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Friction anisotropy of Aluminum 6111-T4 sheet with flat and laser-textured D2 tooling

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Proper friction control during a sheet metal forming process can positively influences the quality of the final product. The effects of textured tooling surface and the rolling direction of the strip surface with respect to the sliding direction, the sliding velocity, and the contact pressure on friction coefficient were investigated in this study with Aluminum 6111-T4 sheet and D2 tool steel. A flat-on-cylindrical setup was used to measure the friction force by pulling a strip sample across a tooling sample. The tool steel has laser-textured micro wedge-shaped dimples. The results showed a reduction in friction coefficient by using a textured tool. In addition, in the tests, the relative motion direction parallel to the sheet rolling direction leads a lowest friction coefficient compared to other orientations.
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1. Introduction

Friction in sheet metal forming influences the quality of the final product in terms of geometry and surface finish, tool wear and production cost [1,2]. Many researchers have investigated in the roles of lubricant and surface conditions of toolings and workpieces in complex metal-forming processes [3,4]. In addition, textures can serve as micro-reservoirs to keep lubricant in the area of surface interaction. Properly designed texture geometry can make the trapped lubricants generate a hydrodynamic lift and positively affect the lubrication status, thus leading to a reduction in friction [5]. Dimples or grooves may also function as micro-pockets to accommodate wear debris and reduce scratching during a forming process [6]. The presence of surface textures at desired tooling locations should promote favorable hydrodynamics when sliding a sheet surface over the tooling surface during a lubricated forming.

Properly designed surface texturing has been found to reduce wear and friction, but improve load capacity. Silicon carbide disks textured by reactive ion etching were tested with purified water as the lubrication, and the results indicated a 2.5 times, or higher, load-carrying capacity of that of the corresponding non-textured surface [7]. Pettersson and Jacobson [8] studied physical–vapor–deposition (PVD) coated diamond-like carbon (DLC) silicon wafers textured with grooves or square depressions created by lithography and anisotropic etching; the results showed reductions in friction and wear in sliding boundary lubrication conditions. A number of techniques have been used for surface texturing [5,9,10]; among them, the Laser–Surface–Texturing (LST) is one of the most popular technologies [5]. LST provides high repeatability due to its precise process controllability and wide material applicability. An investigation on laser-textured D2 steel cylindrical surfaces with rectangular and flat-bottomed dimples, interacted with DP600 steel strips, revealed a up to 40% friction coefficient reduction [11], in which the contact pressure range was between 30 and 120 MPa and the sliding speed was between 0.3 and 0.7 m/min. In another work [12], dimples were created either by laser beam machining (LBM) or by abrasive jet machining (AJM). Textured silicon nitride samples mated with hardened steel pins were tested in a pin-on-disk tribometer, and the results showed 20% friction reduction under boundary lubrication conditions. Although the LBM-produced dimples had an angular geometry and the AJM-produced ones had a spherical geometry, no significant difference in the results was observed. Another pin-on-disk research [13] studied the effect of surfaces processed with LST, subjected to combinations of different experimental conditions, such as sliding speed, contact pressure, and lubricant viscosity, on friction reduction. Comparison of the friction behaviors of polished, ground, and laser-textured disks showed reduction in friction by the samples processed by LST. It was found that the most beneficial effects of laser-textured surface have

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been achieved at higher speeds and high loads, and by applying a lubricant with a higher viscosity, due to apparent hydrodynamic lift under these conditions.

Several researchers have investigated the effect of textured surfaces on tool life. The lifetime of a titanium nitride (TiN) coated cold forging tool, for example, was increased up to 169% by micro-textures covering 20% of the working area [14]. High-strength steel drill bits, laser textured with rectangular pockets ($450\,\mu m \times 50\,\mu m \times 4\,\mu m$), were tested by drilling titanium plates. Reduction in chip adhesion and increase in tool life were observed [2]. This work reveals that 10% coverage of the textured surface area is a reasonable choice for tool life enhancement.

Both texture shapes and their orientation deserve attention [15–17]. Investigations on the influence of the direction of wedge-shaped micro-channels in aluminum strip surfaces showed a decrease in friction with the increase in the angle between the grooves and the drawing direction [18]. Another research [19] examined the impact of the surface roughness orientation of electrical discharge textured (EDT) and mill-finished (MF) aluminum 6111-T4 sheets on friction, where the EDT surfaces showed reduction in friction at the contact pressures higher than 62 MPa. Under lower contact pressures, sliding friction along the parallel direction of the MF sheets was lower than that along the transverse direction.

A summary of the influence parameters mentioned in the reviewed papers is provided in Table 1.

The role of roughness orientation in friction control is complicated and sensitive to the variation of the lubrication status. Although many have explored on the effect of roughness orientation on friction in lubricated and unlubricated interfaces, few are pertaining to the combined effect of texture and mating surface roughness orientation in boundary lubrication. The study reported in this paper is focused on the influence of surface roughness orientation of rolled sheets on friction when such a sheet is mated with a tool steel surface, with or without a texture.

2. Material and friction tests

2.1. Material and surfaces

Strip samples of 7 mm in width and 400 mm in length were cut from 1 mm thick AA6111-T4 sheets. In order to investigate the effect of the surface roughness orientation of the sheet on friction coefficient, the strips were cut 0° (parallel), 30°, 45°, 60°, and 90° (perpendicular) to the rolling direction of the sheet. The roughness orientation is defined with respect to the direction of the relative motion of the two interacting surfaces; moving a strip of 0° cut to the rolling direction parallel to the motion direction is referred to as the longitudinal orientation in the sense of rough-surface lubrication, and likewise, moving a strip of 90° cut to the rolling direction perpendicular to the motion direction is referred to as the transverse orientation. Fig. 1 shows the parallel (longitudinal) and perpendicular (transverse) orientations of the rolled roughness of the strip surfaces with respect to the sliding direction. After cutting, each strip was cleaned and the edges were filed so that the strips were burr-free.

2.2. Experimental setup and testing procedure

The friction tests used a flat-on-cylindrical line contact to simulate a high-pressure sheet-tooling contact condition. A schematic of the apparatus is shown in Fig. 2(a), consisting of a cylinder, a support shaft, and a computer-controlled rack. Fig. 2(b) shows the structure of the apparatus. Although the instrument design has been reported previously [20,21], its key features are repeated here for clarity.

The contact area of 7 mm in width and of 6 mm in length of the end surface of the upper cylinder was laser-textured to have micro-wedge shapes of 100 μm long, 400 μm wide, and 20 μm deep, as shown in Fig. 3. 10 rows by 8 columns of dimples were made parallel and perpendicular to the sliding direction. The material of the cylinder is D2 steel, a commonly used material for tools in forming equipment. The aluminum 6111-T4 strip was positioned between the laser-textured steel cylinder surface and the support shaft onto which a Teflon wrap was placed, so that the friction between the supporting shaft and the sheet metal can be negligible compared to the friction between the tool cylinder and the sheet metal. Furthermore, the strip was clamped and connected to a computer-controlled rack to pull it across the textured area of the cylinder. The velocity was adjusted with a speed controller. The rack was connected to a force gauge to measure the pulling force and stream the data to a computer where it was recorded. The data were analyzed in an Excel table with the Toriemon-USB software. Counterweights were added to the machine to increase the normal load on the specimen interface. A test with a non-textured tool was also performed to provide the baseline information.

The upper cylinder surface was kept stationary, while the sheet sliding speed was varied from 2.5 to 14.5 mm/s in reference to the previous research studies [11,21,19] for sheet forming applications. The contact pressures tested were 90 and 120 MPa. The SAE 10W lubricant was applied on each strip with a brush. Table 2 provides the experimental parameters. Since different sliding speeds were employed, a different number of measurement points were chosen in the calculation of the averaged force; for the speed of 2.5 mm/s, 6.25 mm/s, and 14.5 mm/s, 80, 50, and 30 datum points were used, respectively.

The apparatus is capable of running friction tests with a sliding speed up to 100 mm/s and a sliding distance from 330 mm up to 460 mm. The friction coefficient was calculated based on the measured pulling force and the applied normal force. After each test, which includes four runs at a set of constant conditions, the textured cylinder was cleaned with acetone in an ultrasonic bath to remove residual lubricant and wear debris. One aluminum strip was used for two runs, but each time used a new contact surface area.

3. Results and discussion

The effects of the texture orientation on friction under the influences of sliding speed, contact pressure, and rolling direction of the sheet were experimentally investigated. The average standard deviation of the friction coefficient of all performed tests is about 0.004, confirming that the testing process is stable. The average friction coefficient, μ, based on the measured data was computed and plotted. The sliding velocity was varied from 2.5 to 14.5 mm/s, and three relevant orientations between the sliding direction in the friction test and the sheet rolling direction were used, i.e., 0° (parallel), 45°, and 90° (transverse). A sample friction curve is shown in Fig. 4, obtained from the test ran at the speed of 2.5 mm/s and the contact pressure of 120 MPa, for the mating between a sheet surface with parallel orientated roughness and a textured tool steel surface.

Fig. 5 illustrates the difference between friction coefficients for a textured tool steel surface (T) compared with those performed with a non-textured tool steel surface (NT) at different contact pressures and sliding speeds with respect to the surface roughness orientation. Fig. 6 compares the friction coefficients at different contact pressures and speeds with respect to surface roughness orientation for a textured tool steel surface, and Fig. 7 for a non-textured tool steel surface. Note that again, “the sheet rolling direction” is referred to the direction of the last rolling operation in making the sheet metals.

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