Enhancement of tribological properties of stainless steel 904L by Laser surface nano-texturing

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Abstract

The purpose of this study is to investigate the influence of laser surface structuring on tribological properties of stainless steel grade 904L. More specifically, the contribution of Laser-Induced Periodic Surface Structures (LIPSS) on tribological properties is studied. This paper deals with experimental conditions employed to structure the surface using a femtosecond laser. Moreover, experimental results carried out with a Linear Reciprocating Tribometer (LRT) are presented. This device allows us to show the evolution of friction coefficient and wear versus number of cycles performed for a tungsten carbide – stainless steel contact. The obtained results are convincing and constitute a first step in the view to enhance cutting tools life by nano-texturing.

Keywords: Texturation, Friction coefficient, Wear, Micro-tribometer

1. Introduction

In the last decades, ultrashort pulsed lasers have been used to tackle issues in various fields such as medicine, industry and military. Nowadays, this process is also used for controlling the properties of a material thanks to an ultrashort time scale and a very high laser intensity. Laser surface structuring is an efficient technique to enhance tribological properties and controlling the wettability of a material. Many researchers demonstrated that this method reduces friction and wear in different applications [1-2]. For instance, this approach can be used to improve cutting tools efficiency in turning, biomedical implants and mechanical seals. In this view, different kinds of structures as micro-dimples [3] and micro-grooves [4] have been already proposed in literature. However, few researchers investigated the effect of LIPSS on tribological properties [5,6]. Up to now, different principles of LIPSS creation mechanisms are proposed including three main models which are interference between incident light and generated surface electromagnetic wave [7], excitation of surface plasmon polaritons [8] and self-organization [9]. We propose to study the value-added of nano-structures in tribological properties of stainless steel 904L. First, we will explain how to machine these kind of structures before analyzing the variation of the tribological properties of textured and non-textured surfaces through an experimental test with pin-on-disc tribometer.

2. Laser texturing experiments

The sample on which tests were carried out is stainless steel grade 904L mirror-polished with diamond particles (from 9µm to 0.5 µm), leading to a roughness Ra ≈ 50 nm. A part of the sample is smooth and the other part is structured. Texturing was performed using a Ti-sapphire laser source (Spectra Physics Spitfire Pro femtosecond laser system, USA) with an energy of 0.5 mJ/pulse at a wavelength of 800 nm and a repetition rate of 5 kHz. The pulse duration is equal to 130 fs and the polarization of the beam is linear. The Gaussian nature of the focused laser beam was verified by CCD camera measurements. The surface of the sample was placed perpendicular to the direction of the laser beam, in the focal plane of a lens with focal length equal to 50 mm.

When undertaking experiments with femtosecond laser, the notion of fluence is to be considered instead of energy. It can be defined as an energy per unit area. The Gaussian distribution of the focused laser beam is shown in Fig. 1 below.

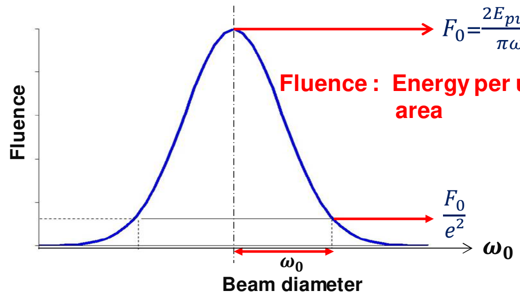

Fig. 1: Gaussian distribution of laser beam

A set of static laser shots were realized at different fluences, as shown in Fig. 2, and with various number of cumulated pulses. Laser impacts were observed with a scanning electron microscope.

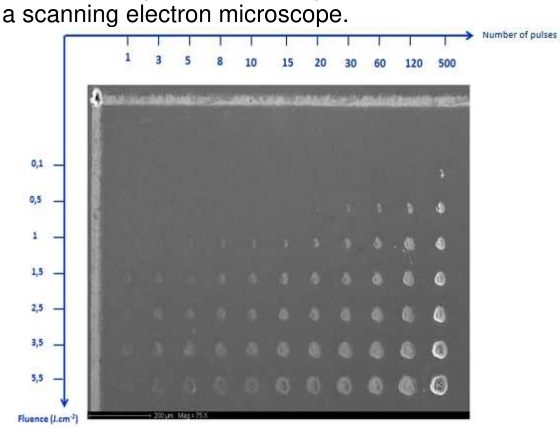

Fig. 2: Static laser shots matrix varying fluence and number of pulses

Three interaction regimes have been identified in the laser-material interaction corresponding to three different fluences thresholds (F_{th}): below a minimum value ($F < F_{ths}$), there is no interaction. For higher fluences to F_{ths} without exceeding the ablation threshold $F_{th\alpha}$ LIPSS appear, it corresponds to the texturation regime. When increasing the fluence ($F_{th\alpha} < F < F_{th\lambda}$), we are in the low ablation regime which also corresponds to the athermal regime. For higher fluences ($F_{th\lambda} < F$), the high ablation regime is reached, also called the thermal regime.

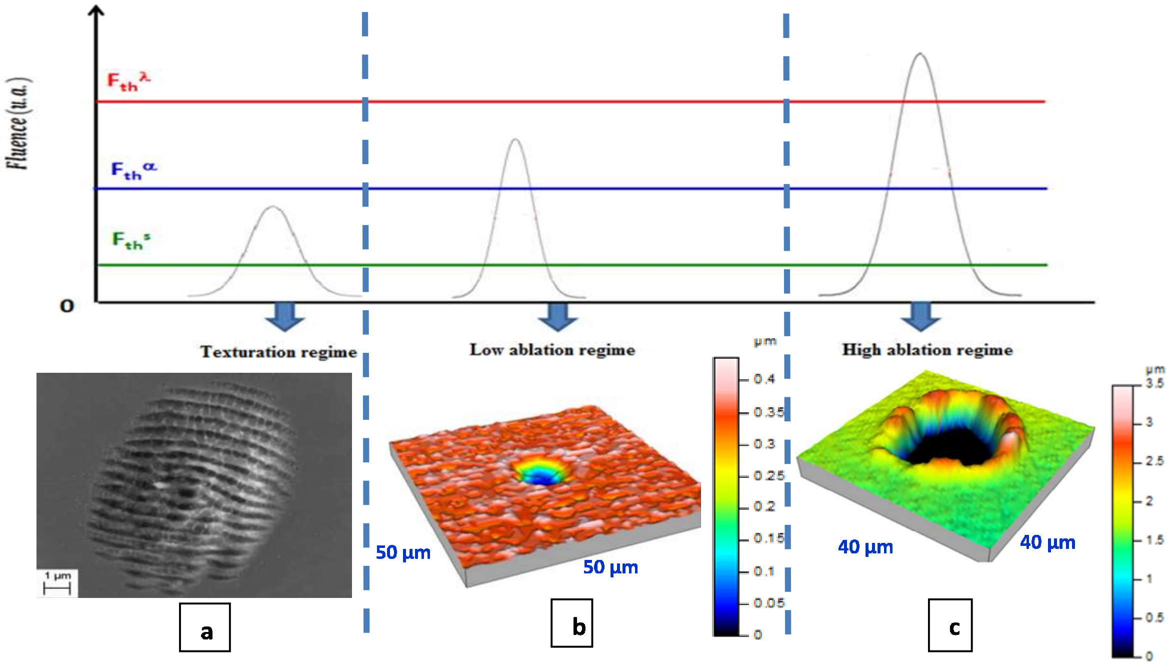

Fig. 3: Different interaction regimes of stainless steel

After the laser treatment, the morphology of the surface of the sample was observed by atomic force microscope (AFM) shown in Fig.4 and a scanning electron microscope (SEM) as shown in Fig. 5.

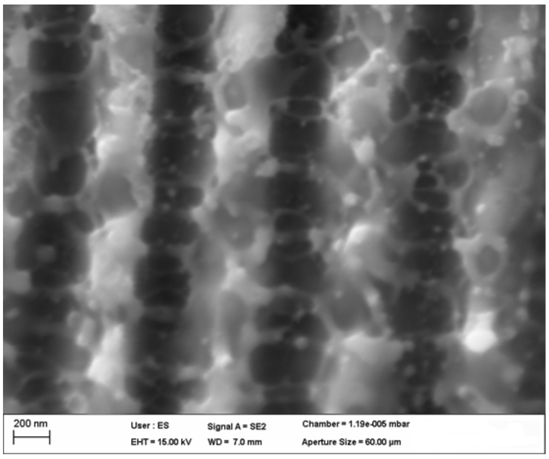

Fig. 4: AFM image of produced LIPSS in stainless steel

Whilst AFM measurement permitted to determine the depth and wavelength of LIPSS machined, the SEM image allowed to assign a value to the wavelength while offering a more global picture of LIPSS. In our experiment, LIPSS have a mean wavelength of 650 - 730 nm and a mean depth of 220 nm.

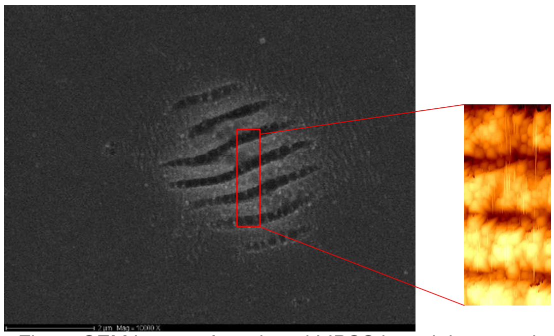

Fig. 5: SEM image of produced LIPSS in stainless steel

After having identified the texturation threshold fluence through the set of experiments explained previously, we managed to define the fluence needed to machine LIPSS. The desired structures are obtained with a peak fluence of 0.4 J/cm² and a radius at 1/e² of peak fluence equal to 11 µm.

Laser surface structuring was achieved by scanning the sample with parallel laser paths spaced at 15 µm intervals with a scanning speed equal to 12 mm/s. We can note that LIPSS orientation is perpendicular to the scanning direction. There is no Heat Affected Zone (HAZ).

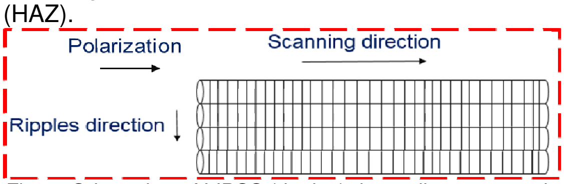

Fig. 6: Orientation of LIPSS (ripples) depending on scanning direction and polarization

3. Tribolological tests

A set of tribological tests were conducted using a pin-on-disc Linear Reciprocating Tribometer. A LRT is used to show the evolution of friction coefficient depending on number of cycles performed, it is designed as a ball hanged at the extremity of a pin which slides back and forth over the sample. Such item is fixed on a bearing containing a lubricant which is mounted on XY-table.
A tungsten carbide ball with a diameter of 5 mm was used for these tribological tests. The normal force applied is equal to 2 N. The friction distance is equivalent to 1 mm with a sliding speed of 1 mm/s.

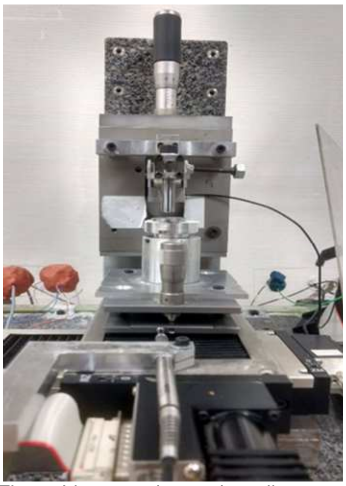

Fig. 7: Linear reciprocating tribometer

3. Results and discussion

A range of tests was conducted under lubricated conditions on a smooth and textured surfaces (lubricant Oil Form B2R). We observed the evolution of friction coefficient depending on number of cycles performed. After analyzing the scratched areas with a confocal microscope (Alicona Infinite Focus), we have determined a wear volume for both smooth and structured surfaces. Textured surface showed a lower friction coefficient than smooth surface as shown in Fig.8.Friction coefficient is more stable versus time. This reduction of friction coefficient may be due to the role of LIPSS which act as reservoirs of lubricant.

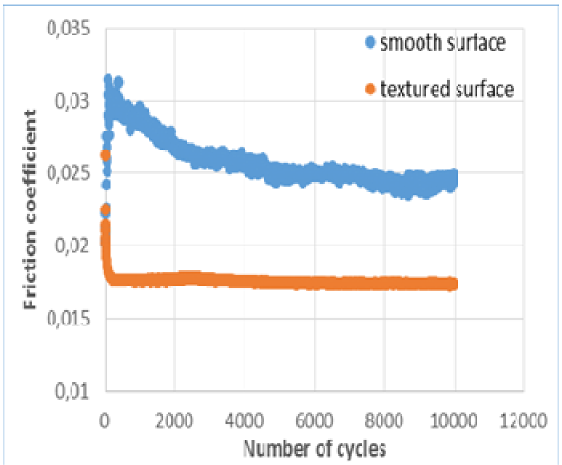

Fig. 8: Friction coefficient respect to the number of cycles of textured and smooth surface

In terms of wear of scratched surfaces at 10000 cycles, it also decreased from $21.5.10^4$ μm^3 for smooth surface to $5.83.10^4$ μm^3 for textured surface as shown in Fig.9. Damaged surface on the textured area (Fig.10.a) has a lower width than on the smooth area (Fig.10.b). It may explain the influence of LIPSS on wear process.

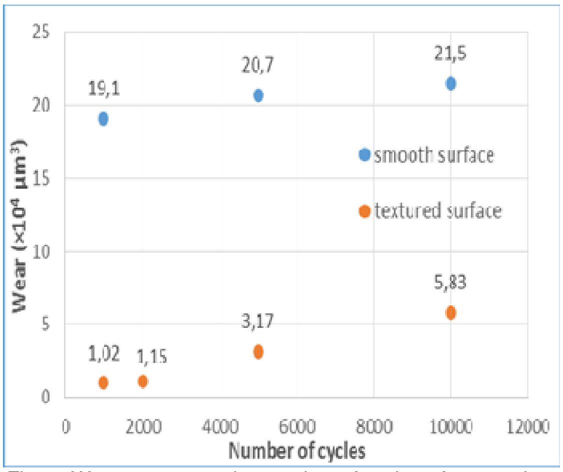

Fig. 9: Wear respect to the number of cycles of textured and smooth surface

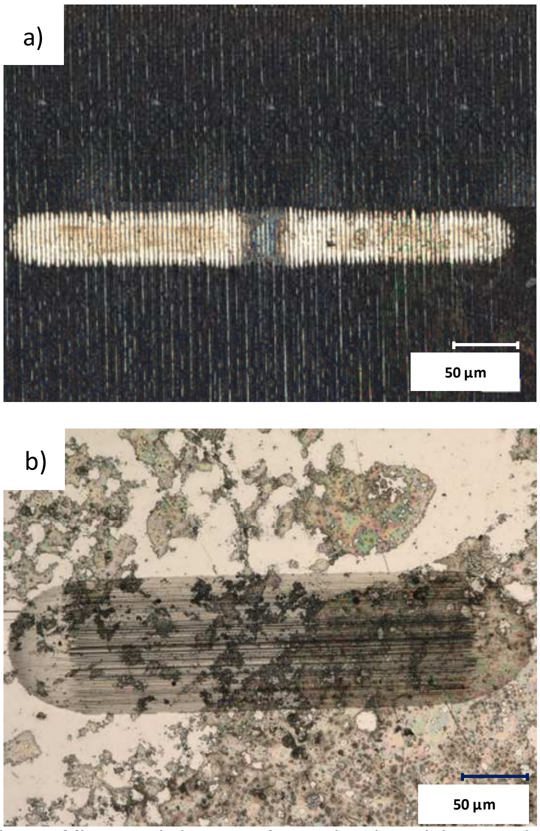

Fig. 10: Microscopic images of scratches in stainless steel a) textured surface b) smooth surface at 10000 cycles

4. Conclusion

This paper presents the surface nano-structuring of a 904L stainless steel in order to enhance its tribological properties. Pin-on-disc tests allowed us to determine gains in terms of friction and wear. It is showed that generated LIPSS can reduce friction coefficient and wear in lubricated condition. A possible mechanism of the improvement of tribological performance of the textured surfaces is that they are constantly lubricated through LIPSS which behave as lubricant storages. Other tests which consists to investigate the effect of the combination of LIPSS and grooves, varying shapes and arrangements, are under processing. This study will be extended to other materials as tungsten carbide and titanium based coatings in order to evaluate the interest of this technique to enhance cutting tools life when machining stainless steels.

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