Surface & Coatings Technology 307 (2016) 702–712

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Methodology of laser processing for precise control of surface micro-topology

M. Ahmed Obeidi, E. McCarthy *, D. Brabazon

Advanced Processing Technology Research Centre, School of Mechanical & Manufacturing Engineering, Dublin City University, Dublin 9, Ireland

ARTICLE INFO

Article history:
Received 14 June 2016
Revised 28 September 2016
Accepted in revised form 29 September 2016
Available online 30 September 2016

Keywords:
Surface texturing
CO_2 laser
Micro-profiling
Micro-texturing
Stainless steel
Moiré pattern

ABSTRACT

Laser surface texturing of materials potentially offers precise control of surface structure and mechanical properties. This has a wide range of applications such as control of frictional forces, control of bond strength in interference fit joints, and production of antifouling surfaces. To achieve such texturing in a well-defined, useful manner, precise control of the applied laser processing parameters over a sizeable surface area is required. This paper presents the development of a method for creating highly repeatable and predetermined moiré textured patterns on metallic samples via laser processing. While the method developed is broadly applicable to various materials and laser systems, in the example detailed here the surfaces of cylindrical stainless steel samples were processed with a pulsed CO_2 laser. The resulting modified surfaces contained texture geometries with pre-definable peak-to-peak widths, valley-to-peak heights, and texture directions. The method of achieving this theoretically and experimentally is detailed in this paper. The relationship between the laser processing parameters and resulting diameter increase was confirmed via Design of Experiment response surface methodology. Precise control of the laser textured cylindrical surface outer diameter and texture pattern are key factors in determining the potential suitability of this process for application to the production of interference fit fasteners. The effects of the laser processing parameters and topologies of the resulting re-solidified metal profile on the surfaces were assessed in detail with a focus on this application.

1. Introduction

Laser surface texturing is used as a beneficial processing method for piston sleeves in order to reduce friction. Etsion et al. showed that a fuel saving of 4% can be achieved by producing a micro-dimpled surface using laser texturing on diesel engine piston rings [1]. By taking into account the number of cars using diesel engines in just the United States, the diesel fuel saving would be around 120 million barrels/year [2]. Experimental work has shown that ideal situation of hydrodynamic lubrication can be achieved when the aspect ratio of the laser texture (micro dimple depth/diameter) is between 0.01 and 0.1 [1,3–5]. Due to the high degree adjustability of the laser processing parameters, accurate control of the dimensions of the processed surface in terms of ablation, melting, and heat affected zone (HAZ) can be achieved [1,2,4,5]. The level of precision achievable in this regard via laser processing is impossible to be achieved using conventional machining methods.

For many industrial applications, surface roughening is sought for certain locations on the part to be processed, while retaining the core bulk material properties unchanged. The texturing of the piston rings is one example of this. Another example is the different levels of roughness required for hip implants, where the implant stem often requires micrometer level roughness to allow for implant bonding into the body, and the ball head has to be very smooth in order to allow for free movement. Laser texturing can also be used to inhibit the adhesion of undesirable biological elements to implants. Infections are a common source of implant failure [6,7]. The presence of bacteria or biofilms on the implant can lead to infection, and also inhibit osseointegration [8]. Cunha et al. investigated the use of laser surface texturing on titanium to reduce the adhesion of *Staphylococcus aureus* and biofilm formation [9]. They observed that the laser textured surfaces had a lower bacteria adhesion than the untreated surfaces, due size of the surface features, and the distance between them, being smaller than the size of the bacteria. The authors contrasted this method with alternative methods where a coating of an antimicrobial agent, such as copper, silver nitrate, silver, titanium, or drug-functionalised nanoparticles, were deposited on the surface of the implant. These methods potentially introduce toxic elements to the patient's body which laser surface texturing does not, making it potentially a safer anti-microbial surface preparation option. Further work on titanium implants, has been shown that laser processed surface can also be tailored to preferentially promoted human biospecies attachment and growth, indicating the higher levels of biocompatibility achieved from this processing [10].

Advances in laser technology have allowed for new types of surface texturing to be achieved such as submicron-scale ripples called laser induced periodic surface structures (LIPSS) [11–13]. These ripple patterns

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* Corresponding author.
E-mail address: eanna.mccarthy@dcu.ie (E. McCarthy).

http://dx.doi.org/10.1016/j.surfcoat.2016.09.075
0257-8972/

arise from interference between the incident radiation and surface electromagnetic waves, and are highly dependent on polarisation [14]. These small scale and highly uniform patterns mirror textures seen in nature (e.g.: the lotus leaf), and can be suitable for applications such as self-cleaning surfaces, structural colouring, and antireflective surfaces.

Laser surface texturing can be used to alter the hydrophobicity of a surface [15–17]. Superhydrophobic surfaces have a number of applications, such as self-cleaning glass [18–20], drag reduction [21–23], and in microfluidic devices [24–26]. Ta et al. created superhydrophobic metal surfaces using laser surface texturing [15]. A 1064 nm SPI fibre laser was scanned over the surface of copper and brass substrates, creating textured surfaces that were initially hydrophilic but aged to become superhydrophobic reaching a maximum contact angle (152°) after 11 days. The authors attributed this effect to the surface roughness created by the laser texturing, and the change over time in surface chemistry. Thus the method proved to be an effective, direct write, fast-processing, and low waste method of modifying the wettability of metal surfaces.

An application which has not yet been investigated, is the use of laser surface texturing for interference fit connections. Interference fit connections are typically formed via the high frictional force generated between a shaft and hub. This is produced via the forcing of an oversized pin or dowel into a mated drilled hole. These connections require high insertion forces and tight tolerances on the diameters of the shaft and hub, and often suffer from excessive plastic deformation which can lead to premature failure of the joint [27]. Laser surface texturing allows for precise control of the outer diameter of the shaft, as well as defined interference volume from control of the surface texture. In interference fit joints, a key factor is the interference value, defined as the difference between the hole diameter and the diameter of the insert. The strength of the joint is dependent on the interference value such that very high machining accuracy is required. Commercially available interference fit pins have typical tolerances in the range ± 0.0045 to 0.08 mm. For example, a typical interference fit fastener (DRIV-LOK knurled pin) has a nominal interfering diameter 9.881 ± 0.076 mm and is recommended for interfering with a hole diameter of 9.576 ± 0.051 mm, giving a positive interference ranging from 0.178 to 0.432 mm. While within this range of positive interference, good bonding would be expected, a significant difference in the level of plastic deformation and associated bond strength is expected from such difference in levels of interference. Controlled diameter increases through laser texturing could provide an easier and less expensive method of achieving such precise diameters. The increased control over the overall interfering volume could also prevent the excessive plastic deformation noted from conventional interference fit joints, thereby providing a more reliable joint.

There has been some examination into the control of surface topography by laser treatment. Du et al. characterised the laser texturing of rollers by Nd:YAG, investigating the relation of the input parameters to surface roughness and hardness of the texture [28]. Vilhena et al. investigated the creation of micropore textures on steel surfaces [29]. They related the laser parameters to the micropore profiles, and tested the sliding wear behaviour. However, the use of laser texturing for finely controlling the generated surface pattern and increase in pin diameter for interference fit fasteners has not previously been presented. In this paper, we therefore present a novel method for prescribing the texture before laser processing, and setting the laser parameters to achieve this texture after processing.

2. Material and methods

Fig. 1 shows a schematic diagram of the laser process utilised in this study. The cylindrical pin samples were rotated with a DC motor which was used to provide an adjustable speed range from 0 to 5000 rpm. The carrying stage provided translational speed within the range of 0 to 5000 mm/min. A computerised numerical control (CNC) CO_2 laser machine Rofin DC-015 of 1.5 kW maximum average power and a laser beam focus diameter of 0.2 mm were utilised. Argon gas was delivered in line with the laser beam during processing. The role of this assist gas was to protect the laser focusing lens from the laser-induced plasma, which may harm the lens, and to provide an inert gas surrounding to reduce surface oxidation of the sample. The pin sample was supported by a freely rotating centre bearing opposite to the DC motor, to prevent sample off centre spinning.

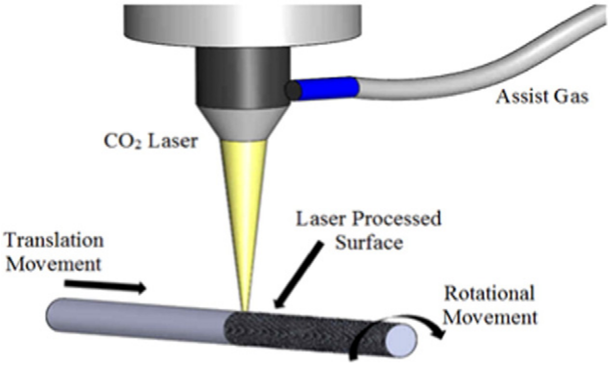

Fig. 1. Schematic diagram for the CO_2 laser scanning process of cylindrical samples.

Stainless steel 316L cylindrical pin samples were used in this study to examine the effect of laser process control parameters on generated surface textures. Cylindrical samples were employed instead of flat samples, as this allowed for higher scanning speeds, resulting from the interacting angular and translational speeds. This provided a suitable shape for an interference fit pin as one possible final application. The as-received samples were 10, 12, 16, and 20 mm in diameter, and were cut into lengths to allow translational scans of 10 mm length along the pin with different laser processing parameters. The laser parameters examined were the power (W), pulse repetition frequency PRF (Hz), and the percentage of overlapping laser spots (%). An important measured outcome response was the increase in the samples' diameters (mm). This increase in diameter results from the controlled surface melting and re-solidification. In order to improve the laser energy absorption, samples were sandblasted which increased the surface roughness to approximately 1.5 μm.

The assist gas pressure was tested at different levels. The increase in metal surface thickness and the presence of oxidation, roughness, and moiré pattern were recorded. The assessment test of the effect of gas pressure was conducted using laser processing parameters of 500 W, 300 Hz, and −20% overlap. From this test, an optimum argon gas pressure of 0.3 MPa was identified which resulted in reduced oxide formation but also lower levels of gas consumption. This pressure level was applied for the rest of the samples produced in this study which resulted in better definition and visualisation of the generated patterns due to the reduced occurrence of surface oxide. A block scheme for the experiment can be found in Fig. 2.

2.1. Control of micro-texture longitudinal and circumferential dimensions

Three possible laser spot overlap scenarios are shown on the schematic in Fig. 3. Zero overlap indicates that the laser spots in both circumferential and axial directions were arranged such that they touch only tangentially, as shown in Fig. 3(b). Positive overlap occurs where the laser spots interfere with each other by a certain defined percentage, as indicated in Fig. 3(a), and conversely negative overlap indicates the presence of unprocessed gaps between each successive laser spot, Fig. 3(c). For each of these cases in this work, the rotational and translation speed were set such that the laser spots were overlapped to the same extent in the circumferential and longitudinal directions. The mathematical relationship between translation and rotational speed required