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High-speed sliding friction of laser-textured silicon nitride in water against rubber

Arnold Ismailov[1], Tero Kumpulainen[2], Jorma Vihinen[2], Erkki Levänen[1]
[1]Department of Materials Science, [2]Department of Mechanical Engineering and Industrial Systems, Tampere University of Technology, P.O.Box 589, FIN-33101 Tampere, Finland
arnold.ismailov@tut.fi, tero.kumpulainen@tut.fi, jorma.vihinen@tut.fi, erkki.levanen@tut.fi

Abstract

The effects of a specific laser patterning on friction of silicon nitride bulk ceramic in water against rubber were investigated. A dimple-like patterning was applied to the surfaces of silicon nitride bulk ceramic blocks with pulsed laser drilling. Friction measurements were conducted with a special device designed for high-velocity sliding wear and friction testing of hard materials in wet conditions. Sliding velocities in the water-lubricated test ranged from 3.3 to 33 m/s and the load was 80 N. Anomalies in friction behaviour were observed in 8.3 and 16.7 m/s, which can only partially be explained with test equipment characteristics.

1.0. Introduction

Friction and wear are the two main reasons for part replacement in large industrial machinery. Tribological applications often benefit from using ceramics due to their superior mechanical properties, like hardness and compressive strength that grant them high wear resistance. Engineering ceramics generally have good chemical stability, which is useful for lubricated sliding conditions. Silicon nitride is highly resistant to wear and it also has the capability to form an oxide layer that shows very low friction when water is present[1].

Micro-scale surface patterning is a frequently researched possibility to reduce friction in several different kinds of lubricated sliding[2,3,4,5]. The two main hypotheses propose that the dimples act either as lubricant reservoirs for improving hydrodynamic contribution between two sliding surfaces in lubricated conditions or as particle traps for ensuring the retention of optimally smooth surface for sliding through minimum wear[2]. The optimal structures for these differ in terms of area density of dimples. Higher dimple densities generally provide more hydrodynamic lift, whereas lower dimple density is used for lowering wear of smooth surfaces in environments with hard particles.

Surface modifying can be done with several methods, including ion beams, etching and mechanical machining. Laser is one of the more convenient ways to produce geometrically uniform and accurate micro-scale structures on a hard surface. The advantages of this method include fast processing and low mechanical stresses due to non-contact nature of laser machining process.

In this study we focus on studying the effects of sliding velocity on friction of a specific laser structured silicon nitride surface in wet conditions against rubber. Lapped and non-lapped surfaces were tested to see if this reportedly significant part of producing dimple patterns has a noticeable effect also in our test environment.

2.0. Materials and methods

2.1. Structured silicon nitride blocks

Nanosecond laser with good beam quality suits the micromachining of accurate features well. Pulsed lasers, as opposed to continuous beams, provide a rapid cycle of heating and cooling that reduces the amount of thermal loading in a bulk material. Dimple processing was carried out with a nanosecond pulse laser (see Table 1). Short pulse width minimizes heat affected zone (HAZ) and enables the producing of fine features with high processing speeds. A galvo scanner integrated into laser processing platform was used for processing dimple patterns.

The geometrical details of the dimple pattern were chosen based on findings in other papers published on the subject. A grid-type formation of dimples with 60 µm separation (pitch) in both vertical and horizontal direction was produced on polished silicon nitride surfaces (see Figure 1). Processing parameters were chosen so that the dimensions of the dimples would be as follows: depth of 5µm and 25µm in diameter, producing an aspect ratio of 5.

The initial scheme to produce dimples with a single pulse was abandoned due to the sub-optimal geometry and insufficient depth (< 1 µm) of the dimples that the method produced. Instead, several pulses were used for producing a single dimple, which in essence means the processing method became laser drilling. The eventual pulse count per dimple was 12; producing a deep enough dimple with sufficient headroom for lapping. The average depth of a dimple produced on a polished surface before lapping was 6 µm. By using multiple pulses the depth of a dimple can be adjusted by pulse count instead of resorting to pulse energy variations. The drawbacks for increasing pulse energy would be that the amount of melting and the extent of heat effects would increase as well. These would again have a direct effect on the dimple patterning geometry. However, the drilling approach is not without its flaws: Using multiple pulses increased the amount of burr on the edges of the dimples. Height of the burr is roughly 0.2 – 0.3 µm and is formed when sequential pulses hit molten material, sending part of the melt on the edges. Even this amount of burr is undesirable, as it adds to the roughness of processed surface, potentially affecting its performance in lubricated sliding. Two samples with identical patterning were produced; one was lapped and the other was left in the state immediately after laser processing.

The dimple density was 9.46%, as determined from a lapped surface by means of image analysis. The density value is lower than what would be produced by calculating it with ideal values of pitch (60 µm) and dimple diameter (25 µm). The pitch is confirmed by SEM images, thus it means that the average dimple diameter was a lot lower than intended; well below 20 µm. Table 2 presents the final accurate geometrical parameters of the dimple array.

2.2. Friction measurements

The effects of laser patterning on friction were measured with a special device designed for high-velocity sliding wear and friction testing of hard materials. The basic operating principle (see Figure 2) of the device resembles that of the ASTM G65 standard rubber wheel abrasion test. As a distinction from the standard test, sliding velocities in our device are adjustable and can reach up to 40 m/s. Also, slurry or water can be used as sliding medium, as opposed to dry silica sand of the standard test. This leads to lower wear rates[6] than with the standard test, which in turn means better focus on friction instead of wear. For engineering ceramics using water as the sliding medium for short tests results in negligible wear. Thus, it can be assumed that the evolution of friction in this case is not the result of wear.

Friction measurements were performed according to the details presented in Table 3. Sliding velocity was increased from 3.3 to 33.3 m/s and decreased along the same steps to minimize the error margin and to observe the possible hysteresis of friction force. A sample was in contact with the rubber drum and under the 80 N load the entire time it took to make the loop from low to high sliding velocity and back. The duration of every measurement was two minutes including acceleration. This time period was enough for all velocities to reach a stable 60 second interval. There were brief, 10 to 30 second pauses between velocity changes.

Thus, all measurements started from a standstill and under full load without changing sample orientation or position in the sample holder.

3.0 Results and discussion

The friction behaviour of laser structured silicon nitride is shown in the Figure **3**, where the friction coefficient values reported are the ones observed at 90 seconds into the 2-minute measurement. Friction coefficient values calculated from measured tangential forces ranged from 0.11 to 0.17. The lapped surface produced lower friction in 3.3, 8.3 and 33.3 m/s sliding velocities. The non-lapped surface showed lower friction in 6.7 and 16.7 m/s, though the difference between the two surfaces in 6.7 m/s is considered to be well within the error margin.

Previous studies performed with the high-speed sliding test rig suggested, that a key transition in lubrication regime exists in the sliding velocity range 5-10 m/s, the exact value depending on the material and the surface topography. Surfaces with micro-scale topographies generally produce lower friction in the test environment. Hot-rolled AISI 316L steel surfaces showed relatively low friction in 6.7 and 8.3 m/s in the initial stages of 60 minute tests before the naturally dimpled surface topography was lost due to wear[7]. The lapped silicon nitride surface in this study replicated this result. The supposed reason for this is that the velocity range in question is the transition regime mentioned above. Wear tests run on ceramics show that above 7-8 m/s the wear marks become uneven, with significantly less wear in the centre region of the contact area[6]. This is a clear indication of improved lubrication conditions at the area in question.

Some remarks need to be made about the test environment. The counter face for samples to slide against is rubber, which is commonly used for wear-testing devices but more rarely for friction measurement. The subject of rubber friction in sliding consists of two main aspects: adhesion that correlates with the actual contact area and elastic deformation of the rubber that produces a hysteresis phenomenon[8]. Contrary to the sliding between two essentially inelastic surfaces, friction in a rubber contact is primarily caused by the dynamic loading interactions due to extensive plastic deformation. It has been found, that a certain level of roughness in rubber contacts provides lower friction than smooth surfaces, especially in conditions containing water. The additional roughness of the non-lapped surface causes higher friction in 3.3, 8.3 and 33.3 m/s, which is a clear indication that all types of roughness are not optimal for water-lubricated sliding against rubber. Lapped surface produces a better result for those velocities.

A distinct anomaly in the expected friction behaviour is in the 16.7 m/s velocity. The friction coefficient shown by the non-lapped surface is coherent with the rest of the data: friction is low at 16.7 m/s and slightly higher at 33.3 m/s where the hydrodynamic contribution can be higher. The lapped surface produces the highest friction of all at 16.7 m/s, which can be explained by dynamic loading against rubber for this specific sliding pair. The effect is most likely caused by variations in lubrication regimes within the contact interface: It has already been shown in our previous studies that at some velocity range the centre area of the contact interface enters a different lubrication regime compared to peripheral parts of the contact, reducing wear in the process. It is possible that the added dimension of roughness in non-lapped surface provides a low-friction surface for the specific range of sliding velocities above 10-15 m/s. This possibility is somewhat supported by the relatively low friction in 33.3 m/s as well, though the lapped surface was far superior in that extreme of the velocity range.

4.0. Conclusions

A dimple-type patterning was applied on silicon nitride bulk ceramic blocks by pulsed laser. Friction for these surfaces was measured with a special high-velocity sliding test rig in the speed range of 3.3…33.3 m/s under 80 N load. The main findings in this study are the following:

- Intricate geometries, like micro-sized spherical dimples are best produced with several pulses instead of just one. Using multiple low-energy pulses enables good controllability of the processing and keeps thermal loads in the bulk material lower than using a single high-energy pulse.
- Friction behaviour of non-lapped and lapped surfaces was similar in lower sliding velocity range; 3.3 and 6.7 m/s. Increasing v to 8.3 m/s produced even lower friction for lapped surface, whereas the non-lapped surface showed a severe rise in friction with identical test parameters. Lapping is thus recommended especially for wet sliding contacts where lubrication conditions are not static and mixed lubrication is dominant.
- The effect of not lapping a dimpled surface produced surprisingly low friction in high velocities, which can at least partially be attributed to the additional roughness compared to the lapped surface. The anomaly encountered with a lapped surface in 16.7 m/s suggests there is a significant difference in contact characteristics compared to non-lapped. This is very likely caused by differences in lubrication at different parts of the contact area.

The need for further studies is evident: More tests need to be run in tighter intervals between sliding velocities to better see the exact transition ranges for friction evolution. Dimpled structures with different geometries will be tested in future.

5.0. Acknowledgements
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Table 1: Specifications of processing laser

Wave length (nm)	515
Q-switch repetition (kHz)	10
Pulse width (ns)	17
Mode	TEM_{00}
Cooling	water

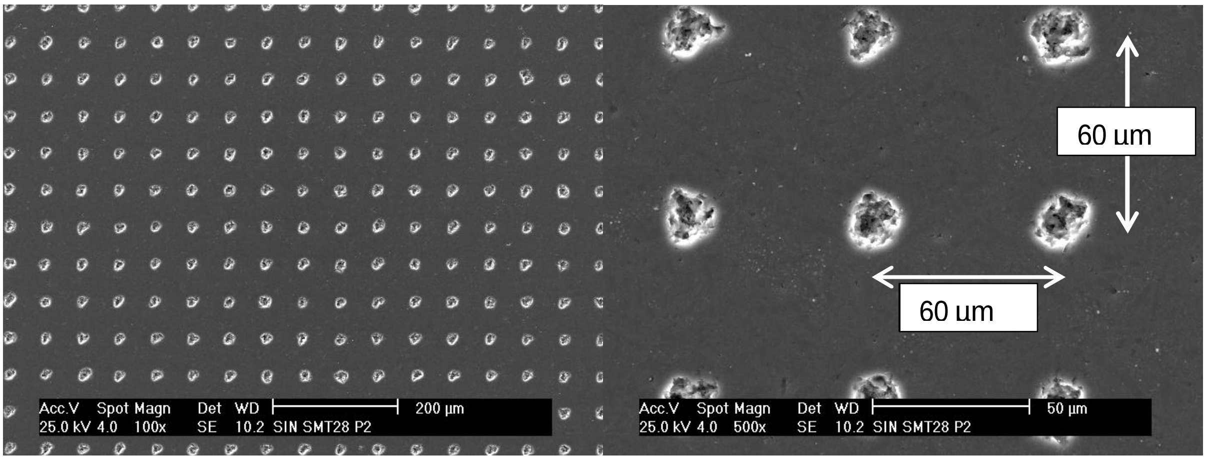

Figure 1: SEM images of the geometry of the dimple pattern on polished silicon nitride (lapped after processing).

Table 2: Geometrical parameters of dimple patterning

Pitch, p (µm)	Diameter, D (µm)	Dimple density (%)	Depth, h (µm)	Aspect ratio D/h
60	18.8	9.46	6.0±0.5	3.13

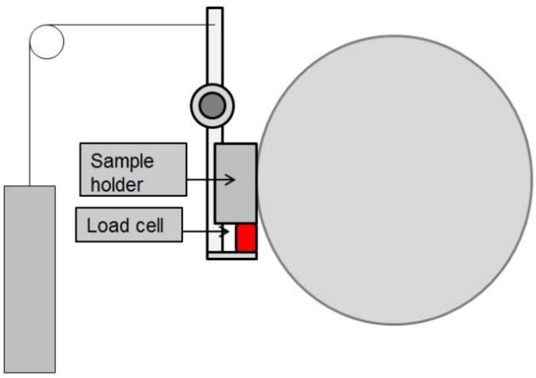

Figure 2: Friction measurement principle.

Table 3: Friction measurement parameters

Sliding velocities, v (m/s)	3.3/6.7/8.3/16.7/33.3
Load, W (N)	80
Surface pressure, P (MPa)	0.4
Measurement duration, t (s)	120
Temperature, T (°C)*	18
Medium	water

*Temperature near sample holders

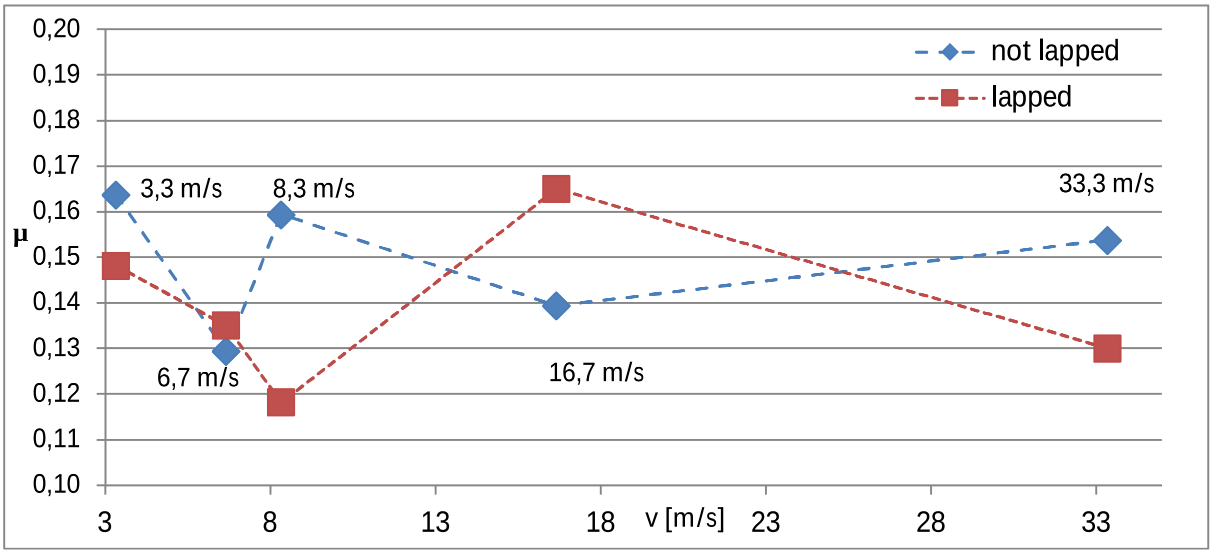

Figure 3: Friction coefficient for lapped and not lapped surfaces in different velocities.