Tribology International 91 (2015) 67–73

Contents lists available at ScienceDirect

Tribology International

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

# Directional friction surfaces through asymmetrically shaped dimpled surfaces patterned using inclined flat end milling

Jesus Resendiz, Eldon Graham, Philip Egberts*, Simon S. Park

*Micro Engineering Dynamics and Automation Laboratory (MEDAL), Department of Mechanical & Manufacturing Engineering, University of Calgary, 40 Research Place NW, Calgary, Alberta, Canada T2L 1Y6*

ARTICLE INFO

*Article history:*
Received 4 March 2015
Received in revised form
28 May 2015
Accepted 19 June 2015
Available online 29 June 2015

*Keywords:*
Micro-patterns
Functional surfaces
Micro-flat end milling
Friction

ABSTRACT

In this study, directional friction effects by creating asymmetrically shaped dimpled surfaces on an aluminum workpiece were investigated. The surfaces were created using the inclined micro-flat end milling process. Inclined micro-milling forces were modeled, and subsequent comparisons with the measured forces have provided validation. These simulations also showed that the flat end mill used to produce these dimpled surfaces was not symmetric. Tribological characterization of the friction properties of the surface using reciprocating tribometer and a hemispherical ruby counter surface indicated that these asymmetrically shaped dimples lowered the overall friction coefficients measured under both dry and lubricated sliding conditions. Moreover, the results also demonstrated a sliding direction dependent response, in terms of the measured friction coefficients.



## 1. Introduction

Functional surfaces play an important role in the behavior of engineering parts, such as those in mechanics, electronics, information technology, energy, optics, biology, and biomimetics [1]. Reduction of friction depends on many factors: one of the important factors is the topography of the rubbing interfaces [2]. For example, patterned surfaces are one mechanism by which the lifetime of hip replacements can be extended [3]. In more conventional engineering mechanical systems, such as in automotive lubrication, functional surfaces in the form of micro-dimples have been shown to reduce friction between mechanical components through the following mechanisms: debris caused by mechanical wear of the sliding surfaces can be trapped by the textured surface [1,4]; the textured patterns can act as lubricant reservoirs, allowing for a faster transition to the elastohydrodynamic lubrication regime as the device is switched on [5]; and, textured surfaces can also influence the hydrodynamic pressure between surfaces, which can result in increased load carrying capacity [4,6,7].

Since uniformly shaped surface features can be difficult to produce, many researchers have observed anisotropic frictional effects that depend upon the orientation of surface features to the sliding direction [8]. Depending upon the type of surface structures, frictional performance is often superior in a specific direction [4,9]. In fact, anisotropic frictional effects arise naturally in many materials, such as wood and composites, due to the material structure and surface roughness [8].

Compared to other surface texturing methods, such as wet or dry etchings, abrasive jet machining and laser processes, inclined micro-milling can be an efficient and cost-effective method to fabricate micro-dimples, because complex systems are not necessary. Inclined micro-milling is very precise and does not have high energy consumption, and a mask is not required. The micro-milling technique significantly reduces the time needed to fabricate dimpled surfaces by creating a row of dimples in a single pass of the cutter. Many other machining methods are not efficient by comparison, as individual dimples are made through repeated horizontal and vertical movements of the cutting tool; thus, pattern surfaces from inclined micro-milling exhibit improved tribological properties [10].

Determination of the optimal structure that can influence the friction response of a mechanical system is of particular interest. Such surfaces have been realized through ball end milling [11] and fly cutting [12]. Advantages of micro-milling producing micro-textured surfaces include high material removal rates, accurate surface finishes, and few restrictions on workpiece materials [13]. It has also been shown that micro-milling can be used to produce a variety of different surface structures by altering the cutting technique [14]. Micro-milling thus represents a very flexible method, and, with the right combination of cutting technique

* Corresponding author at: 40 Research Place NW, Calgary AB, T2L 1Y6.
*E-mail addresses:* jdjresen@ucalgary.ca (J. Resendiz), ejgraham88@gmail.com (E. Graham), philip.egberts@ucalgary.ca (P. Egberts), simon.park@ucalgary.ca (S.S. Park).

http://dx.doi.org/10.1016/j.triboint.2015.06.025
0301-679X/

and tool geometry, a wide variety of surface structures can be developed. However, care must be taken when using micro-milling to pattern surfaces, as in machining patterns, oscillations of cutters while rotating, cutting tool wear or breakage, tool deflections, non-uniformity of cutting conditions, varying rigidity of the workpiece or clamping system, and abrupt movements of the workpiece while texturing can detrimentally influence the resulting surface structure [15]. Predictive modeling of the machining forces is one mechanism by which of these disadvantages can be reduced, as several of these challenges can be identified beforehand, such as cutting tool wear or breakage and tool deflections. Furthermore, comparison of measured machining forces with those predicted by the model can be used to identify issues with patterning the surface, such as issues with uniform cutting, oscillations in the cutter, or tool wear.

The performance of textured surfaces depends upon the geometry of the surface patterns. It is, therefore, essential to understand how different machining parameters affect the resulting topographic structure. In this paper, the cutting forces are evaluated to determine the effect of machining parameters on tool longevity and efficiency, as well as patterning performance and efficiency. The surface topography generated by a flat end mill on aluminum alloy Al6061 is characterized to ensure the machining simulations match experimental measurements. Finally, the tribological performance of anisotropically shaped micro-dimples is evaluated and shown to have sliding direction dependent friction coefficients. An understanding of the basic relationship between these parameters allows manufacturers to optimize the tool path and surface features and minimize, tool wear and deflection.

## 2. Methods

### 2.1. Machining of patterned surfaces

Flat and dimpled surfaces were machined using a home-built computer numerical control (CNC) micro-milling system. This system is graphically depicted in Fig. 1(a) and photographed in Fig. 1(b). The CNC was mounted and secured on a vibration isolation table to insulate the machining system from the ground. An electric spindle (NSK Astro-E 800Z) was mounted onto a bracket that allowed the spindle to rotate at an inclination angle relative to the sample surface and to be secured during machining. Translation of the workpiece below the spindle during machining and friction testing was achieved by mounting the workpiece on linear precision stages (Parker Daedal 10600). These linear precision stages were actuated with stepper motors that were computer controlled (National Instruments PXI-1042Q). Calibration of the stepper motors was made by measuring the real displacement of the stage using a Keyence Laser Displacement Sensor (LK-G3001) in relation to the number of steps counted during the translation of the stage.

Samples were produced by fixing the Al6061 workpiece to a piezoelectric table dynamometer (Kistler 9256C), allowing for future measurements of cutting and friction forces. Before producing dimples, the surface of the aluminum workpiece was flattened by milling the top layer of the surface with the spindle positioned so that its long axis was perpendicular to the workpiece surface normal.

To ensure a sufficient supply of oil for lubricated surfaces during friction testing, a small depression of about 2 mm was machined onto the surface of half of the workpiece. This depression ensured that the lubricated and unlubricated surfaces had the exact same surface normal in subsequent friction testing. Following the surface planning and milling of the oil reservoir, the surfaces were polished using a P800 grit sandpaper to remove machining marks and reduce surface roughness. The surface roughness was measured over a $1 \times 1$ mm$^2$ area to be less than $0.11 \pm 0.02$ μm (Mitutoyo SJ-201P).

To measure cutting during dimple fabrication and friction forces, analog signals from the table dynamometer were amplified by a factor of 10 (Kistler Charge Amplifier 5010) and digitally recorded (National Instruments BNC-2110) at a sampling rate of 1 kHz. Dimpled surfaces were produced by fast translation of the sample workpiece while the end mill, now inclined at angle of 60° to the surface normal, was close enough for the flutes to cut the surface. A flat end mill (PMT® TS-2-0350-S) containing two flutes and with a diameter of 889.0 μm was used, producing dimples of approximately asymmetrically shaped dimples that were approximately 30 μm deep and 300 μm in the largest lateral dimension. Further details of the shape of the resulting surface texture are discussed in the next section.

### 2.2. Modeling of inclined flat end milling forces

Conventional cutting force models for flat end mills can be modified to predict forces for inclined flat end milling. Three force components on the milling cutter must be considered to account for the effects of spindle inclination. Inclined cutting of dimples with a flat end mill is periodic and not continuous as in upright milling, and each flute enters the workpiece surface with a certain frequency. Since the tool geometry of a flat end mill allows for uniquely shaped dimple geometries, an investigation into how cutting forces are affected is warranted. Using the conventional force model, cutting forces can be identified while the end mill is inclined in local $x'$–$y'$–$z'$ coordinates. Afterwards, they can be

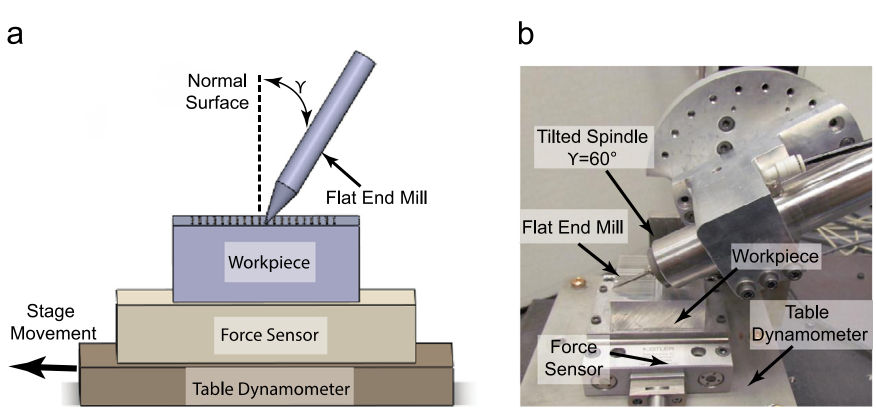


**Fig. 1.** (a) Schematic of the machining system used. The flat end mill is tilted with respect to the surface normal of the workpiece to produce the dimpled surface. (b) Photograph of the end mill setup used to produce the dimpled surfaces. The spindle in this case is at an inclination angle ($\gamma$) of 60° with a flat end mill attached.