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Galling mechanisms during interaction of tool steel and Al–Si coated ultra-high strength steel at elevated temperature

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ABSTRACT

Occurrence of galling in hot forming is detrimental to the quality of produced parts and process economy. Material transfer from Al–Si coated work-piece to the tool material has been studied in this work. PVD coatings (AlCrN, TiAlN and DLC) on tool steel substrate have been considered as well as plasma nitriding and their tribological behaviour was compared to the case of an untreated tool steel. Galling initiates through accumulation and compaction of wear debris when untreated tools are used whereas the PVD coatings resulted in increased galling due to adhesion. Plasma nitrided tool steel showed negligible galling due to formation of glaze layers and the formation of such layers depends on the occurrence of wear of the nitrided tool steel.

1. Introduction

In metal forming processes, the quality of the produced parts as well as the life of the forming tools are vital for the economy of the process. In any forming process, the monitoring and control of wear of tools is therefore extremely important. Ultra-high strength steel (UHSS) parts are nowadays commonly produced by means of hot forming processes. In many instances, the UHSS is coated with an Al–Si coating which at high temperatures interacts with the Fe from the work-piece steel substrate and forms hard intermetallic phases [1–3]. These intermetallics drastically affect the tribological behaviour of the system and can cause wear of both the tools and the produced parts.

As a severe form of adhesive wear, galling of tools is a frequent and major problem when forming the Al–Si coated UHSS. It not only adversely affects the produced parts but also increases the downtime for maintenance of tools. In metal forming, at low and elevated temperatures, surface roughness of the tools has been found to be of great importance in galling initiation [4–6]. In his study [5], Schedin observed that galling has a tendency to initiate at the irregularities on the surface. He further stated that keeping in view the way galling initiates (adhesion), material transfer cannot be completely avoided and only the growth rate of the transferred layer may be controlled. During the forming process, die corners are regions where temperatures and normal contact pressures are high and these sites are prone to galling. It has been proposed that high local temperature and normal contact pressure can be of great importance in the occurrence of galling [7].

Surface engineering has been suggested as a possibility to overcome galling as this can prevent adhesion between the tool and the work-piece surfaces. At low temperatures, DLC coatings have been reported to have good galling resistance in lubricated conditions, and with smoother surface even under dry conditions [6,8]. Eriksson and Olsson [9] evaluated the galling and wear characteristics of CrN, Ti, AlN and CrC/C PVD coatings in lubricated sliding contact with different high strength steel sheets. They suggest that besides the frictional properties of the coatings, the size and density of surface defects also influence the material pick-up tendency since both macro particles and shallow craters will affect the interaction with the counter surface.

Some studies pertaining to the use of lubricants for reducing galling problems in hot stamping have been done [10]. It was found that the use of lubricants helps in decreasing the stamping load and the die wear. However, it is unclear whether the use of such lubricants would have a beneficial effect in reducing galling during hot forming of Al–Si coated UHSS. The influence of surface engineered tool steels and the tool steel grade has also been considered by some researchers [11,12]. The use of some coatings on the tool steel has been reported to have a negative effect on the wear of the produced parts (work-piece) and in some cases the use of coatings also increased galling tendency in hot stamping. Boher et al. [12] found that for all the tool steel grades, adhesion of fine particles from the Al–Si coating onto the tool steel surface was prevalent. They suggested that modification of the chemistry of the tool steels could lead to a better adhesion and abrasion resistance.

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The authors in their previous work also observed that accumulation and compaction of debris are key features in material transfer when uncoated tool steels slide against Al–Si coated UHSS [13,14]. Big lumps of material develop due to accumulation of debris and this effect is enhanced under high contact pressures.

In the case of the Al–Si coated UHSS sliding against uncoated tool steels, the surface topography of the tools plays an important role in the occurrence of galling. In a recent study [14], the authors have identified that surface topography parameters such as *Rsk*, *Rv*, *Rp* and *Sm* are of great importance when describing the susceptibility of a tool steel surface to initiate galling as these parameters relate to sites where debris can be accumulated.

Despite these efforts, the detailed mechanisms responsible for galling of Al–Si coated UHSS at elevated temperatures are not yet fully understood. An understanding of the initiation mechanisms is necessary in order to develop new and improved ways of alleviating galling. The main aim of this work is therefore to clearly describe the galling mechanisms that are encountered during the interaction of Al–Si coated UHSS with tool steels, with and without surface modification. The surface modifications studied in this work were hard PVD coatings and plasma nitriding.

2. Experimental

2.1. Experimental materials and test specimens

The tool steel specimens used for the tribological tests were in the form of a pin of Ø2 mm made from a quenched and tempered tool steel. Three variants of the pin specimens were used; uncoated tool steel specimens, PVD coated specimens and plasma nitrided specimens. The chemical composition of the tool steel is the same as that commonly used in the actual hot stamping process and it is a quenched and tempered tool steel.

The uncoated tool steel specimens were used with two different surface finishes; one surface was prepared by coarse grinding whilst the other surface was obtained by milling. The surface roughness Sa was 2.7 μm and 2.4 μm respectively.

The three different PVD coatings that were considered were AlCrN, TiAlN and a DLC (diamond like carbon). The coatings were deposited on polished and nitrided tool steel specimens resulting in a duplex surface modification. Before the surface modification, the specimens were polished to a surface roughness (*Sa*) of ~50 nm.

It is known that after PVD coating deposition, surface defects are created. It has to be kept in mind that the effect of surface irregularities may be amplified when hard coatings are used. To consider the effect of surface defects, polishing of the PVD coatings was done until a surface roughness of ~90 nm was achieved.

In Fig. 1, micrographs of the cross-section of the PVD coated pins are shown. As can be clearly observed, the TiAlN coating is the thickest (~10 μm) and the thinnest is the DLC coating (~2 μm). The AlCrN had a thickness of ~3 μm.

Plasma nitriding treatment without any coating was also considered and two of its variants were studied; one was a traditional plasma nitriding process and the other was plasma nitriding with a post-oxidation treatment. Fig. 2 shows the oxide layer formed during the post-oxidation treatment. Similar to the previous case, the specimens were also polished to a surface roughness Sa of 50 nm before the surface treatment.

The cross section of the oxide layer formed during the post-oxidation treatment, Fig. 2, revealed that the layer is relatively dense, only a small amount of pores could be observed. It is also well adhered to the substrate. The thickness of this layer is ~3 μm.

The properties of the evaluated pin specimens are listed in Table 1. The hardness and operating temperature values of the PVD coatings given in this table were provided by the supplier, the surface roughness Sa and the thickness values were obtained from laboratory measurements using a 3D optical profiler and SEM cross sections respectively. The values of the plasma nitrided specimens were all measured in laboratory. The hardness of the plasma nitrided specimens was taken at the surface using a micro Vickers hardness test using a load of 200 g for 15 s.

The counter material specimen for the tribological tests was in the form of a disc. The geometry was Ø16 mm and 1.7 mm height and it was an Al–Si-coated UHSS which was spot welded onto a steel backing plate of Ø24 mm and 6.3 mm height. The surface roughness of the Al–Si coated specimen was ~2.5 μm in the as delivered condition.

2.2. Test equipment and procedure

Tribological tests were carried out using an Optimol SRV high-temperature reciprocating friction and wear tester. The detailed

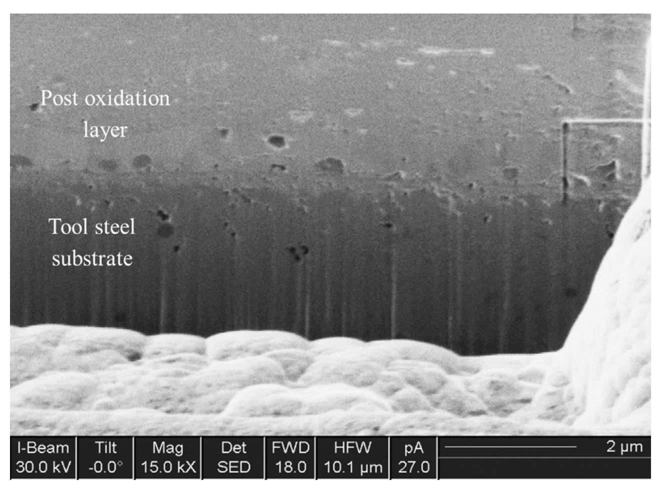

Fig. 2. Cross section of post oxidation layer formed on the plasma nitrided specimen.

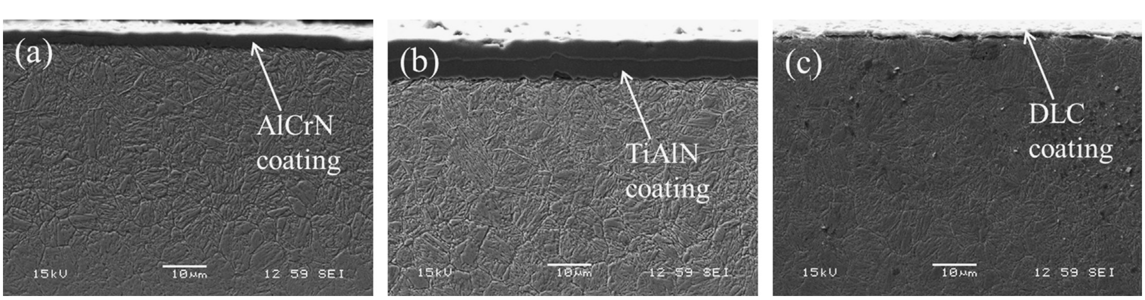

Fig. 1. SEM images of the cross section of the as delivered (a) AlCrN, (b) TiAlN and (c) DLC coatings.