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Laboratory simulation of wear during hot extrusion of aluminium

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Abstract

The study of the wear of a tribological pair of soft and heated metals in contact with a hard counter body is very demanding. The main difficulty with such studies is the deficiency of reliable experimental data due to the problem of maintaining the prescribed contact pressures for a long time between hot softer metal and hard body. A very important tribological system that belongs to this group of demanding systems is present in aluminium hot extrusion, where temperatures of billets lie in the range 450-500 °C, the contact pressure is up to 30 MPa and the sliding velocity in the range 5-100 m/min. In order to gain a deeper insight into the wear behavior in aluminium hot extrusion, laboratory wear tests on nitrided samples at various contact pressures were carried out. The description of experimental setup and main characteristics of the degradation progress of the tested surfaces are presented.

Introduction

Aluminium hot extrusion (see Figure 1a) is a forming process, whereby a billet material is forced by compression to flow through a suitably shaped opening in a die and is used for manufacturing of various shapes of profiles, which have found their application in the automotive, transportation, aeronautics, space technologies, etc., due to their small weight and good mechanical properties. During the process of hot extrusion the billet is usually preheated to temperature between 450-500 °C, and extrudate exit the die with sliding speed between 5 to 100 m/min. The contact pressure on the bearing surface of the die can reach values above 50 MPa, while locally temperatures can increase above 600 °C, as a consequence of heat generated during the process due to plastic deformation of the billet and due to friction on the contact between the extruded profile and the surface of the die [1–3]. The die opening through which the extrudate passes gives the prescribed shape and dimensions to the profile, while the tribological conditions on the bearing surface in the opening influence the quality of the extrudate surface [4–6]. The transition zone (see Figure 1b) is the most exposed spot on the bearing surface at the beginning of wear process. It is generally assumed that on various bearing surfaces of a given extruded profile, various contact pressures are present. Dies for hot extrusion of aluminium are

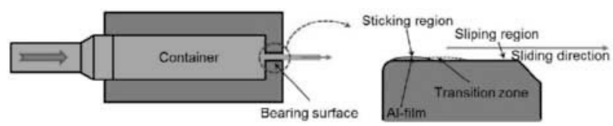

Figure 1: Principle of hot extrusion and bearing surface on the die.

required to have good resistance to abrasion and adhesion, corrosion, fatigue, and they mast be chemically stable against hot aluminium. Increase of wear resistance of the die and consequently prolongation of its in-service life-time can be achieved by additional improvement of its surface, which is in industrial practice usually done by gas nitriding. In order to increase dies in-service-time, it is essential to find the degradation paths of the nitrided surface layer on the bearing surface. In Al hot extrusion various damages on nitrided bearing surfaces of dies can be observed and reasons for their occurrence and their different previous progress are still not sufficiently experimentally clarified [5–8]. The main reason for this is the difficulty in establishing and maintaining the appropriate tribological system for laboratory testing that corresponds to Al hot extrusion, where the soft and hot Al is in a sliding contact with a hard specimen. Namely during wear testing it is very difficult to maintain the prescribed contact pressures for longer time between softer metal, which is heated close to melting temperature, and hard body. In scientific literature studies dealing with wear of tools that are in contact with aluminium are relatively rare and are mainly dealing either with testing at room temperature [9–11], or at high temperature, but at low contact pressure [12–15]. The reasons for lower number of publications on this subject are probably connected to difficulties with heating of aluminium and controlling its prescribed temperature, as well as with extremely long-lasting tests as a result of the low contact pressures used, which is the consequence of "soft" aluminium that is heated close to its melting point.

The aims of the present contribution are thus: (i) to describe the experimental setup and equipment for testing of wear of tribological pair of hard body in sliding contact with hot aluminum, which enables long-term maintenance of different contact pressures, and (ii) to present the main characteristics of the degradation progress of the nitrided surfaces that have been tested at low, medium and high contact pressures.

Materials, experimental set-up and methods

In order to study the wear mechanisms at various contact pressures the wear testing was conducted using nitrided blocks made of AISI H10 tool steels, with chemical composition given in Table 1. The blocks were gas nitrided using the following parameters: 1h of nitriding at 490 °C with a nitriding potential (KN) of 16.1, which was followed by 4h of nitriding at 550 °C at a nitriding potential of 2.4. To approach the surface roughness of the industrial dies, the surfaces of the tested blocks were deliberately made coarser by employing rough whetting with paper, $R_a \sim 0.21\,\mu m$. The analysis of nitrided blocks revealed microhardnes of 1100 MPa, nitriding depth of 110 μm and compound layer thickness of 10 μm.

Table 1: Chemical composition of the die steels AISI H10 used in experiments.

C	Si	Mn	Cr	Mo	V	Fe
0.3	0.3	0.38	3.0	2.8	0.45	balance

The basic design of the testing equipment is block-on-cylinder and was wholly-designed and build in our laboratory. The sketch map of its main components is given on Figure 2a, while conditions occurring during testing between block and hot aluminium discs are sketched on Figure 2b. The main idea of the device set-up is in proper engineering of controlling and supplying prescribed ratios of heat to Al cylinder via direct heating with heating coil or by indirect heating trough additional steel and copper discs. By such design it is possible, at approximately the same radial outer surface temperature of Al cylinder, to obtain various temperature gradients from the surface. Consequently different contact lengths between Al cylinder and tested block at the same prescribed normal force can be established and thus also various contact pressures can be applied for wear testing. Heating of Al cylinder is controlled by a point Infrared Pyrometer IG 8 (IMPAC Electronic GmbH) indirectly through copper discs, which have high emission coefficient that enables more accurate measurement and control of temperature and consequently testing at constant conditions. Note that direct measurement of temperature of Al cylinder does not assure constant conditions: firstly, due to low emission coefficients of Al, and secondly, due to its variation that is caused by changing of surface roughness during testing. Before the start of the test prescribed surface temperature and temperature gradient must be established, which for e.g. 550 °C takes approx. 15 minutes and after that automatic temperature regulation is applied where temperature usually does not oscillate more than ±1 °C during wear testing. Since testing is frequently conducted close to the melting point of some phases in Al-alloys (e.g. eutectic Mg_2Si in AA 6063) evenly heating of Al cylinder across its width and rim must be ensured, otherwise due to

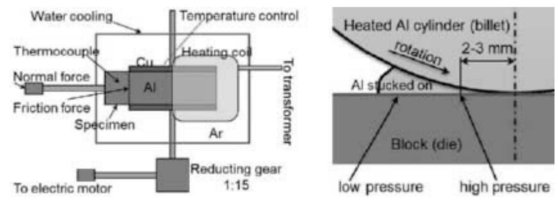

Figure 2: A sketch map of homemade testing equipment with main components (a), pressure conditions on contact between tool and aluminium disc (b).

Figure 3: Main components of block-on-cylinder testing equipment.

high normal load the Al cylinder deforms from circular to elliptical shape and test must me stopped. The required temperature filed is assured with appropriate construction of Al cylinder and Cu and steel disks as well as with proper design of the heating coil. During testing normal and tangential force, rotational speed of cylinder, temperatures of cylinder and surface layer of tested die are measured and saved in the computer. To prevent oxidation of Al cylinder argon inert atmosphere is created in the test chamber. Cylinder is driven by a 3.0 kW electric motor with randomly adjustable revolutions with an intermediate reducing gear. The main components of described block-on-cylinder testing equipment are shown on Figure 3.

In the present investigation normal force was set to 1920 N. Three different contact lengths, i.e. 13, 10, and 7 mm were applied that correspond to three different contact pressures, and which are hereafter referred to as low, medium, and high contact pressures. Temperature of Al cylinder was set to 550 °C and temperature of sliding surface to slightly below 600 °C. Relative sliding velocity of Al cylinder was set to 0.5 m/s. The Al cylinder was made of AA 6063 aluminum alloy with chemical composition given in Table 2. In order to gain more information about degradation process on tested surface the results after 30, 60, 120 min of testing are given.

Table 2: Chemical composition of the Al-cylinder AA 6063.

Mg	Si	Fe	Mn	Al
0.5	0.5	0.19	0.05	balance

For determining of microhardness, microstructure and phases of nitrided surfaces the following equipment were used: microhardness by Fischerscope H100C, OLYMPUS BX60M optical microscope and Siemens Analytical D5000 diffractometer with Cu anode. On tested surface energy dispersive spectroscopy, scanning electron microscope, and backscattered electrons analyses were carried out using JEOL JSM 5610 equipment. Microstructures have been prepared using nital etchant.

Results and discussion

Initial microstructures

The obtained microstructure of the nitrided blocks is shown in Figure 4a, where it can be seen that the thickness of the compound layer is about 10 μm and some nitrides are present on the grain boundaries. During nitriding of the die steels in general two different types of microstructure are formed on the die surface, i.e. microstructure with compound layer on top and diffusion layer under it, and in the second case, diffusion layer alone. Compound layer usually consist of brittle iron nitrides, i.e. ε-$Fe_{2-3}N$ phase, γ'-Fe_4N phase or mixed phases (ε+γ'). In the present case the XRD patterns of the nitrided surfaces given in Figure 4b revealed that the compound layers is almost ε-mono-phased, since the amount of γ' phase is very low.

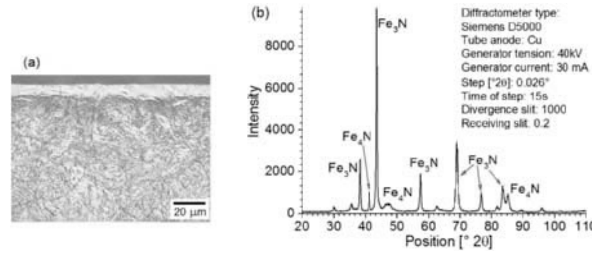

Figure 4: Initial microstructure (a) and XRD pattern (b) of nitrided blocks.

Wear progress on tested samples

The main characteristics of development of the wear progress at low contact pressures that can be observed after 30 min of testing are two initial types of degradation. The first is based on initial cracking and the second on initial fragmental removal of the compound layer without cracking as shown on Figure 5a. The first type of degradation is predominately related to the occurrence of porosity in the compound layer and the second type of degradation can be ascribed to the adhesion between the hot Al and the compound layer, where the removed fragments are relatively small in comparison to the fragments that were removed through the compound-layer initial cracking. It should be emphasized here that initially the surface roughness is relatively low in comparison to the roughness of the areas where partial removals have already taken place and lower roughness leads to a lower friction and consequently the amount of fragments removed due to adhesion is decreased in these areas.

After 60 min of testing at lower contact pressure the degradation process continues and results in the increased cracking of the compound layer, in the increased number of areas with a partial removal of the

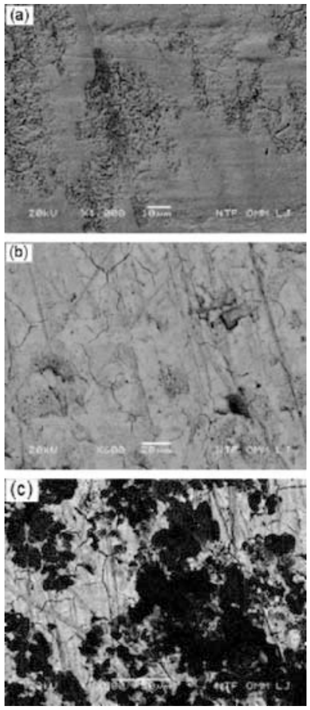

Figure 5: Tested surface of blocks after 30 min (a), 60 min (b), and 120 min (c) of testing at low contact pressure.

compound layer and in appearance of small islands where the compound layer is removed up to the diffusion layer (see Figure 5b). Also an increased number of spots where the compound layer is only partly removed with porosity on the spots of the removal can be observed. It was found that three different types of such removal can be distinguished. The first type of removal is connected with spreading of cracks, which begins on pores close to interface and is connected to the normal pressure and friction. The second type of compound-layer removal is found on spots where the porosity is present and the appearance of a new surface indicates that this type of removal is a consequence of the adhesion between the hot Al and the compound layer. The third type of removal can be observed at spots of triple-point cracking, which are more brittle and have a lower strength due to the porosity that is usually present there. A comparison of microstructures after 30 and 60 min of testing shows an increased number of cracks in the compound layer for the latter.

After two hours of testing at lower contact pressure (see Figure 5c) the cracking of the compound layer continues in terms of their width and depth and new cracks appearing on the surface. Besides the cracking of the diffusion layer, which has a large influence on the wear, a chemical attack can also be observed. The cracking can be attributed to the increased friction between block and the Al cylinder. Namely, hot aluminium in contact with the diffusion layer has a tendency to stick to it, but due to the rotation of the cylinder this sticking is interrupted. Due to this periodic sticking between the hot aluminium and the cracked diffusion surface, which is followed by its detachment, the fragmental removal of the compound layer at such spots is taking place, which consequently leads to the formation of small craters. At this stage of degradation there are almost no undamaged areas on the tested surface. From these results it can be concluded that the dominant wear mechanism at low contact pressure is adhesion.

Figure 6a shows the appearance of the tribologically loaded surface after 30 minutes of testing at medium contact pressure, where the partial removal in the shape of small islets, i.e., micro-craters with diameters of about 20-30 μm, can be distinguished. It can be assumed that this type of compound-layer

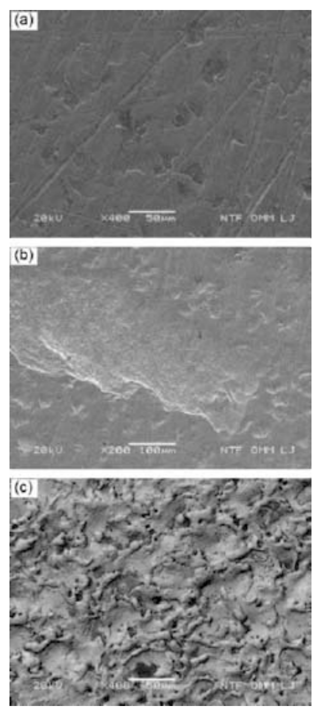

Figure 6: Tested surface of blocks after 30 min (a), 60 min (b), and 120 min (c) of testing at medium contact pressure.

degradation is based on two different mechanisms: on strong adhesion, and on initial surface cracking of the compound layer due to the presence of porosity. The first assumption is based on the observation of smaller removed islets where no cracking was found around these spots. Thus, the process of degradation, which is based on adhesion around these islets, results in the partial removal of the compound layer. The presence of the porosity does not always result in initial cracking, but sometimes in an initial removal by adhesion. In the latter case, the presence of porosity in the compound layer accelerates its removal and is a consequence of the decreased shear strength at such spots, and thus thicker and larger areas of the compound layer can be removed. On the other hand, the combination of the presence of porosity and a sufficiently high contact pressure results in the second mechanism, i.e. the initial surface cracking of the compound layer, which is then followed by adhesional removal. From comparison of Figures 5a and 6a, it can be concluded that the higher density of removed islets in comparison to the surfaces observed at the lower contact pressure is the consequence of the higher contact pressure that results in both the initial degradation mechanisms, i.e. the strong adhesion and the initial surface cracking.

After 60 min of testing at medium contact pressure the density of micro-craters is increased as well as their width and depth (see Figure 6b). It can be seen that the islets of the initially partly removed compound layer increased in depth and width and the diameters of the micro-craters are about 25-45 μm. Furthermore, areas where the compound layer is removed are oriented preferentially in the sliding direction of the Al cylinder, which can be attributed to the locally poorer characteristics of the compound layer. On the other hand, the occurrence of small islets with a deeper removal can be attributed to the locally emphasized increased density of the porosity through the entire thickness of the compound layer, which consequently leads to accelerated adhesional removal at such spots. Thus it is reasonable to conclude that adhesion as a consequence of the high contact pressure is responsible for the accelerated compound-layer removal.

Figure 6c shows the appearance of surface after 120 min of testing at medium contact pressure, where high density of islets can be observed. Their depths extend into the diffusion layer, and the widths and density of the micro-craters are considerably increased if this surface is compared to that observed after 60 min of testing. In this figure the phenomenon of unification of the micro-craters is also visible. Those with thinner walls and larger depth tend to lie perpendicular to the sliding direction.

It can be concluded from obtained results that the essential differences in the surface damage for testing at low and medium contact pressures are in type, density and time of occurrence of a typical mode of surface degradation and, contrary to medium contact pressure, the removal of the compound layer at low contact pressure has no preferential orientation direction.

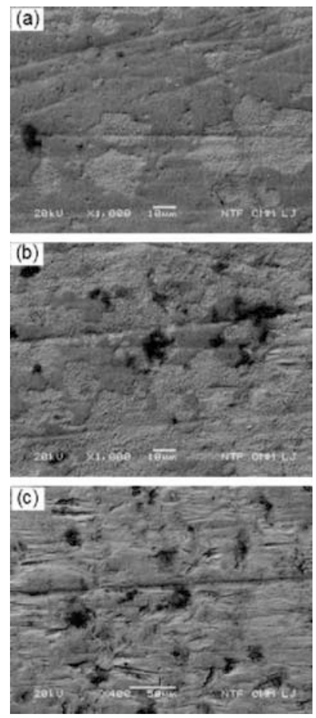

Figure 7: Tested surface of blocks after 30 min (a), 60 min (b), and 120 min (c) of testing at high contact pressure.

The degradation paths for the high contact pressure are related to the increased friction stresses and, consequently, to the higher adhesion. Figure 7a show the appearance of the surfaces after 30 min of testing. It can be seen that already at this early stage of testing the removal of the compound layer is preferentially oriented in the sliding direction and the removal is based on adhesion. No cracking can be observed on the tested surfaces, only removed areas of sizes of approximately 30 μm in diameter and very small removed islets of about 2 μm in size, which indicates a mechanism of expansion of small removed areas.

Figure 7b show the surface after 60 min of testing at high contact pressure, where the process of expansion of small islets and appearance of small furrows, which are oriented in the sliding direction, can be clearly distinguished.

After 120 min of testing at high contact pressure, the number and size of the furrows increased and the surface is very damaged as shown on Figure 7c.

Conclusions

Our homemade testing equipment block-on-cylinder was improved to enable studying wear behaviour of tribological pair of hard die that is in sliding contact with hot aluminium. Experimental set up was designed so, to enables applying different contact pressures and temperatures by which laboratory simulation of wear occurring during hot extrusion of aluminium alloys can be conducted. It allows controlling and measuring the most important parameters of die wear, i.e. temperatures of cylinder and surface layer of the block, normal and tangential force, relative slippage velocity between block and cylinder, etc. Testing equipment was employed for study of degradation progress of nitrided surfaces at low, medium and high contact pressures. It was found that adhesion is the main wear mechanism for all tested contact pressures and that contact pressure have a decisive role in determining of wear mode and degradation paths. It was observed that surfaces of the blocks tested at medium contacts pressures have features found on both blocks tested at high as well as at low contact pressures, i.e. the formation of micro-craters, which was mostly found at low contact pressures and the removal of the compound layer that is oriented in the sliding direction, which is more emphasized at a high contact pressure. It was further found that formation of islets at a medium contact pressure starts with strong adhesional removal without cracking or with the surface cracking of the compound layer. The main difference between the surfaces obtained at low and medium contact pressures is in the density of the removed islets and in their surface area at the same testing times. The next difference is that the extension of craters in the sliding direction does not appear at a low contact pressure. In the early stage of the compound-layer degradation at medium contact pressures the removal is not preferentially oriented, but it becomes so in the later stages of testing, while at high contact pressures the removal of the compound layer is preferentially oriented in the sliding directions from the very beginning of the degradation process.

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