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Transient softening in lubricated sliding contacts due to strain path changes

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ABSTRACT

The present work investigates microstructure evolution in pure aluminium under lubricated contact conditions. The initial wear scars were obtained in unidirectional sliding up to a pre-defined number of cycles N. After this pre-imparted severe plastic deformation, the sliding direction was reversed and the resulting microstructure was characterized using hardness measurements and microscopy techniques. The results show that immediately after reversing the strain path, the material significantly softens, as known in uniaxial tension-compression experiments. After the transient softening stage, the new microstructure becomes established and the polycrystal work-hardens again. The results obtained proof the presence of strain path change effects in metals undergoing sliding contact and highlight the importance to take these effects into account in component design in order to avoid undesired material softening.

1. Introduction

Many metallic components used in diverse industrial applications often experience changes in loading direction during their operational lifetime. The change in loading direction in metals results in an offset of the yield stress, which is commonly known as “Bauschinger effect” and is attributed to internal backstresses induced before reversing the strain direction. This effect is named after the pioneering work of Johann Bauschinger, who described for the first time in 1886 the differences in yield stress during alternating loading [1].

However, in metallic materials pre-deformed by severe plastic deformation, the changes undergone at the microstructural level are so dramatic that upon strain path changes not only an offset in yield stress is observed but also significant changes in flow stress evolution. Depending on the severity of the pre-deformation imparted, the flow curve is characterized by a transient softening stage. Rauch et al. showed that strain path changes lead to a transient flow stress stagnation or even strain softening, before the material recovers its strain hardening behaviour again [2]. Transient strain softening has been observed in tension-compression tests on copper [3] and severely deformed copper by equal channel angular extrusion [4], shear tests on AA1050, AA6022 and low carbon steel at room and cryogenic temperatures [2,5], torsion tests on Nb-microalloyed steel at high temperature [6], tension-shear on mild steel [7], tension-compression of mild and dual-phase steel [8], tension-compression of zircaloy [9], compression of rolled beryllium [10,11] and tension-compression on dual-phase steels [12] among others. Also an increasing transient softening stage has been reported in compression tests for tungsten [13] wires with smaller diameters, i.e. increasing degree of pre-imparted uniaxial elongation. The reason for the transient softening is that after reversing the strain direction, the original microstructure is gradually replaced by a new dislocation structure created in the latter strain path [2]. The effect of strain path changes on polycrystalline metals is thus well-known and has been the subject of a large number of theoretical work in order to account for transient softening in computer simulations [10,14–17].

In tribology, it is well-established that upon sliding contact, the sub-surface zone of polycrystalline metals experiences plastic deformation if contact stresses are higher than the yield stress. The imparted plastic deformation results in an increase in the dislocation density, formation of low-angle grain boundaries and finally grain refinement by consolidation of this low-angle grain boundaries. Strain hardening and Hall-Petch effect due to grain refinement both lead to an increase of the yield stress that at the macroscopic level is visualized as a hardness increase [18–20]. Consequently, in analogy to uniaxial mechanical tests, it can be expected that changes in sliding direction will eventually lead to offsets of the yield stress as a consequence of the Bauschinger effect, which could be measurable as changes in sub-surface hardness according to the Tabor relation.

Within this context, the initial work of Tang et al. revealed that in dry sliding contacts, alternate changes in sliding result in a

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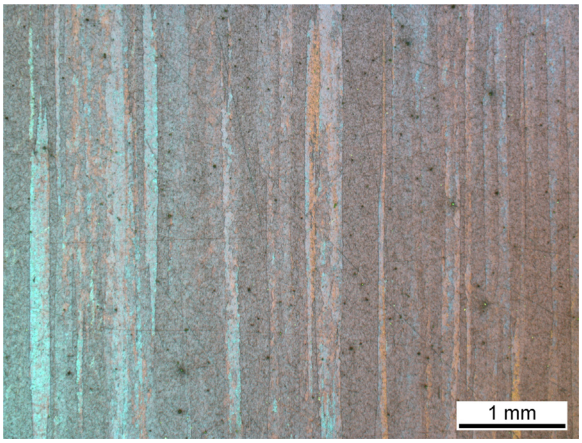

Fig. 1. Microstructure of the as-received AA1050 aluminium alloy.

different sub-surface microstructure that influences hardness and wear of the material [21]. In particular, their research showed that Cu-40%Zn alloy sliding against a steel wheel wears less when alternating the sliding direction, when compared to unidirectional sliding and that wear saturates to a minimum value by increasing the number of reverse cycles. Sub-surface hardness as a function of the number of alternating cycles has an initial slightly rise followed by a decrease of hardness. The differences in hardness are ca. 5 HV being the error reported by the authors less than 2% i.e. less than ± 3.6 HV. A similar trend was found for other loads and sliding speeds when using a steel wheel as counterbody [22].A follow up work showed that this trend is reversed when replacing the steel by a ceramic wheel, leading to higher wear and lower hardness with increasing number of alternating cycles [23]. Following a similar goal, the work of Harea et al. focused on the differences in dislocation structures in LiF single crystals under unidirectional and reciprocating sliding [24]. Their work confirms that continuous changes in sliding direction lead to lower coefficients of friction, subsurface hardness and wear scar widths, when compared to unidirectional sliding. The difference is attributed to the Bauschinger effect.

As shown, the interest in the role of strain reversals in tribology came up recently and number of publications currently available in literature is scarce. Despite of the fact that the role of strain path changes has been thoroughly addressed within the context of bulk materials, it has been seldom considered in tribology. To our best knowledge, all currently available sources study the differences between unidirectional contact and alternating the direction of sliding after the same number of cycles back and forth. However, it is expected that after a sufficiently higher degree of plastic deformation, a single strain reversal may lead to a transient softening stage in analogy with uniaxial tests on severe plastically deformed metals, which could be evidenced as a decrease in sub-surface hardness. The goal of this work is to explore if this softening stage also appears in sliding contacts and evaluate its consequences in terms of wear.

2. Experimental

2.1. Materials and lubricants

Commercially pure wrought aluminium alloy 1050/A (MG Handel AG, Germany) with an aluminium content > 99.5% and hardness 21 HB was selected as model metal for visualizing the role of strain path changes in sliding conditions. The as-received aluminium alloy plates were ground using 2000 grit paper followed by polishing using by 3 μm diamond paste and a final polishing step using oxide polishing suspension in order to obtain a mirror-polished surface with a R_a roughness of about 50 nm. The original grain morphology of the as-received samples was elongated in the axial direction (Fig. 1).

Table 1
Summary of the testing parameters.

Normal Load	100 N
Temperature	50 °C
Sliding velocity	0.2 m/s
Number of reverse cycles for 100 forward cycles	0, 2, 10, 20
Number of reverse cycles for 1000 forward cycles	0, 100, 200, 500, 1000

A tungsten carbide WC94-Co6 ball (Kugel Pompel, Austria) was used as counterbody. The ball had a diameter of 10 mm and a nominal hardness value of 90–91.5 HRA. The tests were performed under fully-flooded lubricated conditions in order to minimize as much as possible abrasive and adhesive wear and impart most of the surface degradation by ploughing. The selected lubricant was additive-free FVA1 reference oil (Weber Reference Oils, Germany) with a kinematic viscosity at 50 °C of 11 mm^2/s. The use of an inert ceramic ball combined with additive-free oil lubrication was pursuing the suppression of tribochemical reactions at the contact interface.

2.2. Tribological tests

The tribological tests were performed in a SRV®3 tribometer (Optimol, Germany) with the available rotation system under unidirectional sliding conditions using a ball-on-disk configuration. The tribological tests were performed with a load of 100 N and a constant sliding speed of 0.2 m/s. A constant oil temperature of 50 °C was set in order to ensure isothermal testing conditions independent of the lab conditions. The testing parameters are summarized in Table 1. All tests series are characterized for having a constant number of rotations in the forward direction (100 or 1000). After having reached the selected number of sliding rotations, the tests were stopped and some of the wear scars were run in the reverse direction for an increasing number of reverse cycles.

Hardness measurements were performed according to Brinell testing method using a load of 10 Kgf and a ball diameter of 2.5 mm. Initial measurements performed directly on top of the wear scar were inaccurate as a consequence of the rough topography on the tested scar after the test. In order to reduce the scattering of the results, the authors decided to ground the sample carefully, down to the bottom of the wear scar. After this process, Brinell hardness was measured on the polished bottom of the wear scars. At least 8 individual measurements were performed to ensure statistical relevance of the results. The typical standard deviation was less than 4%.

Hardness was measured on selected cross-sections using instrumented nanoindentation. The measurements were performed using a Hysitron Triboindenter TI900 (Minneapolis, USA) equipped with a diamond Berkovich indentation tip with 100 nm tip radius. Hardness values were calculated from the load vs. depth curves according to Oliver and Pharr [25]. In our case, the selected load was 2 mN. Each value shown is the average of ten individual measurements. The nanoindentation measurements were performed with the aim to obtain hardness values in the immediate vicinity of the surface interface. Under these conditions, macroscopic hardness is not a suitable method since measurements too close to the surface would be inaccurate due to edge effects and valid measurements would be too far from the surface to capture the desired region of interest.