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Improvement of hardness and wear-resistance of direct laser interference patterned bearing steel surface using laser surface heating approach

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Abstract

In this work, we report on the laser heat treatment of periodic topographies produced on bearing steel plates using Direct Laser Interference Patterning (DLIP) technology. The hardening treatment allowed tuning the surface hardness from 210 to 827 HV. The combination of the patterning and laser hardening approaches permitted to improve the wear-resistance of the structured surface by ~ 50 % at contact point pressure of ~17.87 GPa. The outcomes indicated that by applying the proposed joined methodology it is conceivable to hold the higher hardness of the bearing steel plates and simultaneously to keep intact surface microstructures.

Keywords: Direct Laser Interference Patterning; laser surface hardening; wear; functional surfaces

1. Introduction

Direct Laser Interference Patterning (DLIP) has emerged as a practical technology to enhance surface functionality, for instance to improve tribological properties of steel parts (Stark, et al., 2019). In this case, the aim is to create a microstructured topography that can diminish friction and wear, especially for a mixed lubrication regime in which two steel parts, body and counter-body are in contact. Indeed, it is know that most degradation mechanisms, like wear, fatigue, and corrosion, start at the surface denoting the importance of the laser treatment.

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Furthermore, the life period and functionality of tribo-pairs with improved tribological properties is related with the durability of those functional patterns. Thus, the undesirable deterioration of the produced surface patterns represents a technical problem of the mechanical contact, and can be fundamentally improved by increasing the hardness of the microstructures. So far, various strategies are being utilized to improve wear resistance of surfaces, like surface hardening through diffusion treatments (boriding, thermo-reactive deposition, and diffusion (TRD) (Christiansen, et al., 2017)) as well as physical vapor deposition (PVD) (Kunze, et al., 2015), and plasma-enhanced nitriding (PAN) (Garcia-Giron, et al., 2018). Nevertheless, these methodologies have a few restrictions, in particular if they have to apply in combination with textured surfaces.

The research reported in this work proposes an approach that combines laser surface hardening with laser patterning to improve the durability of microstructures on bearing steel surface. Specifically, a nanosecond two-beam interference arrangement is used to produce a line-like pattern with 8.5 µm spatial period on bearing steel, that is thereafter hardened with a high power diode laser. The surface topography before and after laser heat treatment are analyzed and micro-hardness and scratch hardness tests are performed.

2. Experimental

The laser patterning and hardening experiments were performed on a bearing steel surface with surface roughness Sa of 0.74 µm. At first, the samples were treated utilizing a compact self-developed interference patterning optical configuration (DLIP-µFab, Fraunhofer IWS, Germany), outfitted with a pulsed Q-switched Nd:YLF laser (Laser-export Tech- 1053 Basic, Russia), operating at 1053 nm and providing 12 ns (TEM00) pulses with pulse energies up to 290 µJ at 1 kHz pulse repetition rate. Each laser pulse passes through the two-beam DLIP system (Figure 1 (a)) and overlaps with an interference angle $\theta = 7.10°$ on the sample surface, leading to the generation of line-like patterns of spatial period Λ = 8.5 µm in an area of ~110 µm in diameter (DLIP-pixel). The samples were mounted on mechanical stages (Aerotech PRO155-05, USA) and translated in lateral directions such that, larger areas up to 100 x 100 mm² can be textured. The arrangement of the pulse position occurs consecutively such that first overlap in the x-direction (feed direction) and then substrate is moved in the y-direction by hatch distance. In the experiments, laser fluence was set to 6.58 J/cm², and overlap in x-direction and y-direction were set to 92.23% and 73.45% respectively (El-Khoury et al., 2020).

For the hardening treatment, a high power diode laser was used (Laserline LDF 400-5000RD, Germany) operating at wavelength of 910-1030 nm with an output power of 1.6 kW was used, allowing a surface temperature of 1050°C. The power density distribution in the working plane had a top-hat geometry with a beam diameter of ~7 mm. In order to adapt the laser track width and optimize the intensity profile, a self-developed scanning head (LASSY, Fraunhofer IWS, Germany) was used (Bonß, et al., 2010). LASSY consists of a fixed 90° reflection mirror with 1D scanning mirror was used in tandem with linear axis was used to deflect the laser spot across the surface in a meander-shaped track (Figure 1(b)). The laser tracks were generated in meander-shape with feed rates between 200 – 400 mm/min at a scanning frequency of 100 Hz. The laser hardening process was run under argon (Ar) as a shielding gas.

The impact of the laser hardening on the micro-hardness of the steel substrates was studied using micro-indentation measurement system (LECO AMH-43, USA). The wear resistivity under highly loaded sliding/abrasive contact conditions was simulated by scratch tests utilizing a MCT3 device (Anton Paar, Austria) (Gee, et al., 2001). The scratch tests in this study were performed using a diamond stylus with spherical tip of 50 µm radius moving with a normal load that was progressively increased from 0.03 to 3.00 N with a 3 N/min load rate and a 3 mm/min lateral speed. The topography of DLIP structured surfaces was investigated before and after laser hardening treatment using high-resolution scanning electron microscopy (JEOL JSM 6610LV) operating at a voltage of 15 kV as well as white light interferometry (Sensofar S Neox, Spain) in fields of 351 µm × 264 µm employing a 50x magnification objective.

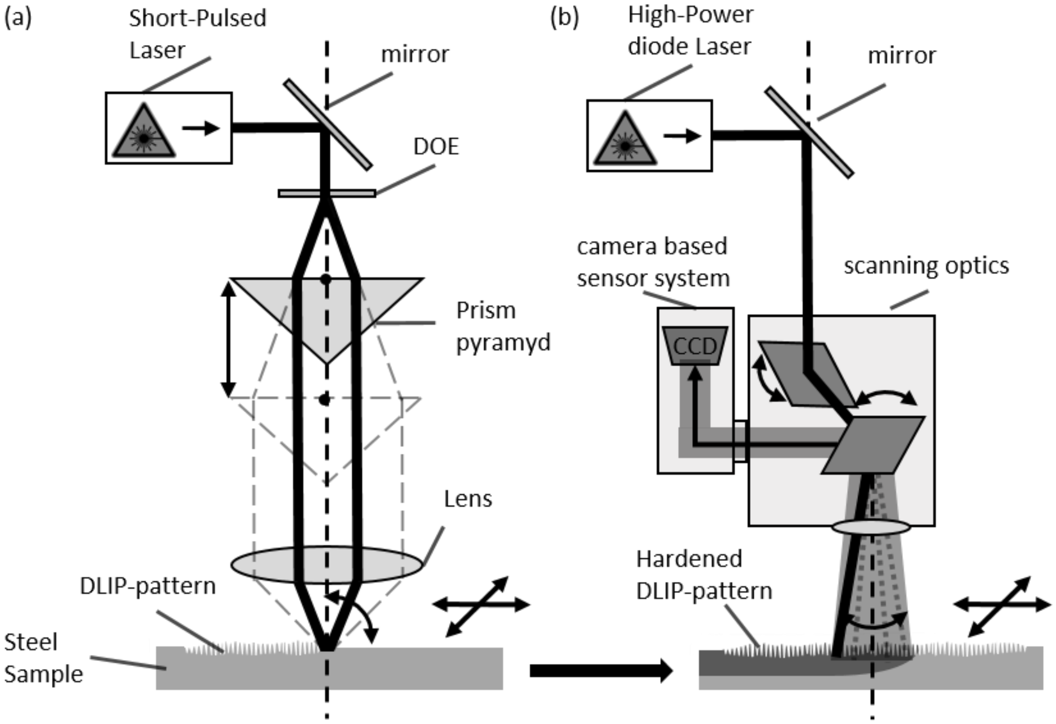

Fig. 1. Schematic representation of (a) the DLIP treatment and (b) laser surface hardening subsequent process

3. Results and discussion

The periodic structures on the steel samples were produced utilizing the DLIP-system with the parameters described in chapter 2. An example of produced line-like pattern is depicted in Figure 2 (a). Note that during nanosecond-pulsed laser treatment, ablation as well as redeposition of the molten material driven by Marangoni convection and recoil vapor pressure takes part in the structuring mechanism, and thus creating structures with high aspect ratios (El-Khoury et al., 2020). The created surface structures showed a depth of ~9.53 ± 0.87 µm, as surveyed by confocal microscopy measurements. The DLIP patterns were subsequently post-treated by laser surface hardening (LSH) under Ar-shielding conditions at 200, 400 and 800 mm/min feed rates (Figure 2 (b)). Figure 2 (c) shows the DLIP structures after the laser hardening process under Ar-shielding atmosphere, denoting that the periodic lines were not damaged by the hardening treatment. In the last case, the structure depth of the DLIP pattern was 9.21 ± 0.93 µm, which is very similar to the initial condition.

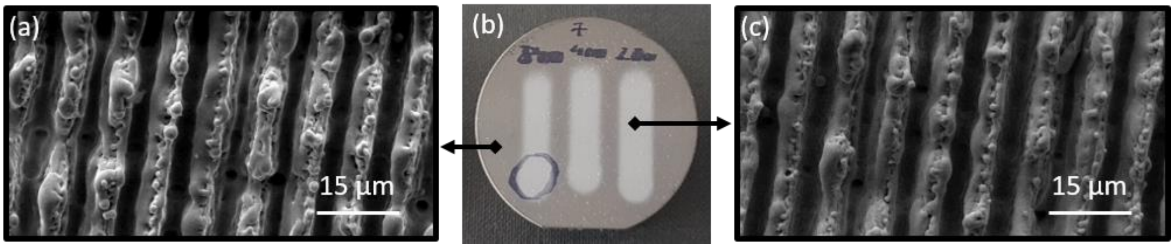

Fig. 2. (a) DLIP line-like periodic structure produced at 6.4 J/cm² laser fluence and 95.86% and 76% overlap in x and y-directions respectively; (b) 100Cr6 sample treated by DLIP and LSH processes; (c) line-like patterns hardened under Argon shielding gas at 200 mm/min feed rate

After that, microhardness measurements (Micro Hardness V-Test-analog), were performed on the DLIP treated and hardened surfaces, showing that the hardness was improved up to 827 HV in comparison to the hardness of the untreated steel of 210 HV (El-Khoury et al. 2021). The hardening depths varied with the feed rate, from 0.85 to 0.5 mm for 200 to 800 mm/min, respectively. Clearly, when the scanning speed is reduced, the interaction time of the laser and material is enhanced and the laser energy accumulated at the surface reaches deeper regions and the depth of hardened layer increases (Buling et al., 2016).

The wear performance of the non-hardened and laser-hardened DLIP surfaces were evaluated by scratch tests utilizing an indenter of 50 µm diameter, as summed up in Figure 3 by representative SEM micrographs. Depending on the surface finish, different wear behaviors were observed. While ploughing is the overwhelming impact on the non-hardened DLIP surface (Figure 3 (a-c)), the laser-hardened DLIP surface (Figure 3 (d-f)) display a brittle-like degradation of the DLIP surfaces along the wear track.

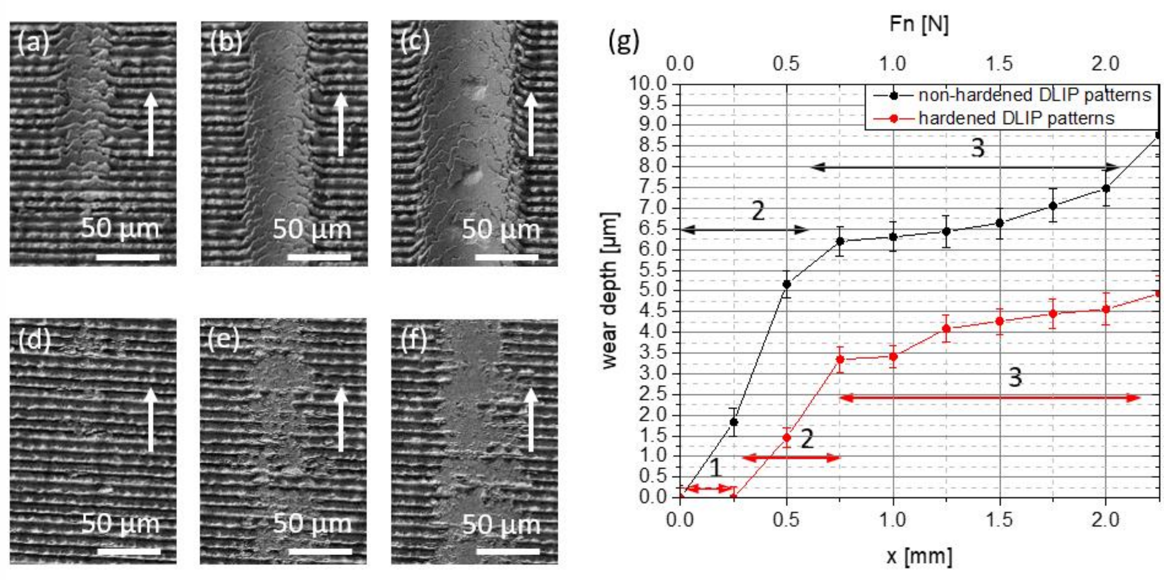

Fig. 3. Scratch test results performed with 50 µm diameter indenter on non-hardened (a-c) and hardened (d-f) under Ar shield gas DLIP structures at (a, d) 0.25 N, (b, e) 1.00 N and (c, f) 1.75 N normal load. Arrow on SEM images shows the direction of indenter movement; (g) wear depth resulted from scratch test on hardened and non-hardened DLIP structured surfaces (fitting curves are for eye guiding) (El-Khoury, et al., 2021).

The resulted wear depths from scratch tests were quantitatively analyzed by the confocal measurements which are summarized in Figure 3 (g). The wear depth evaluation reveal a three-segment behaviour. Up to 0.25 N of normal load (or 14.2 GPa of point pressure according to the Hertzian theory), no wear occurs for the hardened surface in comparison to the non-hardened structures. In particular, the DLIP non-hardened samples showed wear from the very beginning of the scratch test (Figure 3 (a)). This observed wear delay is denoted as segment 1 in Figure 3 (g). Segment 2 is characterized by an extended degradation of the structures for both scenarios. Furthermore, the hardened structures are about 200% extra proof against wear at a normal load 0.50 N (or 17.9 GPa point pressure) as compared to the non-hardened structures. In segment 3, only a minor wear depth increase became located for both surface types as full contact took place and the effect of the structured pattern becomes negligible (El-Khoury, et al., 2021).

4. Conclusions

The presented approach in this work, consisting on applying laser hardening on DLIP patterned steel surfaces has proven to be an effective strategy to improve the wear-resistance of microstructures. In fact, the hardness of the structured surfaces was increased from 210 to 827 HV 0.1, while preserving the shape and depth of the microtextures. Performed scratch tests showed that the wear-resistance of the surface textures was enhanced up to ~ 200 % at a contact point pressure of 17.87 GPa. Thus, hybrid processing scheme pave a way for functional surface patterns with a significantly higher wear resistivity and thus suited for demanding application scenarios such in the field of tribology and beyond.

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