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The role of surface texture on friction and transfer layer formation during repeated sliding of Al–4Mg against steel

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ABSTRACT

In the present investigation, various kinds of textures, namely, *unidirectional*, *8-ground*, and *random* were attained on the die surfaces. Roughness of the textures was varied using different grits of emery papers or polishing powders. Then pins made of Al–4Mg alloys were slid against steel plates at various numbers of cycles, namely, 1, 3, 5, 10 and 20 using pin-on-plate reciprocating sliding tester. Tests were conducted at a sliding velocity of 2 mm/s in ambient conditions under both dry and lubricated conditions. A constant normal load of 35 N was applied in the tests. The morphologies of the worn surfaces of the pins and the formation of transfer layer on the counter surfaces were observed using a scanning electron microscope. Surface roughness parameters of the plates were measured using an optical profilometer. In the experiments, it was observed that the coefficient of friction and formation of the transfer layer depend on the die surface textures under both dry and lubricated conditions. More specifically, the coefficient of friction decreases for *unidirectional* and *8-ground* surfaces while for *random* surfaces it increases with number of cycles. However, the coefficient of friction is highest for the sliding perpendicular to the *unidirectional* textures and least for the *random* textures under both dry and lubricated conditions. The difference in friction values between these two surfaces decreases with increasing number of cycles. The variation in the coefficient of friction under both dry and lubrication conditions is attributed to the change in texture of the surfaces during sliding.

1. Introduction

Texture of the die surface plays an important role in metal forming operations as it primarily controls the frictional behavior at the contacting surfaces. By introducing specific textures on the die surfaces, the tribological properties at the contact interface can to a large extent be controlled. For example, it is possible to generate the required stresses to deform metals to a desired shape by controlling the surface texture and thus the frictional shear [1,2].

Efforts have been made to study the influence of die surface texture on friction in metal forming operations [3–7]. Costa and Hutchings [3] investigated the influence of surface texture on friction during metal forming processes. They concluded that the friction was strongly influenced by the relative orientation between the grooves generated on the die surfaces and the drawing direction. Lakshmipathy and Sagar [4] investigated the influence of the directionality of die grinding marks on the friction in open die forging under lubricated conditions. Their research indicated that the friction factor, based on ring tests, was lower for a criss-cross die surface pattern than for a die surface pattern that was unidirectional ground. Määttä et al. [5] studied the friction of stainless steel strips against different tool steels. They concluded that the surface topography of the tool has a marked effect on the friction between the tool and the work-piece. Malayappan and Narayanasamy [6] analyzed the bulging effect of aluminium solid cylinders and concluded that barreling depends on the friction which in turn depends on the surface texture at the flat die surfaces. The relation between friction and surface topography for various lubricants was studied by Hu and Dean [7] using upsetting tests. They reported that a random smoother surface could retain more lubricant and reduce friction.

Attempts have also been made to simulate the tribological conditions that are encountered in metal forming operations by means of simple laboratory sliding tests. More specifically, the influence of surface texture on friction was extensively examined by Staph et al. [8] who studied the effect of surface texture and surface roughness on scuffing using a "caterpillar disc tester". Using steel discs of varying roughness and texture, they concluded that both sur-

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face texture and surface roughness influence frictional behavior. Koura [9] studied the effect of surface texture on friction mechanism using a universal testing machine. Steel specimens were prepared to various degrees of roughness by grinding, lapping and polishing. The results showed that the behavior of surfaces and thus friction during sliding depends on the degree of roughness. Menezes et al. [10] investigated the influence of directionality of surface grinding marks on friction under both dry and lubricated conditions. The authors concluded that the coefficient of friction significantly depended on the directionality of grinding marks on the harder steel surfaces. Menezes et al. [11–14] further studied the effect of surface texture on friction and transfer layer formation. Their results showed that the coefficient of friction could be altered by more than 200% by changing surface textures. This research [11–14], however, was confined to a single sliding event. In forming operations, however, the dies can be reused for multiple operations. Thus, it is important to analyze the effect of surface texture of the die on friction and formation of transfer layer during sliding at various number of cycles against soft materials.

In the literature, efforts have also been made to study the tribological behavior as a function of surface texture during sliding at various numbers of cycles. Blau et al. [15] studied the effect of surface grinding mark direction on the reciprocating friction and wear behavior of silicon nitride (GS-44) using silicon nitride (NBD200) and stainless steel (AISI 440C) balls. They concluded that orienting the grinding marks transverse to the sliding direction was optimal for lowering friction and wear. Costa and Hutchings [16] studied the influence of surface topography on lubricant film thickness using reciprocating sliding. Among the patterns investigated, chevrons were the most effective and grooves were the least effective in increasing hydrodynamic film thickness.

It can be inferred from the above investigations that the knowledge of the influence of surface texture on the friction during multiple pass sliding operations is not adequately understood. Thus, in the present investigation, attempts have been made to study the influence of surface texture of the harder plate on coefficient of friction and transfer layer formation when Al–4Mg alloy pins slid for numerous cycles against steel plates of different texture and roughness using pin-on-plate reciprocating sliding tester.

2. Experimentation

2.1. Materials

In this study, the pin in the testing apparatus was made of Al–4Mg alloy and the counterpart plate was made of 080 M40 (EN8) steel. The pins were 10 mm long, 3 mm in diameter with a tip radius of 1.5 mm. The dimensions of the 080 M40 steel plates were 28 mm × 20 mm × 10 mm (thickness). The pins were first machined and then electro-polished to remove any work-hardened layer that might have formed during machining. Hardness measurements of the Al–4Mg alloy pin and steel plate were made at room temperature using a Vickers micro hardness tester with 100 g load and 10-s dwell time. Average hardness numbers, obtained from 5 indentations, were found to be 105 and 208 for the pin and plate, respectively.

2.2. Surface texture preparation

To prepare the steel samples for the experiments, three different surface textures – *Unidirectional*, *8-ground*, and *Random* – were created on 080 M40 steel plates. The *unidirectional* textures were produced on the steel plates by grinding the steel plates against different grits of emery papers (220, 400, 600, 800 or 1000 grit size) in a unidirectional fashion. These different grits were used to vary the surface roughness of the steel plates. Thus, five unidirectional textured surfaces with different roughness were obtained. Another five unidirectional textured surfaces with different roughness were prepared. The difference between the former and latter unidirectional surfaces is that the grinding marks direction in the latter surface is perpendicular to that of the former surface. The *8-ground* textures were produced on the steel plates by moving the steel plate on emery papers along a path with the shape of an "8" for about 500 cycles. Here too, different grits of emery papers (220, 400, 600, 800 or 1000 grit size) were used to vary the surface roughness and again five 8-ground textured surfaces with different roughness were obtained. The *random* textures were generated on the steel plates by moving the steel plate against the pad of disc polishing machine. To vary the surface roughness, five kinds of abrasive media (in slurry form) such as 220 grit SiC powder, 600 grit SiC powder, 1000 grit SiC powder, Al_2O_3 powder (0.017 μm), or diamond paste (1–3 μm) were used. Thus, five random textured surfaces with different roughness were obtained. Fig. 1(a)–(c) illustrates the 3D profiles and the top views of steel surfaces generated by unidirectional grinding, 8-ground and random grinding, respectively. The 3D profiles were recorded for a scan size of 2.4 mm × 1.8 mm using an optical profilometer. The surface roughness R_a, was recorded for each plate. The R_a indicated in Fig. 1, is the 3D surface roughness. It can be seen that the surface roughness values, for different textured surfaces, all fall in to a general range of values, thus allowing the effect of texture to be studied in detail.

2.3. Apparatus

Experiments were conducted using a pin-on-plate sliding apparatus, the details of which are presented elsewhere [14]. This apparatus has different sliding modes including; constant load with unidirectional sliding, progressively increasing load with unidirectional sliding and constant load with reciprocating sliding. In the present study, experiments were conducted at a constant normal load of 35 N under reciprocating sliding mode. Before each experiment, the pins and steel plates were thoroughly cleaned first in an aqueous soap solution and then with acetone in an ultrasonic cleaner. The surface roughness (R_a) value of the pin before the tests was found to be 0.3 ± 0.05 μm. In the experiments, the pins were slid at a velocity of 2 mm/s against the prepared steel plate for a track length of 10 mm in the forward direction (first half cycle) and then backward direction (another half cycle) to the initial position for each sliding cycle. The normal and tangential forces were continuously acquired using a computer with data acquisition electronics.

Experiments were conducted under dry conditions to obtain five parallel wear tracks on the same steel plate. Each wear track was produced by different number of reciprocating sliding cycles such as 1, 3, 5, 10 and 20. It was found that the coefficient of friction varied significantly at lower number of cycles and the variation was decreased with increasing number of cycles. For this reason, the cycle numbers are chosen such that the difference between two successive numbers increases with increasing number of cycles. The coefficient friction did not vary much beyond 20 cycles; hence, the experiments were restricted to 20 cycles. Note that a single pin was used for all the 5 sliding cycles. After the dry tests, the Al–4Mg alloy pin was removed and a new Al–4Mg alloy pin from the same batch was used to perform lubricated tests. For the lubricated tests, a drop (i.e., 0.05 ml) of commercially available engine oil lubricant (SAE 40, API rating SJ class) was applied to the surface of the same steel plate and the tests were performed to obtain another five parallel wear tracks of different number of reciprocating sliding cycles similar to dry tests. The viscosity of the lubricant oil was found to be 40 cSt at 40 °C and had the extreme pressure additive