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Fretting wear behavior of controlled ball impact treated aluminium alloy under dry sliding condition

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ABSTRACT

Fretting wear occurs when two contacting solid surfaces are subjected to a relatively small amplitude oscillatory motion in the order of few microns. In addition to the introduction of compressive residual stresses and increased substrate strength controlled ball impact treatment results in the formation of nanostructured grains at the surface. Fretting wear studies were performed on the untreated and controlled ball impact treated aluminium samples using a steel counterbody at constant slip amplitude and at different applied normal loads using a fretting wear test rig. Displacement amplitude and normal force determine the nature of the slip regime. The tangential force coefficient decreases with increasing normal loads under fretting conditions. The contact between the fretting surfaces makes the asperities interlock with each other at low applied normal loads, and results in a high tangential force coefficient, whereas at high applied normal loads tangential force coefficient decreases. Crack initiation and debris formation are the predominant types of damage observed in the fretting specimens due to micro-displacement between the junctions of two contacting members. The steady state tangential force coefficient, wear volume and specific wear rate of the ball impact treated samples were lower than those of the untreated coarse grain aluminium samples. The improvement in the tribological properties of the treated sample is attributed to high dislocation density, more number of grain boundaries, presence of compressive residual stresses and increase in substrate strength with associated grain refinement. The increased substrate strength and the presence of compressive residual stresses prolonged the crack initiation time and crack tip blunting retards the crack propagation resulting in decreased wear debris formation and wear volume. The surface morphology of the wear scars was analyzed using an optical microscopy and scanning electron microscopy, to identify the failure modes and fretting wear mechanisms. At low applied normal loads a complex adhesion and oxidation type of wear mechanism was observed and abrasion was found to be a dominant wear mechanism at high applied normal loads.

1. Introduction

Fretting is a relatively small amplitude oscillatory movement occurring at the interface of two normally loaded contact surfaces [1]. Fretting is a very intricate phenomenon, and its wear mechanism involves at least two or more mechanisms to occur simultaneously depending on the operating conditions while for reciprocating sliding, wear mechanism is comparatively simpler. The transition between fretting wear and reciprocating wear is best defined using volumetric wear rate [2]. An important distinction between fretting and reciprocating sliding wear rises from the ease with which the wear debris can escape from the contact region and the stroke length [3]. Although gross slip fretting is often considered as reciprocating sliding at very short stroke lengths, there are significant differences in wear rates and mechanisms to warrant the distinction. Fretting wear is dominant in the gross sliding contact condition where no stick zone is formed in the contact area. During the fretting process, stick slip motion occurs between the sample and the counterbody as there is no pure sliding motion at the contact interface. In the fretting wear process, the magnitude of applied normal force is sufficiently high and the amplitude of the reciprocating motion is small enough to significantly restrict the flow of the fretting debris away from the originating site. Under fretting condition, the tangential force is considered to be generated at the contact interface by either direct interlocking of surface asperities, or by trapping of the oxide debris in between the surface asperities. Depending upon the loading condition, environment and material properties the fretting process can lead to material removal (wear), premature nucleation and subsequent propagation of cracks (fatigue) or both. Many machine elements and engineering structures are often subjected to fretting

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wear due to vibration of the total system and fretting damage is still one of the common modes of failure in industrial machinery [2]. Due to the complexity of the fretting wear process, the understanding of the fretting wear phenomenon is less advanced. To describe the fretting wear process a number of wear mechanisms have been reported. Hurricks [4] divided the fretting wear process into three stages. During the first few thousand cycles the coefficient of friction is high and metal to metal contact is predominant and the major mechanism involved in this stage is metal transfer and adhesion, which results in local welding and roughening of the surface. In the second stage oxidized debris begins to accumulate at the contact interface, through oxidation of either existing wear particles or the virgin metal under the worn oxide layer. If the oxidized particles are harder than the target surface metal, abrasive action begins. After prolonged period of sliding the friction coefficient attains the steady state condition. During the final steady state stage abrasive action of the wear particles is decreased by the formation of a compacted debris bed. Surface fatigue promotes most of the damage at this stage. Waterhouse and Taylor [5] pointed out that delamination process which mainly results from the pile-up of dislocation and coalescence of voids can cause material removal in the later stages of fretting producing plate-like particles. During the fretting process the generation of the wear debris is of utmost importance as the wear debris is trapped at the fretted surface and provides a load carrying plateau. Iwabuchi [6] reported that there exist two opposite effects of wear debris in the fretting wear process; (i) the formation of the oxide layer is beneficial during the fretting phenomenon and (ii) the occurrence of abrasive action of the particles during the early stages of fretting is detrimental. These effects depend on the applied normal load and slip amplitude. Berthier et al. [7] argued that mechanisms such as adhesion and abrasion are only particle detachment mechanisms. A wear process should be governed not only by particle detachment, but also elimination of wear particles. The transportation of the wear debris from inside the fretted surface to the outside surface is referred as a third body flow and it is suggested that this third body flow can be affected by contact shape, kinematics, contact dynamics, third body properties and so on. Berthier et al. [7] reported that the relatively soft aluminium and titanium alloys react slightly differently compared to other materials. In these alloys the debris compacts form dense struts which adhere to one of the first bodies and gouge its counter face during the reciprocating motion. Often these struts transfer at the end of the stroke causing local build-up, along with significant increases in tangential force as a newly formed strut butts against an earlier transferred strut.

Increasing the substrate strength by surface engineering is expected to be the perfect solution to improve fretting resistance [8]. Mechanical treatments such as shot peening, oil-jet peening, water-jet peening, and controlled ball impact peening result in the increased substrate strength and impart compressive residual stresses in the surface of metallic materials [9,10]. Controlled ball impact (CBI) peening was developed for the generation of nanocrystalline structure in metallic materials by inducing a high strain on the surface. Nanocrystalline surface layer was formed in the top surface layer of AISI 304 stainless steel [11], aluminium alloy, AA6063-T6 [12] by controlled ball impact treatment. The reciprocating sliding wear [12,13] and fretting wear behavior [14] of the nanocrystalline surface layer showed reduction in coefficient of friction and high wear resistance compared to coarse grained polycrystalline materials. The fretting wear behavior of the nanocrystalline nickel on a copper substrate produced using direct and pulse current electrodeposition showed improved tribological properties than that of the coarse grain polycrystalline nickel [15].

This article describes the effect of surface nanocrystallization on the fretting wear behavior of controlled ball impact peened aluminium alloy, AA6063-T6 samples under dry sliding conditions for different applied normal loads and at constant displacement amplitude using a ball-on-flat configuration. The fretting friction coefficient, fretting wear loss and micro mechanism of the wear scars are also reported.

2. Controlled ball impact peening

Controlled ball impact peening was conducted at a strain rate of 2320 s^{-1} and the samples are precisely moved using programmable logic controlled linear actuator [11]. A single high-carbon high-chromium hardened steel ball of 2 mm diameter (60 ± 2 HRC) is used for controlled ball impact treatment. On the target surface the steel ball makes a single impact (i.e., single pass peening pattern). The ball acquires the kinetic energy from the drive source and the guided high velocity ball impacts on the target surface to be treated. As the ball impacts the target material at a high strain rate an elastic/elasto-plastic deformation occurs in the contact zone. The material deforms plastically when the mean contact pressure developed due to ball impact reaches about 1.07 times the yield strength of the target material. The ball impact velocity is maintained at 0.85 m/s and the shaker was operated at a frequency of 35 Hz [11]. Controlled ball impacts were carried out as the sample is moved at traveling velocities, 0.51, 0.76, 1.02 and 1.27 mm/s which influence the peening pattern. After each pass in x-direction, the sample is moved in y-direction by 25.4 μm.

3. Test material and experimental details

Samples of size 25 × 10 × 6 mm aluminium alloy, AA6063-T6 plates are used for the controlled ball impact treatment. Prior to the treatment all samples were polished using different grades of silicon carbide abrasive paper up to a grit size of # 1200 followed by polishing using fine particles of alumina powder and then finally cleaned with acetone. Before treatment a surface roughness of 0.1 ± 0.02 μm (R_a) was maintained in the entire test samples. The polished aluminium samples were subjected to controlled ball impact treatment. As-peened aluminium samples are subjected to fretting wear tests. The indentation hardness and residual stresses of the nanocrystalline surface are evaluated using a dynamic ultra micro-hardness tester using Berkovich indenter. The grain size of the treated surface was quantified using X-ray diffraction analysis and transmission electron microscopy (TEM). Surface roughness of the treated and untreated samples were measured using a profilometer.

Fretting wear test machine working on the principle of scotch yoke mechanisms designed and developed in-house was used. A brief description of the test rig used in the present study is given here for the ease of understanding although the full details of the fretting test rig are given elsewhere [1]. The rotary motion is converted into linear reciprocating motion by an eccentric connected to a drive motor. The rotary motion is transmitted to a linear motion guide by a connecting rod. An oscillating rod permits the oscillatory motion which connects the linear motion guide and a link ball assembly. The end of the oscillating rod connected to the linear motion guide travels linearly, when the linear motion guide reaches the extreme positions and imposes the displacement of the specimen holder. On the high precision linear motion slide, the moving specimen holder is mounted rigidly. The test specimen is mounted on the lower part of the moving specimen holder and the counterbody is mounted on the quasi-static specimen holder perpendicular to the imposed slip amplitude (i.e., on the upper part of the stationary counter specimen holder). A force transducer (i.e., S-beam type tension-compression load cell) coupled to the quasi-static specimen

Table 1
Initial values of maximum contact pressure (P) and contact radius (a) calculated for aluminum samples fretted against steel counterbody.

Normal load, W (N)	Contact pressure, P (MPa)	Contact radius, a (μm)
2.5	417.1	53.5
5	525.8	67.5
10	662.7	85
15	758.8	97.4
20	835.4	107