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Influence of tool steel microstructure on origin of galling initiation and wear mechanisms under dry sliding against a carbon steel sheet

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ABSTRACT

The drive to reduce lubrication in sheet metal forming (SMF) operations has increased the interest to study the contact between polished tool materials sliding over relatively rough sheet surfaces. Commonly, transfer of sheet material to the tool surface occurs by adhesive wear. In the present work, a study of wear showed that the origination of the damage was complex and several simultaneous wear mechanisms were operative, even though friction did not change remarkably. A low strength carbon steel sheet was tested under dry sliding conditions against conventionally ingot cast and powder metallurgy cold work tool steels. The sheet was sputtered with a thin gold layer, which acted as a marker helping to reveal details of the wear mechanisms. Initial sliding was characterized by local adhesive wear with transfer of sheet material, predominantly, to the metallic matrix of the tool. Seemingly, the carbides have less adhesion to the sheet material than the steel matrix. Subsequently, materials transfer resulted in gradual coverage of carbides with formation of a semi-continuous thin layer of sheet material on the tools surface. Further sliding led to initiation of local microscratching of the sheet surface due to formation of lumps of sheet material adhered to the tool. Comparison of the two different tool steels revealed that the amount of adhered sheet material depended on amount, size and distribution of carbides and was higher for the ingot cast steel with coarser carbide phase. The advantage of the powder metallurgy steel was associated to removal of adhered material from the tool due to a higher amount and a more homogeneous distribution of finer carbides.

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1. Introduction

Adhesive wear is of great concern in several engineering applications where metal surfaces are forced into contact and slid relatively to each other. A lot of efforts have been made on describing the mechanism and several models exist that predict the adhesive wear rate [1–3]. The most ordinary model was postulated by Archard [2], which is consistent with steady state wear observations and assumes wear to be independent of nominal area of contact and directly proportional to the applied load.

In sheet metal forming (SMF), surface damage often occurs due to galling. The wear process is associated with adhesive wear, where the sheet material is transferred to the tools surface. However, most SMF operations are not steady state wear processes. The tribological system is composed as an open system where the sheet surface is renewed at every new forming operation. Therefore, the system is not run-in, which results in relatively high and stochastic wear rates. Hence, the Archard model for adhesive wear is not applicable for predicting wear in SMF. According to the ASTM standard, galling is defined as a form of surface damage arising between sliding solids and distinguished by macroscopic, usually localized, roughening and creation of protrusions above the original surface [4]. However, previous works have shown that three separate stages of the galling wear process may be distinguished and gross macroscopic surface damage occurs as a final stage and as a result of accumulation of surface damage [5–8].

Initially, the contact is characterized by pure sliding between the sheet material and the tool surface. As sliding proceeds, abrasive microscopic scratches are developed on the sheets due to local adhesive wear with transfer of sheet material to the tools surface. Further sliding leads to accumulation and growth of the transferred sheet material and microscratching is substituted by coarse macroscopic scratching of the sheets. Generally, friction is increased at this point, indicating the transition into the second wear regime. Further sliding leads to a continuous transfer of sheet material to the tools surface and, hence, abrasive wear by hardened wear particles is gradually substituted by an adhesive wear mechanism until the entire contact is worn by severe adhesive wear, associated with high friction and gross surface damage [5,6].

Although, it is possible to use the coefficient of friction as an indicator of transitions in wear regimes [5,6], it should be used with

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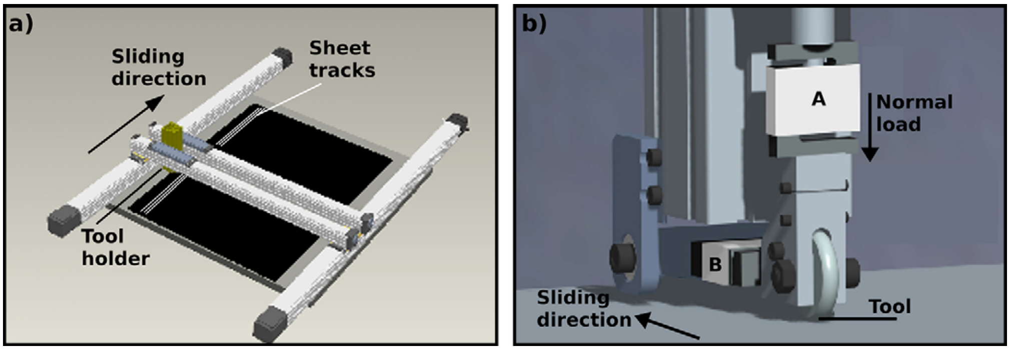

Fig. 1. Principle of the SOFS tribometer where the sheet is fixed on the on the table beneath the tool holder (a). Close-up of the tool holder with normal and friction force gauges (A) and (B). The tool is fixed to prevent rotation during sliding (b).

caution. Firstly, the initial stage with initiation of microscratching is difficult to resolve in friction diagrams and, secondly, some tool materials do not initiate coarse macroscopic scratching, even though subjected to substantial transfer of sheet material. The phenomenon has been discussed related to removal of the transfer layer due to low adhesion between the adhered sheet and the tool, particularly for nitrogen alloyed powder metallurgy tool steels [5,9].

To gain deeper understanding of the galling wear process and the influence of tool microstructure, it is of importance to investigate the very initial contact to reveal how and where the sheet adheres to the tool surface. In the present work, tribological tests were conducted at different test conditions using a slider-on-flat-surface (SOFS) tribometer. Two tool steels were investigated in sliding against a ferritic carbon-steel sheet at dry test conditions. The tests were stopped after short sliding distance and both the sheet and tool surfaces were examined to observe how the transfer layer was developed.

2. Experimental

The SOFS tribometer, which is described in detail in [6], was used for tribological evaluation, Fig. 1. A disc-shaped tool (width 10 mm, diameter 50 mm and transverse radius 5 mm) was forced to slide against the sheet material at a constant normal load of 50, 100, 250 and 500 N for 60 mm at a velocity of 200 mm/min. Sheet and tool surfaces were examined using a scanning electron microscope (SEM) LEO 1530, an Auger microscope (AEM) PHI 660 and an optical profilometer (OP) Wyko NT3300. A thin layer, approximately 20 nm thick, of pure gold was deposited on the sheet surface to make it possible to distinguish on which locations on the tool the sheet was transferred to in SEM. All tests were made at ambient air, in room temperature, at dry test conditions meaning that the sheets were washed with acetone prior to testing. Results from the SOFS tests were extracted from the recorded friction and normal forces data and represented as friction coefficient vs. sliding distance diagrams.

Two different tool steels were investigated; see Table 1 for chemical composition and hardness. The first was an AISI D2 grade cold work tool steel containing relatively large carbides and the second was a powder metallurgical (PM) cold work tool with a more homogeneous distribution of small carbides. The tools were polished to a Ra value of approximately 50 nm. The sheet was a ferritic carbon steel in the as-rolled condition with a surface roughness Ra of approximately 1.3 μm and proof stress at which 0.2% plastic deformation occurs, $R_{p0.2}$, of 260 MPa. Ultimate tensile strength is the highest stress the material withstands, R_m, of 330 MPa, as supplied by the sheet manufacturer.

3. Results

SEM analyses demonstrated that adhered sheet material was present on both tool steel surfaces for all investigated normal loads. However, by evaluation of friction diagrams, no sign of wear was distinguished in terms of changes in friction during sliding. The coefficient of friction remained relatively stable throughout the entire sliding interval at a value of approximately 0.2 for all test conditions, Fig. 2a. AEM analyses of the adhered material showed that the transfer-layer contained iron and gold, Fig. 2b. The absence of Cr, typical alloying element in the selected tool steels, indicates that the iron originated from the sheet substrate due to wear. Hence, wear was not limited to the gold coating alone. The latter demonstrates that the wear mechanisms observed were not governed only by the gold film properties, but, also by roughness and properties of the substrate. The presence of carbon and oxygen was due to the test conditions, which were conducted in air atmosphere. Further, the mixture of gold and iron in the transferred layer led to a brighter contrast, as compared to the tools iron-based metallic matrix, using SEM back-scattered electrons, due to higher atomic number of gold.

Examination of the tool and sheet surfaces showed that the wear was complex and several characteristic wear features were observed throughout the testing. As illustrated in Fig. 3 different regions were characterized in the contact. Locally, sheet material was observed, predominantly, on the metallic matrix of the steels without coverage of carbides, Fig. 3a and b, indicating that the initial material transfer occurred to the steel matrix for both tools. Fig. 3c and d show regions which were subjected to a higher extent of material transfer with gradual coverage of carbide phase.

It was assumed that the continued sliding led to growth of the transfer layer with formation of a thin semi-continuous film of adhered material covering the tools surface. The amount of transferred material was found significantly less on the PM steel

Table 1
Nominal composition of the materials and hardness of the tool steels.

Sample	Alloy type (wt.%)	Carbide amount (vol.%)	Carbide size (μm)	Hardness
PM	1.1C, 1.8N, 4.5Cr, 3.2Mo, 3.7W, 8.5V	20% M(C,N), 4% M,C	<2	63 [HRC]
AISI D2	1.5C, 0.01N, 12Cr, 0.9Mo, 0.8V	13% M_7C_3	<50	60 [HRC]
Sheet	0.05C, 0.20Mn, 0.003N, 0.04A1	–	–	–

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