Tribology International 119 (2018) 567–584

Contents lists available at ScienceDirect

Tribology International

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

Insights into the behaviour of tool steel-aluminium alloy tribopair at different temperatures

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ARTICLE INFO

Keywords:
Elevated-temperature tribology
Aluminium alloy
Tool steel
Oxidation-enhanced wear

ABSTRACT

Friction and wear of a tribopair: aluminium alloy 6082 and tool steel H13, were studied at room temperature and elevated temperatures corresponding to hot forming of aluminium alloys. At the contact pressure of 510 MPa, abrasive wear of the tool steel was the main degradation mechanism observed. At the contact pressure of 810 MPa, galling, i.e., severe adhesive wear of the aluminium alloy occurred at 350 °C, while at all other temperatures, abrasive wear of the tool steel dominated. Oxidation greatly enhanced wear of the tool steel, yielding greater material losses with increase in test temperature. Some of the wear debris that was released from the steel discs accumulated on the pin surfaces and formed a glaze layer capable of plastic deformation.

1. Introduction

Aluminium is one of the most widely used metals at present, only second after steel, due to its high strength to weight ratio, good thermal and electrical conductivities and tendency to passivate, providing resistance to corrosion in several common application environments [1,2]. Furthermore, aluminium is relatively easy to form and machine. Indeed, roughly half of the produced aluminium is given the final shape through cold or hot forming processes, such as extrusion. The objects with a fixed cross-sectional profile may be created by these processes, with examples of the shapes being tubes and various types of open, semi-hollow and hollow sections. In cold and hot forming processes, the main difference is the operating temperature, which is evidently higher in the latter, enabling recrystallization of the material. However, in both processes, the extrusion die gives the final shape of the object [2]. It is typically a steel disk with an opening, shaped and sized to yield the desired cross-sectional profile, and the material to be formed is pushed through it with a ram (a direct extrusion process) or a container holding the material (indirect extrusion). The tribology of the material pair: the aluminium alloy to be formed and the steel die to give the shape, is then of significant importance with respect to the operational performance of the forming process (energy losses due to friction, interruption caused by tool wear) and the quality of aluminium alloy objects (die lines, surface pickups, surface roughness).

Earlier, Heinrichs and Jacobson [3,4] have studied the tribology of aluminium-steel pair related to cold working. By using a test set-up of two crossed cylinders in a sliding contact and a load-scanner test mode from 100 to 1200 N at room temperature, galling, i.e., transfer of work material to the tool surface, was detected irrespective of the surface condition of the test materials (aluminium alloy 6082, tool steel H13) [3]. Although ceramic coatings may prolong the tool life, they were demonstrated to not completely eliminate the galling tendency [4]. At elevated temperatures, the tribological behaviour of the material pair becomes even more complex, due to, e.g., contribution of oxidation to the surface processes [5–7]. However, only during the recent years has the tribology of the aluminium-steel contacts at elevated-temperatures become the topic of a wider scientific interest. Wang et al. [8] have made ball-on-disc tests for aluminium alloy 7745-tool steel H11 pair at 350–500 °C for the determination of friction coefficients as input data for a finite element modelling (FEM). However, their results showed that friction coefficient alone cannot describe the frictional interactions between the materials at elevated temperatures, due to changes in the contact interface with increase in sliding distance. Later, in the tests employing a ball of tool steel H11 in contact with a disc of aluminium alloy 7475, Wang et al. [9] reported the main materials degradation process to be the ploughing of the aluminium alloy. Vilaseca et al. [10] then demonstrated that the tests where the aluminium ball contacts the steel disc more effectively reproduce the real-life observations in the lab scale than the former experimental set-up. In their results, the dominance of galling as the tribological issue was verified. Recently, Pujante et al. [11] used linear reciprocating sliding tests to observe the behaviour of aluminium alloy 2017-tool steel H13 tribopair. Although these ball-on-disc tests were of short duration (10 and 300 s), the

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https://doi.org/10.1016/j.triboint.2017.11.041
Received 28 August 2017; Received in revised form 23 November 2017; Accepted 26 November 2017

dependence of tribological behaviour of the tribopair on the operation temperature was verified.

In general, pin-on-disc [8–10,12,13] and block-on-cylinder [12,14–16] tests are the most common methods to investigate the complex adhesion and friction effects in extrusion processes, particularly in the extrusion of aluminium. The main disadvantage of these two test methods is the small tribological contact area as compared to the real extrusion process. Also, in the real application, the steel is continuously in contact with the aluminium, but the aluminium only comes into the contact once. Nevertheless, both pin-on-disc and block-on-cylinder tests enable insight into the surface processes of the tribopair, when keeping in mind these shortcomings. In this work, an insight into the tribology of a material pair consisting of aluminium alloy 6082 and tool steel H13 was obtained through a series of pin-on-disc tests conducted at various loads and temperatures important for aluminium forming processes, for the durations of 30 and 60 min. The motivation of the work was twofold: first, as it was acknowledged that the application of surface treatments or coatings cannot solve all tribological challenges of the material pair of interest [16–19], it was of vital importance to gain an improved understanding on the behaviour of aluminium alloy-tool steel tribopair at different temperatures and loading conditions. Second, it was clear [20–28] that aluminium is widely used as a coating material to provide various substrate materials protection against oxidation, corrosion and wear at elevated temperatures, thereby further increasing the importance of understanding the elevated-temperature tribology of aluminium-steel pairs. In this work, the obtained results were reflected to the real application (extrusion) and discussed in the light of existing friction models and the characteristics of the selected test method: pin-on-disc.

2. Experimental

2.1. Materials

Aluminium alloy 6082 was used as a pin material in the tests. The standard composition of the alloy is 0.7–1.3 wt.% Si, 0.6–1.2% Mg, 0.4–1.0% Mn, less than 0.5% Cr, and aluminium to balance. The aluminium alloy was obtained as a wire of 10 mm in diameter, of which the pins of 15 mm in length and with a rounding radius of 5 mm were machined. These pins were used in as-received condition as upper specimens of the studied tribosystem. Their surface roughness, expressed as Ra, was 0.31 μm. The measured hardness of the aluminium alloy was 112 ± 4 HV_1. Material for the discs was a tool steel H13, with the standard composition of 0.4 wt.% C, 1.0% Si, 5.2% Cr, 1.3 Mo, 1.0 V and iron to balance. The tool steel had undergone austenitisation at 1030 °C in low-pressure N_2 atmosphere for 30 min, followed by quenching and triple tempering at approximately 530 °C to provide the final hardness of 53 HRC. This hardness was later verified, but also the Vickers hardness of the materials was measured: 557 ± 9 HV_1. The diameter and thickness of the discs were 40 mm and 6 mm, respectively, and they contained a screw hole for fastening. The discs were given the final grinding using a 1200 grit grinding paper; Ra was 0.015 μm.

2.2. Pin-on-disc tests and related the contact mechanics

Tests were carried our using an elevated-temperature pin-on-disc (POD) device, which operates in an electric furnace. The upper specimen, i.e., the aluminium alloy pin, was stationary and attached to the loading system, while the tool steel disc lower specimen was mounted to an electro-mechanical drive that enabled rotational movement of the disc. The tests were carried out using unidirectional sliding mode. The test conditions: sliding speed, normal load and temperature, were kept constant during the tests and the friction coefficient was recorded online. Test conditions were selected to correspond to those in the hot forming process of aluminium alloys, yet the tests were also performed at room temperature. The used test conditions are shown in Table 1. The employed sliding speed was 0.05 m s^{-1}, which was higher than in most studies examining friction in the extrusion processes, reported in Ref. [29], but yet lower than in real applications. The tests were carried out at room temperature (19 ± 1 °C) and at four elevated temperatures corresponding to hot forming of aluminium alloys: 350, 400, 450 and 500 °C, in atmospheric air and a relative humidity of 30–40%. The applied normal loads were 5 and 20 N. Under each set of test conditions, two parallel tests were done. The duration of first of the parallel tests was 30 min, whereas the repetitive measurement was systematically continued for another 30 min (total duration of 60 min). For each test, a fresh pair of pin and disc specimens were applied; before mounting to the device, these were cleaned with petroleum ether, ethanol and acetone in ultrasonic bath, 5 min each, dried and weighed.

Table 1
Test conditions.

Parameter, unit	Value
Sliding speed, m s^{-1}	0.05
Load, N	5, 20
Temperature, °C	Room temperature, 350, 400, 450, 500
Duration, min	30, 60
Atmosphere	Atmospheric air

Friction has a significant influence on the metal forming process and it is important to understand the applicability of classical Coulombian friction law in the interpretation of the results. According to Coulomb's law of friction, the applied normal load F_N introduces frictional force F between the two bodies which are in pressed together due to the coefficient of friction, μ, following [30]:

$$F = \mu \cdot F_N \tag{1}$$

The Coulombian friction model can thus be written as [31,32]:

$$\tau = \mu \cdot p \tag{2}$$

where τ is the friction shear stress and p is the normal pressure. It is acknowledged that the Coulomb friction model describes particularly elastic contacts [33], although it is applied also to contacts with plastic deformation, such as those in hot forming [34]. The plastic deformation situation may be approached using a shear friction model, i.e., Tresca friction model, following [31,32,34]:

$$\tau = m \cdot K \tag{3}$$

where m is the Tresca friction factor and K is the shear yield stress, and m obtains values ranging from 0 (frictionless condition) to 1 (full sticking condition). During recent years, also a combined Coulomb-Tresca friction model has been developed [32] that enables to establish the ratio of μ to m. Furthermore, Leu [35] established the upper limit for Coulombian friction coefficient, $\mu_{\max} = 0.577$, based on the yield conditions of von Mises criterion for plastic deformation, and $\mu_{\max} = 0.5$ based on Tresca definition.

In this work, the experiments were carried out using a non-conformal configuration corresponding to a sphere on a plane surface. The geometry of a contact, called reduced radius of curvature R', may be calculated following [36]:

$$\frac{1}{R'} = \frac{1}{R_x} + \frac{1}{R_y} = \frac{1}{R_{ax}} + \frac{1}{R_{bx}} + \frac{1}{R_{ay}} + \frac{1}{R_{by}} \tag{4}$$

Where R_x and R_y are the reduced radii in the x and y directions, R_{ax} and R_{ay} are the radii of body A in x and y directions and R_{bx} and R_{by} are the radii of body B in x and y directions. Here, $R_{ax} = R_{ay} = 5 \cdot 10^{-3}$ m and $R_{bx} = R_{by} = \infty$, giving $R' = 2.5 \cdot 10^{-3}$ m. The reduced Young's modulus E' is defined as [36]:

$$\frac{1}{E'} = \frac{1}{2}\left(\frac{1-\vartheta_a^2}{E_a} + \frac{1-\vartheta_b^2}{E_b}\right) \tag{5}$$

where υ_a and υ_b are the Poisson's rations of the bodies A and B and E_a and E_b their Young's moduli. Here, $\upsilon_a = 0.33$, $E_a = 70 \cdot 10^9$ N·m^{-2} and