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On design and tribological behaviour of laser textured surfaces

D. Bhaduri[a,*], A. Batal[a], S.S. Dimov[a], Z. Zhang[b], H. Dong[b], M. Fallqvist[c], R. M'Saoubi[d]

[a] *Department of Mechanical Engineering, School of Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK*
[b] *School of Metallurgy and Materials, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK*
[c] *Seco Tools AB, Fagersta, SE-737 82, Sweden*
[d] *Seco Tools (UK) Ltd., Springfield Business Park, Alcester, Warwickshire, B49 6PU, UK*

* Corresponding author. Tel.: +44-121-414-4143; fax: +44-121-414-3958. *E-mail address:* debajyoti.bhaduri@gmail.com, d.bhaduri@bham.ac.uk

Abstract

The paper reports an investigation into the functional response of textured surfaces with different designs that incorporated arrays of micro-dimples and grooves (40μm diameter/width and 15μm depth for both patterns) produced on tungsten carbide (WC) blocks by employing nanosecond (ns) and femtosecond (fs) lasers. In particular, the tribological performance of the textured WC blocks against stainless steel (SS316L) counterbody was evaluated in terms of friction and wear under dry condition compared to an untextured specimen. Friction tests were carried out on a reciprocating sliding tester while unidirectional ball-on-disc method was utilised to assess wear on the mating surfaces. The untextured surface exhibited a continuous rise in the friction coefficient from 0.15 to 0.5 from the start of the cycle to the end while the specimens textured with ns and fs lasers reached steady-state condition after 100 and 200 cycles with values between 0.35-0.45 and 0.3-0.4, respectively. Energy dispersive spectroscopy following wear tests showed a pronounced material transfer from the balls to the textured surfaces with stainless steel filling up some of the dimple and groove cavities; however, the reverse phenomenon was not apparent. Additionally, texturing with the fs laser exhibited formation of nano-ripples/structures in the produced dimples and grooves that can be further studied for creating nano-textured cutting tools or surfaces with super-hydrophobic/anti-ice properties.

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1. Introduction

Surface texturing/structuring has witnessed a substantial progress over the past decades as it is seen as a viable option for surface engineering, resulting in significant improvements in load capacity, wear resistance and friction coefficient of tribo-mechanical parts [1], thereby contributing to the development of sustainable manufacturing and surface functionalisation of components. Various techniques of surface texturing have been developed over the years including additive [2] and subtractive methods such as abrasive machining [3], reactive ion etching [4], electron beam [5] and electro discharge texturing [6]. In comparison to other subtractive material processing technologies, laser surface texturing (LST) has attracted considerable interest for over ~20 years due to its superior flexibility, selectivity, accuracy, efficiency and capability for producing tailor-made surfaces with varying wettability, adhesion and friction properties. Typically LST is carried out by producing arrays of micro-dimples/pores on the surfaces that can serve either as a micro-hydrodynamic bearing in cases of full or mixed lubrication, a micro-reservoir of lubricant in boundary or starved lubrication conditions, or as a micro-trap for wear debris in either lubricated or dry sliding environment [7].

There has been a comprehensive study on the application of LST in improving the tribological performance of friction units. Etsion et al. [8] developed an analytical model to predict the relation between the opening force and operating conditions in a mechanical seal textured with spherical micropores. The area density of the pores and the radius ratio of the seal had a marginal effect on the average pressure, whereas the effect of the pores' depth over diameter ratio was very significant. A unidirectional sliding test on hardened H13 steel specimen textured with micro-dimples broadened the

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range of hydrodynamic lubrication regime in terms of load and sliding speed for both high and low viscosity oil lubricants [9]. It was further recommended that the removal of bulges at the edge of the dimples by lapping after LST was essential in order to optimise the advantageous effects of LST.

Attempt has been made to optimise the LST process parameters to benefit from textured surfaces under different lubrication regimes. Vilhena et al. [10] studied the tribological performance of AISI 52100 steel (structured with various laser pulse numbers, pulse energies and single as well as multi-mode pulses), in a low frequency - long displacement reciprocating sliding test under boundary lubrication condition. The LST specimens typically exhibited a higher coefficient of friction (COF) with respect to the untextured counterpart although texturing was beneficial in reducing the COF at low sliding speeds. On contrary to [10], the positive effects of micro-dimples became apparent with an increase in dimple depth as well as for higher sliding speeds, as observed in another study by Vilhena et al. [11]. It was argued that at greater sliding speeds, micro-dimples acted as micro pressure chambers, that provided a hydrodynamic action. Podgornik and Sedlaček [12] investigated the possibility of using 3D surface parameters (kurtosis and skewness) as the design parameters for selecting the optimal LST patterns for contact surfaces operating under lubricated conditions. For textured surfaces, an increase in the kurtosis and a more negative skewness, obtained by reducing the cavity size, increasing the cavity depth and decreasing the texturing density, were found to yield a lower friction. Tribological behaviour of LST was also assessed in combination with a solid lubricant coating, typically MoS_2 [13,14] and WS_2/Zr [15] with an aim to replace the hazardous lubricating fluids used in rotating/moving mechanical parts/systems.

Laser texturing has been applied on different materials including hardened AISI 52100 [11] and stainless steel [16], cast iron [17], Ti-6Al-4V [13], tungsten carbide [14], Al_2O_3/TiC [15], Si_3N_4/TiC [18] and nickel based superalloys [19]. Ahmed et al. [20] conducted a systematic characterisation of femtosecond laser induced nano- and micro-scale surface features on titanium, stainless steel, aluminium and copper. While undulating grooves covered with ripples and lumpy structures were formed on titanium and steel, maze-like and bumpy features on aluminium and nano-forest, deep well-defined trenches and chaotic rugged microstructures on copper were observed, as shown in Fig. 1.

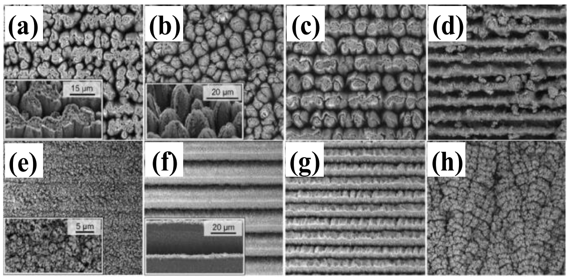

Fig. 1. Representative laser-induced surface structures observed on (a)-(d) aluminium and (f)-(h) copper [20].

Surface texturing was carried out by applying the two main laser-material interaction regimes, i.e. thermal (ns pulse durations) [10,14] and athermal (fs pulse durations) [15,19] lasers. While the former regime is dominated by thermal effects, e.g. metal melting and consequent material re-deposition and re-solidification, the latter leads to almost negligible thermal load and removes material by direct matter sublimation. Athermal processing can also result in nano-textures/ripples on surfaces that have many potential applications in the fields of biomimicry, super-hydrophobicity, colour marking for counterfeit protection and microfluidics; thus the mechanism of nano-texture formation has attracted significant research interest [20].

Although various designs and optimisation of LST patterns have been investigated, the process design methods are still dominated by 'trial and error' approaches, and yet there are large variations in 'optimum' designs obtained by different research groups [1]. The broad objectives of this research is to investigate the effectiveness of LST primarily in dry machining that have been studied by other researchers, too [21], and also to explore its potential benefits in other application areas. Dry machining with textured cutting tools has enormous prospects in sustainable design and manufacturing as it can replace the use of environmentally hazardous cutting fluids. However, it is imperative to identify the texture designs, i.e. LST patterns, and subsequently validate them in order to maximise their functional effects. The authors have investigated different LST designs, i.e. dimples and grooves with various sizes and densities created using ns laser) on tungsten carbide (WC) blocks and cutting inserts to understand the dependencies between the tribological properties and machining performance of textured tools when dry turning Ti-6Al-4V. The results of the investigation have been reported elsewhere [22,23]. Based on the knowledge gathered in [22,23], the current research presents two different designs of LST patterns (dimples and channels of equivalent dimensions but different area coverage) generated on cemented carbide surfaces using both ns and fs lasers and compares their tribological behaviour with respect to an untextured WC counterpart. As the study is ultimately aimed at assessing the machining performance of LST WC tools for dry turning a stainless steel (to be reported elsewhere), the tribology tests reported in this paper utilised SS316L ball as the counterbody. Both reciprocating and unidirectional ball-on-disc tests were carried out under dry environment to determine the friction and wear mechanisms of the textured surfaces under low and high sliding speeds.

2. Experimental details

2.1 Laser surface texturing of WC blocks

Two different laser textured patterns, comprising dimples and grooves, were produced on planar tungsten carbide blocks (20 mm×20 mm×5 mm) with nominal compositions of 94% WC and 6% Co. The trials were conducted on a Lasea L5 laser micromachining centre using both nanosecond and femtosecond lasers of wavelengths 1064 and 1030 nm and a maximum average power of 50 W and 5W, respectively. The