HRC</td>
</tr>
<tr>
<td>PM2</td>
<td>2.3C, 4.8Cr, 3.6Mo, 0.4Si, 8.0V</td>
<td>17% MC</td>
<td>-</td>
<td>-</td>
<td>60 HRC</td>
</tr>
<tr>
<td>Vancron 40</td>
<td>1.1C, 4.5Cr, 3.2Mo, 3.7W, 1.8N, 8.5V</td>
<td>5% M&lt;sub&gt;6&lt;/sub&gt;C&lt;sub&gt;3&lt;/sub&gt;, 14% M(C,N)</td>
<td>-</td>
<td>-</td>
<td>61 and 65 HRC</td>
</tr>
<tr>
<td>Sverker 21</td>
<td>1.5C, 12Cr, 0.9Mo, 0.8V</td>
<td>13% M&lt;sub&gt;6&lt;/sub&gt;C&lt;sub&gt;3&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
<td>61 HRC</td>
</tr>
<tr>
<td>EN 1.4301</td>
<td>0.04C, 18Cr, 8.1Ni</td>
<td>-</td>
<td>Austenitic</td>
<td>300</td>
<td>170±10 HV&lt;sub&gt;0.25&lt;/sub&gt;</td>
</tr>
<tr>
<td>EN 1.4509</td>
<td>0.02C, 18Cr</td>
<td>-</td>
<td>Ferritic</td>
<td>360</td>
<td>180±5 HV&lt;sub&gt;0.05&lt;/sub&gt;</td>
</tr>
<tr>
<td>EN 1.4162</td>
<td>0.03C, 21.5Cr, 0.3Mo, 0.22N, 1.5Ni, 5Mn</td>
<td>-</td>
<td>Duplex</td>
<td>600</td>
<td>270±30 HV&lt;sub&gt;0.05&lt;/sub&gt;</td>
</tr>
<tr>
<td>EN 1.4319 C1000</td>
<td>0.10C, 17Cr, 7Ni</td>
<td>-</td>
<td>Metastable</td>
<td>900</td>
<td>360±30 HV&lt;sub&gt;0.05&lt;/sub&gt;</td>
</tr>
<tr>
<td>EN 10149-2 S 355 MC</td>
<td>0.10C, 0.03Si, 1.5Mn, 0.025P, 0.010S, 0.015Al, 0.09Nb, 0.20V, 0.15Ti</td>
<td>-</td>
<td>Ferrite</td>
<td>355</td>
<td>130±10 HV&lt;sub&gt;0.05&lt;/sub&gt;</td>
</tr>
<tr>
<td>EN 10149-2 S 700 MC</td>
<td>0.12C, 0.10Si, 2.10Mn, 0.025P, 0.010S, 0.015Al, 0.09Nb, 0.20V, 0.15Ti</td>
<td>-</td>
<td>Ferrite</td>
<td>700</td>
<td>230±10 HV&lt;sub&gt;0.05&lt;/sub&gt;</td>
</tr>
</tbody>
</table>
3 Galling tests

Galling resistance evaluations are often performed using different laboratory test methods since it is not economical to run industrial tests. A few advantages with the laboratory test methods are that they, generally, are fast and cheap and process parameters such as sliding velocity, load and contact geometry can be varied in a controlled manner. Depending on the type of test method the tribometers represent different tribosystems such as open or closed systems. In closed tribosystems, the same surfaces are in contact during the tests and similar contact situation is found in for instance the contact between camshafts and valves in car engines. SMF on the other hand is an open tribosystem where the metal forming tool is always in contact with a fresh counterbody surface [31].

In the present study galling tests were performed using a Slider-On-Flat-Surface (SOFS) tribometer, which represents an open tribosystem where a test specimen made of a tool steel is slid against a fresh sheet surface. Prior to wear tests, a double-curved disc is fixed to prevent rotation during sliding. The disc is pressed and slid against a sheet surface up to 1 m stroke length and when the disc reaches the end of the sheet it is lifted from the sheet surface and moved back to the point of origin. The disc sliding movement is reiterated against a fresh sheet surface after a small shift perpendicular to the sliding direction, Figure 3.

Figure 3. Overview of the slider-on-flat-surface (SOFS) tribometer displaying force gauges and the disc fixed in a disc holder.
During SOFS tests, friction is continuously recorded and the changes in friction are correlated to the progression of galling. Wear mechanisms were investigated by analyzing the surfaces of the tested materials after galling tests using FEG SEM LEO 1530 scanning electron microscopy (SEM), Wyko NT 3300 3D optical profilometry (OP) and Innova AFM atomic force microscopy (AFM). In the ranking of material couples, three galling tests at each normal load were performed and the average sliding distance to galling was plotted in a sliding distance to galling diagram.

At a specific normal load, the contact area, and thus the contact pressure, is different for sheet materials with different mechanical properties given that the sheet is plastically deformed. Therefore, the contact pressure is a more suitable parameter compared to load when several materials with different mechanical properties are compared. The contact pressures between different material couples at specific normal loads were calculated using Abaqus software, Figure 4. In the calculations, the tool steel discs 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. Based on experimental data before the onset of galling, a coefficient of friction of 0.1 was used in the model.

Figure 4. SOFS disc and sheet assembly in Abaqus (a-b) and a typical contact pressure contour plot (c).
Prior to SOFS tests, the materials were cleaned using degreasing agent and ethanol. In lubricated tests 5 g/m² sheet of Castrol FST-8 lubricant was used.

3.1 Typical stages of galling

Typical friction data obtained in SOFS tests is shown in Figure 5 and as can be seen in the diagram, three different frictional stages are marked as I, II and II. The first stage is characterized by stable friction and at stage two the friction starts to increase. At stage three the friction is high and unstable. The typical frictional behavior shown in Figure 5 was observed for all tested material couples under all selected pressures.

![Friction Graph](image)

**Figure 5.** Typical friction data after galling tests in SOFS.

In Figure 6 and Figure 7 the progression of galling on the disc surface and the sheet surface is shown. As can be seen in Figure 6 (a), material transfer to the tool steel surface occurs at stage I even though the friction is low and stable. The early material transfer resulted in an adhered thin layer of sheet material on the disc surface. Therefore, galling initiation mechanisms are difficult to detect using friction as an indicator. A possible explanation to why the material transfer is not indicated by friction is that the initial thin layer of adhered sheet material on the tool steel surface might be unstable and could, therefore, be back-transferred from the disc to the sheet as was suggested in [21,32]. SEM of the worn sheet surface showed that only minor wear of the counterbody occurs.
and at stage I in the SOFS tests sheet surface flattening was observed, Figure 7 (a).

Further sliding results in a transition of wear mechanisms which is indicated by an increase in friction at stage II. Typical results from analysis of the disc and sheet surface using SEM and OP respectively shows microscopic lumps on the tool steel surface, Figure 6 (b), and scratching or microscopic plowing of the sheet surface, Figure 7 (b,d). Thus, the increase in friction is a result of scratching of the sheet surface by transferred and adhered sheet material to the tool steel surface. Since sheet surface damage occurred already at stage II, the beginning of this stage was used as indication of galling, marked by × in Figure 5. In the present study, this mechanism was observed for tests against all sheet materials. Similar mechanisms have been reported for other tool steels and sheet materials [32,33].

Figure 6. Typical stages I (a), II (b) and III (c) of transfer and accumulation of sheet material on the surface of the tool steel disc. Arrows indicate the sliding direction of the disc.

At stage III, complete coverage of the contact by transferred and adhered material is typically observed on the tool steel surface. The adhered material, generally, has the shape of a macroscopic wedge as can be seen in Figure 6 (c). Typical appearance of adhesive wear is observed on the sheet surface at stage
III, as seen in Figure 7 (c), and the contact between the macroscopic wedge and the sheet results in high and unstable friction. This situation has been observed for other wear tests [6,34] and corresponds to the standard definition of galling ASTM G40 [6]. However at stage III, the tool steel microstructure hardly influences the galling since the contact area on the surface of the tool steel disc is covered by transferred and accumulated sheet material. Wear mechanisms at stage I and II and the transformation between them are, therefore, of high interest for understanding of the influence of tool steel microstructure on galling initiation.

![Diagram](image-url)

Figure 7. 3D surfaces (a-c) and 2D depth profile (d) of the track surface at the typical stages of galling. Arrows indicate the sliding direction of the disc.
3.2 Ranking of tool materials

To differentiate between different tool steels regarding galling resistance, SOFS tests at different normal loads were performed to evaluate the critical sliding distance to galling. Figure 8 shows a typical sliding distance to galling diagram for several tool materials in lubricated sliding against the duplex stainless steel sheet. The general trend shown in Figure 8, where the PM steels have significantly better performance compared to the conventional ingot cast and forged steel, was observed in Papers I-V.

![Sliding distance to galling diagram](image)

Figure 8. Sliding distance to galling diagram.

3.3 Comparison of two different tribosystems

Galling evaluation with the SOFS tribometer, which represents an open tribosystem was compared to a Pin-On-Disc (POD) tribometer in Paper II. In the Pin-On-Disc test method a pin is pressed against a rotating disc and friction is continuously recorded during galling tests [35-38], Figure 9. The test method is a closed tribosystem and the pin slides in the same wear track during wear testing. One advantage with this type of test method is the rather small amount of test material required for each test. However, the test configuration in Pin-On-Disc test method results in a repeated contact between the mating surfaces and the history of wear on the contacting surfaces is difficult to study.
The tool steels Sverker 21 and Vancron 40 were tested against austenitic stainless steel 1.4301 under lubricated sliding in both SOFS and POD. The Vancron 40 tool steel showed best performance independently of tribosystems. However, galling occurred quicker in POD compared to the SOFS test method. This is illustrated in Figure 10 and as can be seen in the figure, the transition between stage II and stage III occurred quicker for the POD test method.

Figure 10. Friction characteristics for the two test methods.
The transition from stage I to stage II in both SOFS and POD occurred after similar sliding distances. However, the transition from stage II to stage III occurred at longer sliding distance in SOFS. The differences observed between the two different test methods may be related to the fact that SOFS and POD are different type of tribosystems.

In POD the amount of lubricant applied prior to the wear tests may decrease or be pushed away from the contact zone by the pin due to the repeated sliding in the same wear track. Hence, friction would change rapidly if the lubricant layer is broken. Decreased amount of lubricant in the contact zone probably triggered the onset of galling, which was observed as a sudden change in friction for POD, Figure 10. The SOFS on the other hand is an open tribosystem, where the disc always meets a fresh sheet surface and the amount of lubricant is more or less constant during the tests. Therefore, the progressively increased friction during wear tests is best explained by gradual transfer of sheet material to the tool steel surface [39,40].

4 The influence of tool steel microstructure on galling

The microstructural features of tool steels such as size, height and distribution of hard phases differ in dependence on how the steel was manufactured. Conventional ingot cast and forged tool steels generally have larger elongated hard phases formed in clusters compared to the microstructure of PM materials where the hard phases are much smaller and homogenously distributed. The microstructure comprises hard primary carbides embedded in a softer matrix. However, the influence of microstructural features like size, height, hardness and distribution of hard particles on galling initiation mechanisms is not thoroughly understood.

4.1 Microstructural features of the investigated tool materials

4.1.1 Size and distribution of hard phases

The microstructures of the tested steels are shown in Figure 11. As can be seen, the PM steels comprise small and homogenously distributed particles in contrast to the conventional ingot cast and forged Sverker 21 steel comprising comparably large elongated M7C3 carbides in clusters. The size and distribution of the hard phases in Sverker 21 result in larger open areas of matrix compared to the PM tool steels. The PM1 material comprises M(C,N) carbonitrides while
the PM2 steel contains MC carbides. Vancron 40 comprises a mixture of M₆C carbides and M(C,N) carbonitrides.

![Microstructure images](image)

Figure 11. Microstructure of the tested tool steels PM1 (a), PM2 (b), Vancron 40 (c) and Sverker 21 (d).

### 4.1.2 Height of hard phases

The tool steels were polished to a mirror-like surface with $R_a$ value of approximately 0.05 µm. However, due to differences in hardness between the matrix and the primary precipitates the hard phases may protrude above the matrix. To understand the level of protrusion of hard phases in correlation to hard phase type, nano roughness measurements were performed (Papers IV-VI). It was observed that the heights of the different hard phases differed, Figure 12. The heights were approximately 25 nm for the M(C,N) carbonitrides and 5 nm for the M₆C carbides in the Vancron 40 steel, 4 nm for the MC carbides in the PM2 steel and 7 nm for the M₇C₃ carbides in the IC tool steel. The height values, Figure 12 (a), were measured using AFM and additional validating of hard phase type was performed by scanning the same area using SEM, Figure 12 (b-d).
Figure 12. Hard phase heights of the tested tool steels (a) and height differences of the M(C,N) and M₆C indicated by tilted specimen in SEM (b). The height values of the hard phases were extracted from surface AFM surface scans (c) after phase type confirmation in SEM (d).

4.1.3 Hardness of tool steel matrix and hard phases

To investigate the hardness of the tool steel matrix and the hard phases, hardness measurements by CSM Instruments Ultra Nano Indentation Tester (UNIT) was performed on the PM1, Vancron 40 and Sverker 21 steel. Totally 150 indents were performed on the PM1 steel at 2 mN normal load and 10 indents on the Vancron 40 and Sverker 21 steel at 15 mN load. After hardness measurements the steels were analyzed in SEM to investigate if measurements were performed on both hard phases and matrix Figure 13 (a). Indication of
indentation on the hard phase may also be reflected in the load-displacement curve, Figure 13 (b). At maximum load the penetration depth will differ for harder and softer surfaces and decrease with increasing surface hardness.

Figure 13. Indents on the tool steel hard phase and matrix observed in SEM (a) and typical load-displacement curve (b) after hardness measurements by the nano indentation tester.

The results from the hardness measurements are summarized in Figure 14. As can be seen, the hardness of the M(C,N) phase and matrix in the PM1 steel were approximately 1700 HV and 1000 HV, respectively. The hardness of the hard phase M6C and matrix of the Vancron 40 treated to 61 HRC was approximately 1900 HV and 1200 HV, respectively. The hardness of the harder Vancron 40 treated to 65 HRC was approximately 1500 HV and all nano indentations were performed on the tool steel matrix for this steel. Hardness of the M7C3 hard phase and matrix of Sverker 21 was approximately 1900 HV and 1000 HV, respectively, as can be seen in Figure 14. The higher hardness values of the hard phases explain the protrusions of the hard particles above the tool steel matrix, shown in Figure 12, to be due to lower wear rate during polishing.
4.2 The early stage of galling

The galling tests in Papers III-IV focused on the early stage of galling under lubricated test conditions. Similar trend as seen in Figure 8, showing higher performance for PM tool steels compared to the conventional tool material, was observed. In Paper IV for example, interrupted tests were performed in order to investigate the initiation and progression of galling and it was observed that the material transfer to the tool steel surface at stage I occurred after longer sliding distance for Vancron 40 compared to Sverker 21. Material transferred to the tool steel surface as a thin layer after 2 m for the Sverker 21 steel, Figure 15 (a), and after 50 m for the Vancron 40 steel, Figure 15 (b). The thin layer was observed on the hard phases and the matrix for both 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 steel disc.
After sliding distances of 5 m and 70 m for the Sverker 21 and Vancron 40 tool steels respectively, (Paper III), analysis of the tool steel disc showed surface damage. 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 after interrupted tests. The damage was observed at approximately 5 m for the Sverker 21 steel, Figure 16 (a). Similar damage was observed on the Vancron 40 steel surface but at longer sliding distance of about 70 m, Figure 16 (b).

![Figure 16](image)

Figure 16. Tool steel surface damage resulting in wear-induced galling initiation sites for the Sverker 21 (a) and Vancron 40 (b) tool steels. Arrows indicate the sliding direction of the tool steel disc. The sliding distance was 5 m for the Sverker 21 steel and 70 m for the PM steel Vancron 40.

The better performance of the PM tool steels compared to the Sverker 21 steel can be explained by the differences in size and distribution of hard phases. In the conventional Sverker 21 steel the large M₇C₃ carbides of approximately 5-20 µm in length are positioned in clusters. It results in more open matrix areas susceptible to scratching, material transfer and galling for the Sverker 21 steel compared to the PM steels, Figure 11. An additional factor influencing tool steel performance could be hard phase heights. In comparison to the height of the M(C,N) carbides in the PM tool material Vancron 40 of approximately 25 nm, the Sverker 21 steel has lower hard phase heights, Figure 12. The height of the M₇C₃ carbides is approximately 7 nm. Thus, because of open matrix areas and low carbide heights a contact between sheet material and the tool steel matrix occurs for the Sverker 21 steel. This results in a metal to metal contact, quick material transfer, galling and high friction. Similar trend of higher performance of steels with finer microstructure has been reported in [19,41] for other steels.
In Paper I and II, Vancron 40 heat treated to hardness 61 HRC and 65 HRC was tested to investigate the influence of hardness on the galling resistance of tool steels. It was observed that the performance of the Vancron 40 steel increased with increasing hardness. In Paper I for example, the sliding distance to galling was longer for the Vancron 40 steel treated to higher hardness of 65 HRC as can be seen in Figure 8. At 500 N, the sliding distances to galling was approximately 155 m and 35 m for the steel treated to 65 HRC and 61 HRC, respectively. A possible explanation to the increased performance of Vancron 40 with higher hardness is less tool steel surface damage by sheet material flow due to a higher hardness of the tool material, Figure 14. An increased hardness of the tool steel matrix can delay the wear induced tool steel matrix damage, which was observed in tests focusing on the early stage of galling in Paper III-IV, Figure 16. This would result in longer sliding distance until galling occurs and, thus, higher performance of the tool steel as was observed, Figure 8.

In Paper V galling tests focusing on the early stage of galling under dry tests conditions were performed. To investigate the influence of microstructure on the initial material transfer and friction SOFS discs made of 1.4301, 1.4162, DX355 and DX700 sheet materials were tested against tool steel plates made of Sverker 21, Vancron 40 and PM2 steel under dry sliding in SOFS. During testing, the discs were slid in a single stroke against the tool steel plates. To isolate the influence of tool steel microstructure both the sheet discs and tool steel plates were polished to a surface roughness of approximately $R_a$ 0.05 µm. It was observed that hard phase heights influence friction and initial material transfer. Material transfer occurred instantly to the tool steel surface and typical appearance of the transferred material is shown in Figure 17 (a-b) for Vancron 40 at normal loads of 50 N and 500 N. At the lowest normal load of 50 N, transferred material was observed around the higher M(C,N) carbonitrides, Figure 17 (a), and at the highest load of 500 N the material transfer occurred to both the tool steel matrix and hard phases, Figure 17 (b). On steels with lower hard phase heights like the Sverker 21 steel, Figure 12, material transfer was more pronounced around the hard phases. However, material was also transferred to the tool steel matrix as can be seen in Figure 17 (c-d) for the Sverker 21 steel at 50 N and 500 N normal load.
A correlation between friction and hard phase heights was also observed. In Figure 18 the measured and calculated average coefficient of friction from tests performed at 50 N load is shown. As can be seen in the figure the general trend at 50 N normal load was that independently of sheet material type, the COF values were lowest for the Vancron 40 tool material followed by IC and PM2 tool steel. Hence, the coefficient of friction increased with decreasing hard phase heights of the investigated tool materials, Figure 12. The highest COF value of approximately 0.6 was observed for the PM2 tool steel against the carbon sheet material DX355. Lowest COF value of approximately 0.3 was observed for the Vancron 40 tool material against the duplex stainless steel type 1.4162. The observed COF value for the IC tool steel against all sheet material types was approximately 0.45. At higher load of 500 N only minor differences in friction between the tool materials were observed.
The results obtained in Paper V for three different tool materials indicate that the early stage of galling depends on load and heights of hard phases. Investigations of the worn tool steel surfaces at 50 N load showed that the main area of transferred material was around the tool steel hard phases. Thus, at lower load of 50 N the contact was mainly between the sheet and the tool steel hard phases. However, for tool materials with lower hard phase height the contact is also against the tool steel matrix. This results in a metal to metal contact and high friction due to strong adhesion. Therefore, the lowest hard phase height of approximately 4 nm for the MC carbides, as seen in Figure 12, can explain the higher coefficient of friction of the PM2 steel displayed in Figure 18.

Vancron 40 consists of two different hard phases with different heights; M(C,N) carbonitrides and M6C carbides with heights of about 25 nm and 5 nm, respectively. The low friction observed for this steel may be attributed to the better separation of the sheet against the tool steel matrix by the high M(C,N) carbonitrides in Vancron 40, Figure 18. It is generally believed that the carbonitrides has low affinity to steel sheet materials [19,22,42]. Thus, the observed transferred material around the hard phase is likely to occur due to mechanical interlocking of sheet material rather than adhesion between the sheet and the hard phase particles. Because of the lower height of approximately 5 nm for the second hard phase M6C in the Vancron 40 steel, only minor contact between the sheet material and the M6C phase occurs.
Therefore, less material transfer around this phase occurs as can be seen in Figure 17 (a).

At 500 N load, the transferred and adhered sheet material was observed on both the hard phases and matrix of all tested tool materials. Thus, in dry sliding at higher loads the height of the tool steel hard phase was not sufficient to prevent the sheet material to reach the tool steel matrix. Because of strong adhesion in this contact situation, material transfer to the tool steel matrix occurs as was observed, Figure 17. Transfer of sheet material to both the matrix and hard phases of tool materials at higher loads is typical and has been observed in tests under lubricated sliding as well [43].

4.3 Nanowear testing of multiphase materials

In Papers III-IV, the SOFS tribometer was used in tests focusing on the early stage of galling. The contact between the disc and the counterbody in SOFS results in a macroscopic contact area. In this contact it was possible to investigate micromechanisms of galling. Nevertheless, to study galling related mechanisms in a microscopic contact a Hysitron triboindenter TI950 was used. In the triboindenter a diamond probe of Berkovich type with tip radius of approximately 150 nm was slid against the matrix and hard phases of the PM2, Vancron 40 and Sverker 21 steels under dry conditions and reciprocating sliding. During testing, the diamond probe was slid 30 times against the steels and friction was continuously measured. Scans using both SEM and scanning probe microscopy (SPM) were performed prior and after the nanowear tests to ensure that measurements were done on the tool steel matrix and specific phases.

The results from nanowear testing on the PM2 steel are shown in Figure 19. Surface analysis of the steel by SEM prior to testing is shown in Figure 19 (a) and result from analysis of the worn surface by SPM is shown in Figure 19 (b). As can be seen in Figure 19 (a-b) the wear tests were performed over both the MC hard phase and matrix of the PM2 steel. The recorded friction data indicated that the friction was lower at hard phase regions compared to the matrix. This is shown in Figure 19 (c), where the coefficient of friction data at 25 slides in the triboindenter is displayed. As seen in the friction diagram, the coefficient of friction is approximately 0.25 at the MC hard phase and about 0.3 for the matrix of the PM2 steel.
Figure 19. Surface of the PM2 steel prior (a) and after (b) nanowear tests in the triboindenter. In (b) the wear track over the MC hard phase of the PM2 steel is shown. The corresponding friction measurement during testing is shown in (c) indicating lower friction at the MC hard phase.

In Figure 20, the results from wear testing on the M(C,N) hard phase of Vancron 40 are shown. Similar to the results obtained for the PM2 steel, Figure 19, the coefficient of friction is lower at matrix areas compared to the hard phase areas for the Vancron 40 steel. The coefficient of friction after 25 slides are approximately 0.18 for the matrix and about 0.13 over the M(C,N) carbonitride.
Figure 20. Surface of the Vancron 40 steel by SEM (a) and SPM (b) prior to nanowear testing. In (c) the changes in friction with increasing number of sliding is displayed indicating lower friction at the M(C,N) hard phase.

The coefficient of friction values for the matrix and hard phases of the PM2, Vancron 40 and Sverker 21 tool steels measured by the triboindenter during nanowear tests are shown in Figure 21. As can be seen in the friction diagrams, the coefficient of friction is lower at hard phase areas compared to the tool steel matrix areas. The coefficient of friction was highest for the PM2 steel and the coefficient of friction for the matrix and MC hard phase were approximately 0.3 and 0.25, respectively, Figure 21. As seen in Figure 21, the coefficient of friction for the matrix of the Vancron 40 and Sverker 21 tool steels were about
0.18 and 0.15, respectively. The friction values over the M(C,N) carbonitrides and M₆C carbides were approximately 0.13 and 0.14, respectively. Lowest coefficient of friction of about 0.12 was observed for the M-C₃ carbides.

![Graph](image)

Figure 21. The coefficient of friction values for the matrix and hard phases of the tool steels measured by the triboindenter at nanowear tests.

Results from the nanowear tests in the triboindenter indicated lower friction for the tool steel hard phases. Galling is associated with frictional heating and therefore a low friction is beneficial in a tribological contact [26]. Thus, a contact against the tool steel matrix resulting in high friction should be avoided for better tool performance. Similar to results from the tests focusing on the early stage of galling in Paper V, Figure 18, the coefficient of friction was higher for the PM2 steel in the nanowear tests, Figure 21. This is interesting because the results obtained for two different tests correlate even though the contact areas are different in size.

However, the differences between the coefficient of friction values for the hard phases and matrix areas of the steels in correlation to specific matrix and hard phase type are not thoroughly understood. In [42], adhesion measurements of the tool steel hard phases and matrix of Vancron 40 were performed using AFM. It was shown that the adhesion force between the AFM Si tip and the tool steel matrix was higher than adhesion between the tip and the tool steel hard phases. Hence, the higher coefficient of friction for the matrix of the tool materials in Figure 21 may be explained by a higher adhesion between the diamond probe and the matrix of the steels. Correspondingly, different adhesion between the diamond probe and a tool steel hard phase because of
hard phase type may explain the result showing differences between the coefficient of friction values for the different type of hard phases, Figure 21.

### 4.4 Effect of hard phase orientation on galling

Depending on the cutting direction of conventional ingot cast and forged steels such as Sverker 21, the orientation and shape of hard phases differs. This results in different sliding length of sheet material against the tool steel matrix in the sliding direction which can influence the tool steel performance. To investigate the influence of shape and orientation of hard phases on galling, three different surfaces of the Sverker 21 steel were tested against the austenitic stainless sheet material 1.4301 under lubricated sliding conditions in SOFS (Paper VI). These surfaces are described as S1, S2 and S3 in Figure 22. The arrows in Figure 22 indicate the sliding direction of the sheet surface against the Sverker 21 steel in the SOFS tests.

![Diagram of hard phase shape and orientation](image)

**Figure 22.** Hard phase shape and orientation on the S1, S2 and S3 tool steel surfaces and wear test results as a sliding distance to galling diagram.

The hard phases were oriented parallel and perpendicular to the sliding direction for the S1 and S2 surface, respectively. Sliding of sheet material
against more spherical-like hard phases was performed against the S3 surface as can be seen in Figure 22.

At lowest load of 100 N, best performance was observed for the S3 surface with more spherically shaped carbides. The sliding distance to galling for this steel was approximately 135 m and shortest sliding distance was observed for the S1 specimen with carbides oriented parallel to the sliding direction. The sliding distance to galling for this steel was approximately 45 m while the S2 sample with carbides oriented perpendicular to the sliding direction slid for about 100 m until galling occurred. A similar trend was observed at 200 N, while at 300 N there was no significant difference in sliding distance to galling among the surfaces and galling occurred after approximately 20 m, Figure 22.

The results in Paper VI indicate that the shape and orientation of hard phases are important factors influencing galling. Similar to the explanation of the better performance of the PM steels by shorter distance between hard phases and, thus, less open areas of matrix susceptible to wear, the distance between hard phases of the surfaces S1-S3 can explain the galling result seen in Figure 22. It has been shown that short distance between hard phases is beneficial for the adhesive wear resistance for tool steels [41]. The distances between the Sverker 21 carbides in the present study were less for the more spherically shaped carbides in the S3 surface compared to the elongated carbides in the S1 surface, Figure 22. This may explain the better performance for the S3 specimen compared to the S1 sample, Figure 22. In a contact between sheet and tool steel disc in relative motion, the sheet will be in contact with the tool steel matrix for longer sliding distance with the S1 surface where carbides are oriented parallel to the sliding direction. The contact between the sheet and the tool steel matrix results in a metal to metal contact and high adhesion [5,42]. Thus, galling occurs quicker for tool materials with longer open matrix areas in the sliding direction as was observed for the S1 specimen, Figure 22.

The surfaces S2 and S3 in the present study have shorter distance between the carbides in the sliding direction, compared to the S1 surface, Figure 22. The contact between the sheet and the tool steel matrix is therefore interrupted by hard phases in the sliding direction. Thus, high friction and adhesive forces are better avoided. However, the carbides in the S2 surface were formed in clusters resulting in more open areas of tool steel matrix compared to the S3 surface which had higher area fraction of smaller and more homogeneously distributed
carbides. Image analysis using automatic software Leica QWin showed that the area fraction of carbides on the S3 surface was approximately 13% and 11% for the S1 and S2 surfaces. Hence, less open areas of tool steel matrix that is vulnerable to wear can explain the better performance of the S3 surface compared to the S2 surface, Figure 22.

Similar to Paper V showing that the influence of tool steel microstructure on initial material transfer and friction may differ for different load regimes, Figure 17, the effect of carbide shape and orientation on galling decreased with increasing load in Paper VI, Figure 22. One explanation to this may be that at high loads the sheet is pressed down to the tool steel matrix and thus independent on carbide shape and orientation, the real area of contact between the sheet and the tool steel surface is approaching the nominal contact area. Hence, metal to metal contact is dominating in this situation and quick galling occurs, Figure 22.

5 The influence of sheet material type on galling

Galling is associated with material transfer, plastic flow, or both and, therefore, mechanical properties of the sheet materials are of importance since they influence galling. Austenitic stainless steel is generally known to be prone to galling and therefore difficult to form. However, the galling resistance of this material in correlation to other sheet materials is not thoroughly known. It is therefore important to further investigate this material and also compare the galling properties of the austenitic steel to other sheet materials. To investigate the influence of sheet material type on galling several different sheet materials were tested in SOFS under sliding conditions. The tested sheet materials included in this thesis were four different stainless steels; austenitic (1.4301), ferritic (1.4509), duplex (1.4162) and metastable austenitic (1.4310 C1000) and two different high strength low alloyed ferritic steels EN 10149-2, S 355 MC (DX355) and S 700 MC (DX700), Table 1.

5.1 Impact of sheet material strength on galling threshold pressure

In Paper III, Sverker 21 and Vancron 40 were tested against the four different types of stainless steel sheets under lubricated sliding conditions in SOFS. The results of the tests are summarized in Figure 23. In Figure 23 (a), contact pressures are plotted against the total sliding distance to galling for the different tested material combinations. The galling tests in SOFS 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 23 (a) and are used in the diagram in Figure 23 (b).

As can be seen in Figure 23 (a), galling occurred at higher contact pressures and longer sliding distance for Vancron 40 compared to Sverker 21. 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 23 (b). The trend for both tool steels was the same; the critical contact pressure increases with increasing proof stress of the sheet materials. A linear-type dependence between the sheet steel proof stress and critical contact pressures was found and this is displayed with dashed trend lines in Figure 23 (b). The trend lines in Figure 23 (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.

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 tool steel disc showed that the discs were worn, Figure 24.
In literature it was found that the tool material wears by the sheet material if the tool steel to the sheet hardness ratio is less than 2 [44]. 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 steel 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 in Figure 5, 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 steel 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 steel disc is worn moderately but not enough to initiate formation of microscopic lumps on the surface. At \( P > P_{cr} \), the tool steel disc 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 steel 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 23 (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 Paper III, the maximum sliding distance was selected to be 200 m, but simple analysis of Figure 23 shows that the same trend would be observed for 50 m or 100 m sliding distances.

This concept may provide a tool for selection of a proper tool material for a given sheet steel. However, the galling threshold pressures for the given material combinations are calculated for the given geometry of the SOFS disc. For other tool geometries, new contact pressure calculations must be performed in order to use the obtained, in the present study, galling threshold pressures as a first approximation of pressure limits for the material combinations.

5.2 Effect of sheet material proof strength on friction

The influence of sheet material proof strength on galling related problems such as high friction was observed in Paper V. SOFS discs made of 1.4301, 1.4162, DX355 and DX700 sheet materials were tested against tool steel plates made of Sverker 21, Vancron 40 and PM2 steel under dry sliding in SOFS. It was observed that independently of tool steel type, the coefficient of friction decreased with increasing sheet material proof stress in tests performed at higher load of 500 N, Figure 25 and Table 1.

![Figure 25. The coefficient of friction values for the material couples measured in SOFS at 500 N normal load.](image-url)
It has been shown that high strength materials are less prone to galling and thus galling depends on mechanical properties of materials [5,45]. The high coefficient of friction in tests against sheet material with lower proof stress might, similar to the explanation to the result in Paper III showing low galling threshold pressure for low strength sheet materials, be explained by the plastic deformation of sheet material. Sheet material with lower proof stress will flow more easily in between the tool steel hard phases and quickly reach the matrix of the tool materials. This results in high friction because of the metal to metal contact between the sheet and the tool steel matrix.
6 Summary

A contact between the sheet material and the tool steel matrix results in high friction and quick galling due to high adhesive forces in the metal to metal contact. The contact between sheet material and tool steel hard phases on the other hand results in lower friction as was observed in the nanowear tests. Material transfer is also decreased because of the hard phase lower affinity to sheet material. Thus, the contact between the sheet material and the tool steel matrix should be avoided. The results in this thesis indicate that this can be done by careful selection of material couples with the right material properties. It was found that size, shape, distribution and height of tool steel hard phases, hardness of the tool steel matrix and sheet material proof strength are important parameters influencing galling.

The galling resistance of the sheet and tool materials in this thesis was tested in the SOFS tribometer under lubricated and dry conditions. 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 surface of the tool steel disc in SOFS is 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 ranking of different materials, it is difficult to conclude the origin of galling from these tests. To learn more about factors influencing galling initiation it is, therefore, important to study wear mechanisms typical for stage I.

In tests focusing on the influence of tool steel microstructure on the initial friction and material transfer it was found that already after short sliding distances sheet material was transferred and accumulated as a thin layer to the tool steel surface. Galling was influenced by tool steel matrix damage around the hard phases caused by sheet material flow, creating wear-induced galling initiation sites. It was observed that the initial friction and critical contact pressure to galling were influenced by the strength of the sheet material. Galling happened at lower pressures and friction was higher for sheet material with lower proof strength possibly due to more contact of sheet material against the tool steel matrix. Sheet materials with lower strength are softer and can therefore more easily be pressed down to the tool steel matrix resulting in higher friction, quicker tool damage and galling. Hence, sheet material transfer
and flow causing tool steel damage seems to be important parameters influencing the early stage of galling.

Both material transfer and the tool surface damage were delayed in the tests with the PM tool steels. The better performance of the PM tool steels was also observed in the ranking of tool materials where the PM steels, in comparison to the conventional steel, slid for longer distance until the final stage of galling occurred. The tool performance is influenced by microstructure features like size, shape, orientation and distribution of tool steel hard phases. In the conventional steel elongated clusters of the larger hard phase results in large open areas of matrix, vulnerable to material transfer due to high adhesion against sheet material and tool steel damage by sheet material flow. However, the open areas of matrix, and thus the sliding length of sheet material against the tool steel matrix, differ in dependence on cutting direction of the conventional tool material. It was observed that the conventional steel cut so that the contact surface comprised more spherically shaped hard phases showed higher performance. The sliding distance of sheet material against the tool steel matrix for this active surface was shorter in the sliding direction. Thus, the contact of the sheet against the tool steel matrix was interrupted by the tool steel hard phases, which resulted in longer sliding distance to galling. The contact surface with hard phases oriented parallel to the sliding direction showed worst performance because of longer sliding distance of sheet material against the open matrix in the sliding direction. Therefore, the performance of the conventional steel is influenced by shape and orientation of hard phases.

The microstructure of the PM steels on the other hand comprises small and homogenously distributed hard phases with short average distances between the particles. Because of the refined microstructure of the PM tool steel Vancron 40 for instance, this steel better prevents the contact between the sheet material and the tool steel matrix in the sliding direction compared to the coarse microstructure of the conventional ingot cast and forged Sverker 21 steel. Thus, damage to the tool steel matrix is decreased and galling is delayed as it was observed for the PM tool material Vancron 40. In tests with PM tool steel Vancron 40 tested at different hardness, the harder tool material showed best performance. The increased hardness of the steel matrix of Vancron 40 heat treated to 65 HRC results in higher wear resistance and thus it is possible that the tool steel disc damage detected at the early stage of galling is less severe, which results in better tool performance. Hence, tool steel matrix
hardness is an important factor influencing the resistance to wear and galling of tool steels.

It was discovered that in addition to the size and distribution of hard phases, the hard phase height of the investigated tool materials differed. Prior to testing in SOFS, the tool steels were ground and polished to a $R_a$ value of approximately 0.05 µm. However, even though the surfaces were mirror-like, the tool steel hard phases protruded above the tool matrix. The highest hard phase height value of approximately 25 nm was observed for the M(C,N) carbonitrides in the PM steel Vancron 40. In tests focusing on the initial friction and material transfer under dry test condition it was discovered that at lower contact pressures, the coefficient of friction decreased with increasing hard phase heights. The lowest value of the coefficient of friction of approximately 0.3 was detected for the Vancron 40 steel. Material transfer occurred around the hard phases and thus the main contact at lower pressures was mainly between the sheet and the tool steel hard phases. However, for tool steel with lower hard phases the contact is also against the tool steel matrix. This results in a metal to metal contact which results in high friction due to strong adhesion. Thus, the level of protrusion of hard phases is important since it influence the contact of sheet material against tool steel matrix and, therefore, also influence the galling resistance of the tool steel.
Conclusions

This thesis describes different aspects of galling in lubricated and dry sliding contacts between tool steels and sheet materials. The discussion is mainly focused on the influence of tool steel microstructure on galling initiation. The following main conclusions can be drawn from the thesis:

Material transfer of sheet material to the tool surface and tool steel damage around the hard phases caused by sheet material flow occur in the early stage of galling, which results in formation of wear-induced galling initiation sites.

The galling resistance of the tool steels is influenced by microstructural parameters such as size, distribution, shape, orientation and height of hard phases and hardness of the tool steel matrix.

PM tool steels comprising homogeneously distributed, small and high hard phases better prevent the contact between sheet material and the tool steel matrix in the sliding direction. Thus, a metal to metal contact with high friction due to strong adhesion is avoided and material transfer and tool damage are delayed which results in better tool performance.

The galling resistance is higher for PM tool steels with higher matrix hardness possibly due to higher resistance to the formation of the wear-induced galling initiation sites.

The performance of conventional tool steels is influenced by the orientation of the larger and elongated hard phases. Best performance is achieved by orienting the hard phases on the active surface so that shorter sliding distance of sheet material against the tool steel matrix in the sliding direction occurs.

The initial friction and critical contact pressure to galling is influenced by the strength of the sheet material. Galling occurs at lower pressures and friction is higher for sheet material with lower proof strength possibly due to more contact of sheet material against the tool steel matrix. Sheet materials with lower strength are softer and can therefore more easily be pressed down to the tool steel matrix resulting in higher friction, quicker tool damage and galling.
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The influence of tool steel microstructure on galling

Car body components like doors, hoods and fenders are produced by sheet metal forming (SMF). However, materials such as stainless steels are difficult to form because the sheet material tends to stick to the surface of the metal forming tool. This is a major problem because the material transfer and buildup of sheet material on the tool surface, generally known as galling, results in scratching of the final product. Therefore, it is of high importance for the SMF industry to learn more about how to avoid galling. In this thesis, the overall aim was to gain knowledge of the influence of tool steel microstructure on galling initiation under sliding conditions. It was demonstrated that tool steel phase composition, hardness and sheet material proof strength are important parameters influencing galling. Even on mirror-like polished tool surfaces, nano scale roughness due to protruding carbides was discovered. In the early stage of galling, material transfer around carbides and tool steel matrix damage occurred. At longer sliding, tool steels comprising small and homogeneously distributed hard phases showed better performance. A critical contact pressure for galling was defined for different tool steels in dependence on sheet mechanical properties.