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Wear behaviour of thermally oxidised tool surfaces as low-friction separation layers for dry sheet metal forming

D. Yilkiran [a,*], D. Wulff [b], A. Almohallami [a], F. Özkaya [a], A. Bouguecha [a], S. Hübner [a], K. Möhwald [b], H.J. Maier [b], B.-A. Behrens [a]

[a] Institut für Umformtechnik und Umformmaschinen (Institute of Forming Technology and Machines), Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany

[b] Institut für Werkstoffkunde (Institute of Materials Science), Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany

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ABSTRACT

This paper presents the results and analysis of wear investigations carried out on a wear test bench with high strength sheet metal DP600+Z drawn over selectively oxidised α-Fe_2O_3 tool steel surfaces. Wear investigations were carried out with several selectively oxidised specimens by varying the pulling and counter force, and thus the surface pressure on the samples. This allowed for a systematic study of the wear behaviour of the oxide layers under different loads. The specimens were characterised using microscopy (light microscopy, scanning electron microscopy and topography analysis) and scratch testing on a nanoindenter. The study shows that it is possible to realise a dry metal forming process while using α-Fe_2O_3 oxide layers on the tool steel surface. The oxidised surface acts as a friction reducing separation layer and protects the tool against wear. Simultaneously, it was found that the surface of sheet metal drawn over oxidised specimens showed lower zinc abrasion than sheet metal drawn over non-oxidised reference specimens at the same surface pressure. In addition, the oxidised specimens have a reduced Zn pick-up affinity.

1. Introduction

In today's industry friction and wear annually cause enormous amounts of costs. According to current estimates the direct losses due to friction and wear in industrialised countries are up to 7% of the gross national product [1]. The bulk metal forming as well as the sheet metal forming industries are two of the most severely affected sectors in terms of wear related production failures. Conditioning of tool surfaces is widely used to optimise friction conditions and reduce the wear of forming tools [2–4]. In sheet metal forming and particularly in deep drawing, where the contact area is large, tools can wear out fast especially when friction conditions are unfavourable. Conventionally, in order to reduce friction and increase tool wear resistance, liquid lubricating oils are used. The use of these oils, however, has critical disadvantages. Oils and especially mineral oils pollute the environment. Some are even mixed with environmentally very harmful additives, which are often not or only poorly biodegradable [5,6].

Moreover, the use of forming oils results in longer process chains due to additional cleaning steps, and thus, the process is more expensive. Dry metal forming is an ambitious alternative to oil based lubrication methods. According to [7] dry metal forming is defined as "*a process where a workpiece leaves the forming tool without the necessity of cleaning or drying before further production steps such as coating or joining processes*". In current research different approaches for dry metal forming in sheet as well as in bulk metal forming are investigated, e.g. [8–12].

In general, a metal-metal contact between a forming tool and work piece has to be avoided. A better alternative is an oxide-oxide contact, which leads to less adhesion and junction growth [13,14]. The new approach employed in the present study is to generate a thin oxide layer on the surface of hardened tool steel by heat treatment. In this case an oxide-oxide contact is achieved because the specimen is oxidised and the zinc coating of DP600+Z high strength sheet metal features a native oxide.

However, in order to maintain the tool hardness and its geometry, the process temperature must be kept below the annealing temperature of the hardened tool steel so that the tool can be employed directly without any additional mechanical or thermal post-processing steps.

Therefore, a temperature of 500 °C was used for the heat treatments. At this temperature different oxide modifications can appear on the steel surface during heat treatments depending on the process conditions and especially the partial pressure of

* Corresponding author.
E-mail address: dyilkiran@ifum.uni-hannover.de (D. Yilkiran).

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oxygen. Heat treatments under air or oxygen in the temperature region of 450–550 °C lead to the formation of thick oxide layers with an inhomogeneous chemical composition [15,16]. In order to achieve consistent mechanical properties, oxide layers with a controlled, homogeneous chemical composition are desired for dry sheet metal forming.

The formation of oxide layers with a homogeneous composition at 500 °C can be realised by adjusting the partial pressure of oxygen and the process time as reported in Ref. [8]. The characterisation of these oxide layers on the microscopic scale is difficult because the layers are typically very thin (only a few hundred nm). Therefore surface sensitive analysing methods like SEM (scanning electron microscopy), FIB (focused-ion beam) and GIXRD (grazing incidence X-ray diffraction) were performed in related studies [8,17]. Especially GIXRD using synchrotron radiation is a valuable non-destructive technique to analyse the crystal structure and to obtain depth profiles by variation of the incidence angles [18].

The present study focuses on the wear behaviour of oxide layers, which were generated under an N_2 process atmosphere with a partial oxygen pressure within the furnace of (1.5 ± 0.5) 10^{-1} mbar. Under these process conditions an α-Fe_2O_3 oxide structure was formed on the specimens [17], which caused a red/blue discolouration of the entire surface [8,19].

In previous studies that employed strip drawing tests it was shown that α-Fe_2O_3 oxide layers can reduce the friction coefficient between a tool steel surface and a sheet metal strip of DP600+Z [8,19,20]. One main result of the performed strip drawing tests was that the friction coefficients of specimens with microcrystalline α-Fe_2O_3 layers were only slightly higher than the coefficient determined for conventionally oiled reference specimens.

Positive effects of Fe_2O_3 on the friction and wear behaviour have already been reported earlier. Specifically, many studies dealt with friction and wear behaviour of steel tested without lubrication by means of pin on disk tests with steel pins at temperatures between 20 °C and 600 °C [13,14,21–23]. In all these studies it was shown that the formation of the metal oxide was responsible for the reduction of friction. The oxide, mostly Fe_2O_3, was typically generated from metallic debris during severe wear. In mild wear regimes oxide removal and new formation were reported to reach a steady-state condition, and thus, friction and wear were at a constant level. At low temperature the oxides were not beneficial regarding friction and wear behaviour. In [14] it was postulated that a reason for this is the inferior bonding between oxide particles and of oxide particles to the substrate at low temperatures. Another proposed aspect was that at higher temperatures plastic deformation occurs earlier.

Motivated by the reports about the positive impact of Fe_2O_3 on the friction and wear behaviour [13,14,21,22] further investigations concentrated on the effects of nanometer sized oxide particles introduced into the tribosystem [24–26]. In these studies a friction reducing oxide layer was formed on the surface by sintering if the particles were not oversized.

2. Materials and methods

2.1. Materials and specimen preparation

For the wear tests cylindrical specimens as shown in Fig. 1 were machined from tool steel X153CrMoV12 (EU alloy grade 1.2379 with an elemental composition of 12% Cr, 1.55% C, 0.9% V, 0.8% Mo, in wt% and balance Fe).

After hardening the specimens to 56 ± 2 HRC, the surfaces were wet ground to remove the cinder from the hardening process to ensure reproducible starting conditions. The grinding process was executed with a computerised numerical control cylindrical grinder machine (Kellenberger UR 175×1000) equipped with a diamond finishing grinding wheel (D64C50, Kraus & Winter). The cutting speed was 25 m^2 s^{-1} and the coolant was fully synthetic. With an optical 3D-macroscope the arithmetical mean height value of $S_a = 1.04$ μm $\pm$ 0.09 μm was measured. The hardness of the grounded specimens and the DP600+Z sheet metal was determined within three measurements. The average value of the specimens hardness was 641.8 HV30 while the average hardness of the sheet metal was 190.7 HV01.

Prior to the oxidising heat treatments, all specimens were cleaned in an ultrasonic bath with ethanol (> 96.0%) for 10 min. After cleaning they were first rinsed with pure acetone (> 99.5%) and in a second step with pure ethanol (> 99.8%).

The active part of the specimen is a cylindrical geometry which was assembled on a socket with two screws and a bolt to avoid rotational movement during the tests. Due to increased temperatures in forming of high strength steels in real deep drawing processes the specimen socket was designed such as to allow for heating and monitoring the temperature of the wear specimen. Further information about the specimen design can be found in [27]. The geometry of the specimen and the socket for the assembling on the wear test bench is shown in Fig. 1.

For subsequent surface analysis all cylindrical specimens were marked on the front surface at three angles with respect to the direction of sheet metal band motion. The band inlet area equals 0°, and at 45° and 90° from the inlet area the second and third marks were placed (cf. Fig. 1 left).

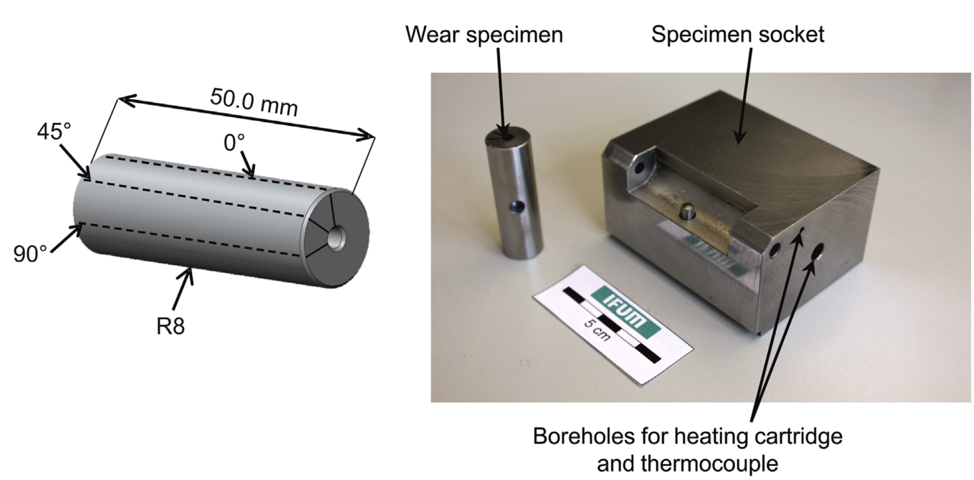

Fig. 1. Geometry of the cylindrical specimen used for the wear investigations (left); and actual specimen and specimen socket (right) [27].