Wear 315 (2014) 87–94

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Transfer of titanium in sliding contacts—New discoveries and insights revealed by in situ studies in the SEM[☆]

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ARTICLE INFO

Article history:
Received 31 December 2013
Received in revised form
4 April 2014
Accepted 5 April 2014
Available online 16 April 2014

Keywords:
Surface topography
Coatings
Titanium
Material transfer
Galling
Friction

ABSTRACT

Titanium and its alloys generally display poor tribological properties in sliding contacts due to their high chemical activity and strong adhesion to the counter surface. The strong adhesion causes a high tendency to transfer and ultimately galling or build-up edge formation, resulting in severe surface damage. As a result, forming and machining of titanium and its alloys are generally associated with significant problems such as high friction, rapid tool wear and poor surface finish of the formed/machined surface.

In the present study, in situ tests in a scanning electron microscope have been performed to increase the understanding of the mechanisms controlling the initial transfer of titanium (Grade 2) in sliding contact with tool surfaces. Tool materials included cover cold work tool steel, cemented carbide, CVD deposited Al_2O_3 and PVD deposited DLC. In these tests, a relatively sharp tip, representing the titanium work material, slides against a flat surface, representing the tool. The contact conditions result in plastic deformation of the work material against the tool surface, thereby simulating forming or machining. The limited and well-defined contact, along with the possibility to study the sliding in the SEM, makes it possible to correlate local surface variations to transfer of work material and frictional response. Post-test characterization of the contact surfaces was performed by high-resolution SEM, TEM, EDS and EELS.

The initial friction was low and stable against all tested materials, but then gradually escalated against all surfaces except the DLC. The friction escalation was associated to increasing levels of transfer, while the DLC stayed virtually free from transfer. From these very initial sliding tests DLC is a promising tool coating in forming and machining of titanium.

1. Introduction

Titanium and its alloys have good mechanical properties, desirable corrosion resistance and low density, and are widely used in e.g. aerospace and chemical process industry. However, in sliding contacts they show poor tribological properties, due to high chemical activity and associated strong adhesion, leading to adhesive transfer to the counter surface. This causes problems in forming and machining, ultimately leading to galling and built-up edge formation, respectively. These processes are associated with high friction and wear, resulting in poor surface finish of the formed or machined titanium surface.

The strong tendency to adhesive transfer of titanium and associated issues has been researched by several groups for many years [1–7]. To reduce the transfer tendency various counter surfaces and surface treatments have been proposed and evaluated. Some ceramic counter surfaces, including alumina and silicon nitride, have been tested with poor results [1–3]. This has been attributed to tribochemical reactions, and for alumina it is due to the formation of titanium aluminides, along with various titanium oxides [1]. Steel counter surfaces have proven to work better than alumina, both when it comes to friction and wear, however still causing adhesive transfer to the same [2]. A carbon based counter surface, polytetrafluoroetylene (PTFE), has on the other hand proven very effective in preventing adhesive transfer [2]. Initial transfer of PTFE to the titanium surface causes a low friction PTFE-PTFE sliding contact. Investigations where the titanium surface has been coated to prevent metal to metal contact during sliding has also been reported in the literature. Thermal oxidation or anodization, to form a thick TiO_2-oxide, protects the surface efficiently from transfer, however with a relatively high friction [4,5]. Combining the anodizing with addition of PTFE or MoS_2 combines surface protection of the oxide with an easily shared layer, which lowers the friction [5]. However, although adhesive transfer of titanium has

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[☆] This paper was presented at the 2013 World Tribology Congress.
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http://dx.doi.org/10.1016/j.wear.2014.04.006

been a thoroughly researched topic, the initiation of transfer is still to be investigated.

The objective of the present work is to increase the understanding of the mechanisms behind the initial transfer of titanium in sliding contact with different tool surfaces during forming, of interest for the manufacturing industry. The system is simplified by studying a contact with commercially pure titanium, without any significant amounts of alloying elements. Neither is coating or surface treatment of the titanium taken into account, due to the extensive plastic deformation and surface expansion often associated with forming processes, and like any solid lubrication of the titanium, they would also have to be removed in a later stage during production and is thereby undesired. Four different counter surfaces are studied; cold work tool steel and cemented carbide, representing commonly used tool materials, an alumina coating, representing a traditional coating for cutting inserts, and a DLC coating, representing a coating that previously have proven successful in galling prevention with aluminium and stainless steel [8,9].

The contact is studied in detail by performing well controlled in situ tests in a scanning electron microscope (SEM). The contact is limited to a single titanium asperity (Ø≈100 μm) in sliding contact with a tool material under a load sufficient to cause plastic deformation of the titanium. Transfer particles can be directly observed and correlated to surface features of the tool material and the friction response in the system. Although being a radically simplified test, it mimics central parts of the contact situation in forming, and gives unique insights into the very initial friction and wear mechanisms. This method has recently proven successful in studying the phenomena of initial material transfer of aluminium and stainless steel [8–11].

2. Experimental

2.1. Materials

Titanium Grade 2, i.e. commercially pure titanium (> 99% Ti), with a hardness of 145 HV, was selected to represent the work material in the present study. Cylinders (Ø2.9 mm, length 15–20 mm) were manufactured by turning, followed by shaping a tip in one end. The final preparation of the tip was grinding with 1000 followed by 4000 grit SiC grinding paper.

The investigated tool materials include nitrogen alloyed powder metallurgical cold work tool steel (Uddeholms Vancron 40, wt%: 1.1 C, 1.8 N, 0.5 Si, 8.5 V, 4.5 Cr, 0.4 Mn, 3.2 Mo, 3.7 W, bal. Fe), cemented carbide (94% WC, 6% Co), chemical vapour deposited alumina (Al_2O_3) and physical vapour deposited diamond-like carbon (DLC), the latter two coatings deposited on cemented carbide and tool steel substrates, respectively. All tool materials were carefully polished, to be able to study differences in tool material chemistry rather than the effect of micro-scale surface roughness. The final polishing step comprised mechanical polishing with 1 μm diamond paste, resulting in mirror-like surface finish with a surface roughness of $Rz < 50$ nm. The surface appearance after the final polishing was imaged using atomic force microscopy (AFM; PSIA XE150), see Fig. 1. All four samples showed small surface irregularities, in sizes up to single nanometres. Further, the alumina surface showed the presence of nano scratches and thermally induced cracks, and the tool steel displayed somewhat larger protrusions (10–15 nm), deriving from carbonitride particles present in the microstructure.

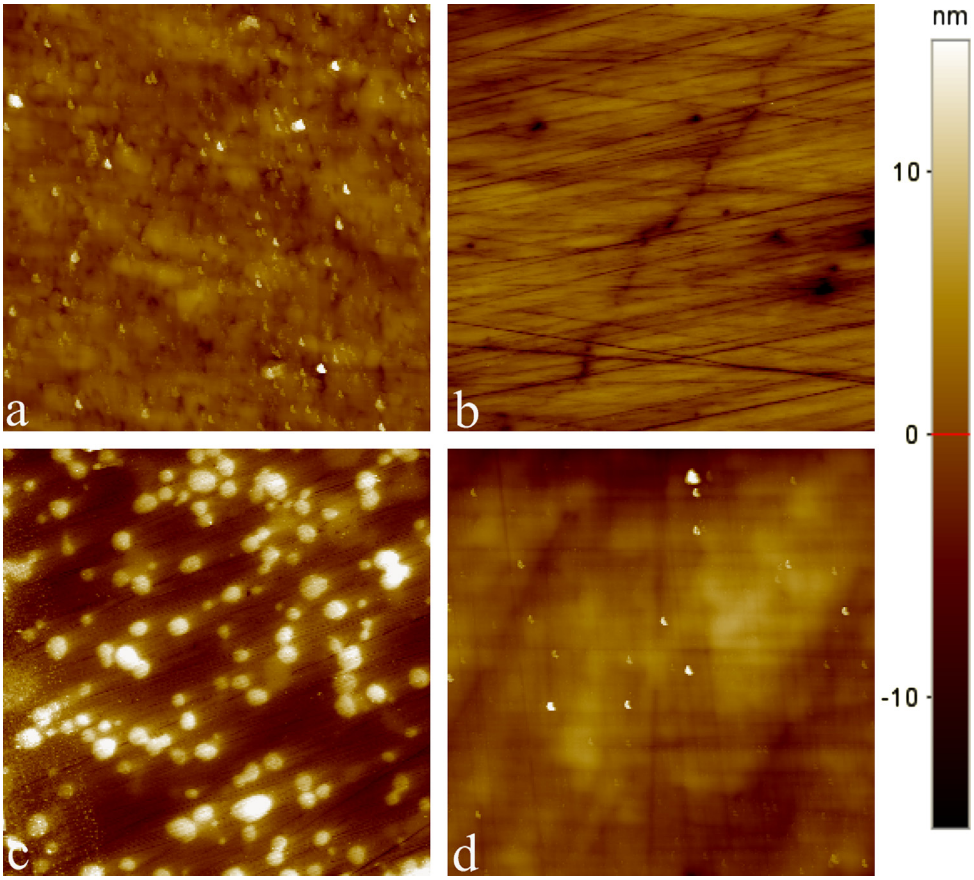

Fig. 1. AFM topography images showing the surface features over an area of 20 μm × 20 μm of the polished tool material flats. (a) Cemented carbide, (b) alumina, (c) tool steel and (d) DLC.