PAPER • OPEN ACCESS

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To cite this article: M Yu Gazizova *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1014** 012014

Correlation of the tribological properties of LIPSS on TiN surface with 3D parameters of roughness

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AbstractThe relationships between friction coefficients and 3D spatial roughness parameters, such as Sci (surface core fluid retention index), Svi (surface valley fluid retention index) and Sbi (surface bearing index), have been investigated for the laser-induced periodic surface structures (LIPSS) on the TiN coatings. Two types of the surface structures (cross-like and parallel ones) with different roughness levels were obtained using a fs-laser. It has been shown that the proposed roughness parameters correlate with the friction coefficients measured for the LIPSSs.

1. Introduction

The reduction of friction coefficients for new composite materials and coatings, development of new approaches in the field of surface engineering is the main task of tribology nowadays. About 23% of total energy consumption in the world is referred to the frictional contact. And most of it, about 20%, is because of friction itself [1]. The problem of developing new wear-resistant materials has been in the second place. Today, technologies enabling to obtain low and ultra-low friction coefficients are needed in tribological contacts. For instance, based on a few studies, the surface structuring by creating a certain multilevel relief (roughness) including grooves, protuberances and pits on micro- and nano-level has proved to be an effective approach to control friction properties of the surfaces. The positive effect of surface structuring has been shown in several works. Successful applications of the surface structuring by laser irradiation methods are known to reduce friction and wear for cutting tools [2], mechanical seals [3], pistons and cylinders [4], bearings [5] implants [6]. However, the problem appears due to the method enabling to modify the surfaces of wear-resistant and hard materials. Thus, the widely used TiN coating, which allows increasing the wear resistance of the components refers to difficult-to-machine materials and, as a rule, its application is the final stage of processing. Reduction of the friction coefficient due to surface structuring for such materials and coatings becomes possible with the appearance of commercial fs-lasers. When working on the surface structuring, the problem appears because of a lack of knowledge to describe the relationships between the surface parameters and the tribological properties. Some of the surface roughness parameters cannot be directly related to friction. To estimate the roughness, a two-dimensional model and such parameters as Ra, Rz, Rsk were used. Unfortunately, these parameters cannot provide reliable surface characterization, because the same Ra and Rz values can be obtained for so completely different surfaces structures [7]. More reliable information about the real surface topography can be provided by spatial 3D roughness parameters. Taking this into account, the investigation of the spatial roughness parameters, which allows predicting the surface properties, including tribological parameters, is of great interest [8, 9].

The aim of this study is to find regularities between functional spatial parameters of roughness and tribological characteristics of TiN coatings with laser-induced periodic surface structures (LIPSS) in the oil friction conditions.

2. Experimental details

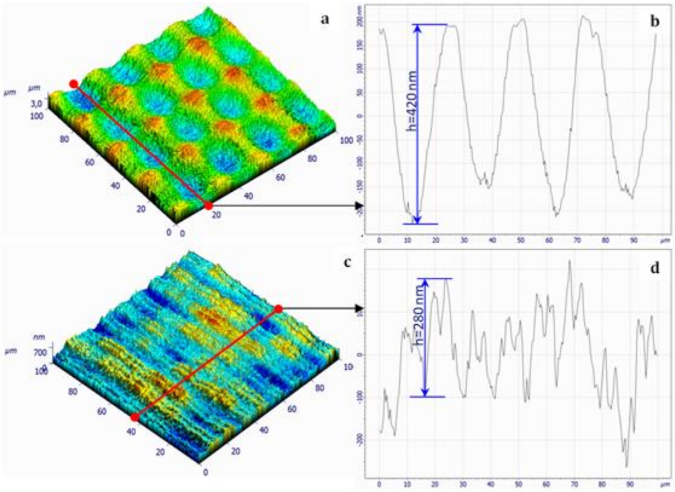
The VT1-0 titanium alloy with TiN coating has been chosen for the purpose of this study. TiN coatings were deposited by a plasma assisted vacuum-arc spraying method. The samples were treated using a PC-controlled three-dimensional motorized translation stage and scanned in air by 1030-nm 320-fs Yb-fiber pulses with a maximal energy of 10μJ in a TEM_{00} mode. Parallel and cross scan modes with a scanning speed of 100 mm/s and pulse energy, *E* of 1.5μJ, 3.2μJ, 6.2μJ were applied [10]. LIPPSs were analysed using a FEI Nova NanoSEM 450 scanning electron microscope (SEM) and an Olympus GX71 optical microscope. The surface topography was characterized with a Ntegra Aura atomic force microscope (AFM). Tribological tests were carried out in air using two lubricants: engine and cutting oils. The lubricants with a volume of 3 ml were added to the friction contact area before starting the test. The "pin-disk" testing scheme was used with a 6 mm pin that is made of steel 304. The counterbody load was 1 N. The rotation speed of the samples was 5 cm/s. The friction path was 450 m. The friction coefficient was measured with an accuracy of 0.001.

The regularities between the functional 3D spatial parameters and friction coefficients (CoF) in oil friction conditions have been analyzed in the frame work of this study. The following parameters were used: Sci (surface core fluid retention index), Svi (surface valley fluid retention index) and Sbi (surface bearing index). Sbi characterize the upper zone of the surface involved in wear phenomena. Sci characterizes the main void volume acting as a lubricant reserve. It is presumed that these voids locate at a distance of 0.05*h*-0.8*h*, where *h* is the profile height. Svi characterizes the void volume of the deepest valleys.

3. Results and discussion

The formation of LIPSSs oriented perpendicularly to the polarization of laser radiation was analyzed using AFM [10]. The cross-like structures found in the samples can be classified to three different regions: (1) the untreated TiN region (figure 1a, red area), (2) the area corresponding to a single laser scanning pass (figure 1a, green area) and (3) the area with the intersection of the laser scanning lines (figure 1a, blue area). The surface roughness level is higher for the cross-like structures in comparison with that for the parallel ones (figure 1). Thus, Sa (arithmetical mean deviation of the assessed profile) and Sz (maximum peak to valley height of the profile) depending on the irradiation energy for parallel structures was measured to be 61-132 nm and 459-523 nm, respectively. The Sa and Sz ranges for the cross-like structures varies from 166 nm to 321 nm and from 417 nm to 1039 nm, respectively.

Tribological tests of the samples before and after surface modification showed that the wear processes have not been found regardless of the irradiation parameters, the surface structures formed after processing and, especially, the test conditions applied in this study. At the same time, a decrease in the friction coefficient after fs-laser irradiation has been identified. For instance, the friction coefficient was 0.14 for the TiN coating in test using both engine oil and cutting tool oil as a lubricant. Its values varied in the range from 0.04 to 0.13 after the surface structuring, except the sample with parallel structure processed with an energy of 1.5 mJ. The friction coefficient has been measured to be 0.55 for these samples in the test using engine oil as a lubricant. Thus, it can be concluded that there is a positive effect in the TiN coating surface structuring referring to the improvement in wear resistance and the reduction in friction coefficients.



Values of surface roughness parameters after fs-laser processing with different laser energies

	Energy, mJ	S_m, mkm	S_{ci}	S_{vi}	S_{bi}
Parallel structures	1.5	6.0	1.61	0.10	0.29
	3.2	9.3	1.45	0.11	0.71
	6.2	4.3	1.58	0.10	0.17
Cross-like structures	1.5	25.0	1.54	0.07	1.67
	3.2	41.7	1.30	0.12	1.92
	6.2	54.5	1.19	0.13	1.22

Figure 1.Surface structure of TiN after fs-laser processing (a, c), cross-sectional profile of surface (b, d) and 3-D spatial parameters of LIPSS.

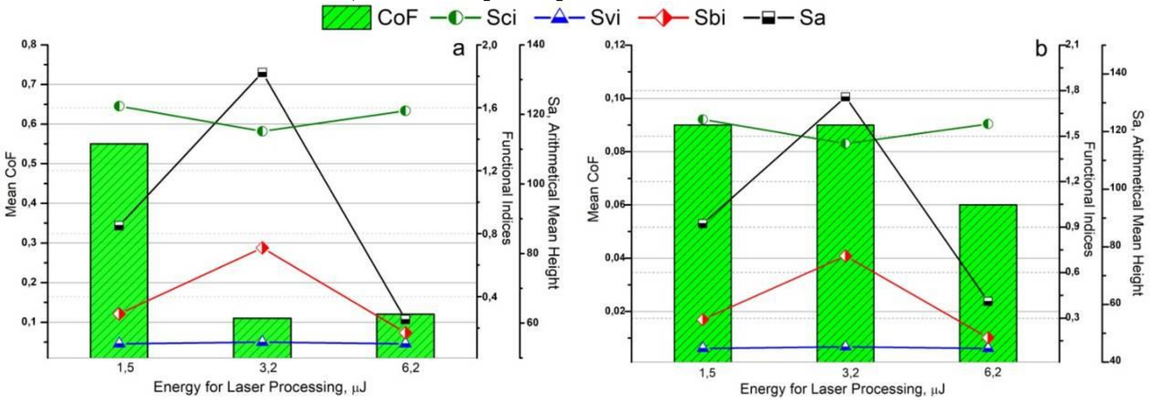


Figure 2.Regularities between the friction coefficients and 3D spatial roughness parameters for the surfaces with the parallel structures at friction in the engine oil (a) and cutting tool oil (b).

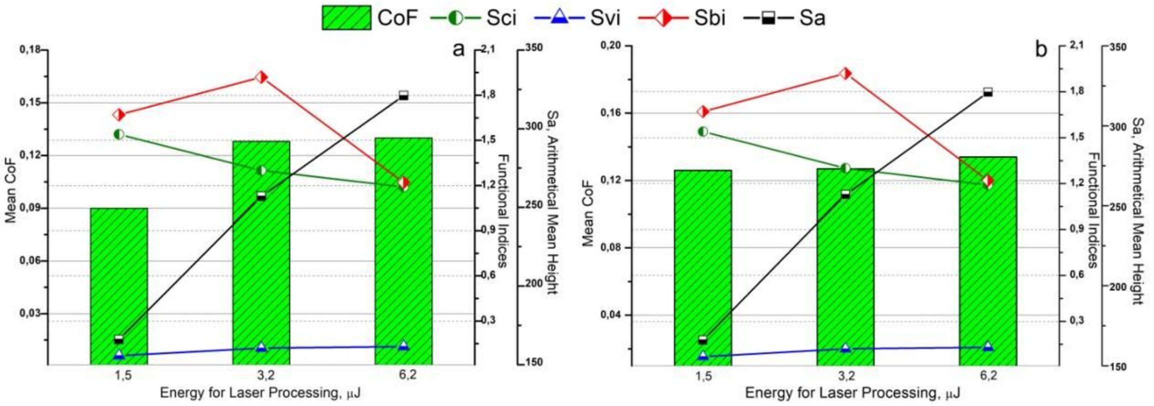


Figure 3.Regularities between the friction coefficients and 3D spatial roughness parameters for the surfaces with the cross-like structures at friction in the engine oil (a) and cutting tool oil (b).

Based on the AFM data analysis, the 3D spatial parameters of the LIPSS (figure 1) were calculated. These parameters were compared with the tribological tests (figures 2 and 3). For the samples with the parallel structures tested in the engine oil, the minimum friction coefficient was measured when the Sbi values increased, i.e. when the contact areas increased (figure 2a). On the contrary, with friction in the cutting tool oil, a reduced in the contact area allows a decrease in the coefficient of friction, respectively, the Sbi value decreases in comparison with other 3D spatial parameters (figure 2b). In this case, there was a clear correlation between Sbi and the friction coefficient, namely, higher Sbi values correlated with lower CoF. The dependence of Sci change is inversely proportional to Sbi change, namely, the smaller the contact area, the smaller the volume of retained fluid. It should be noted that the Sa values measured for the parallel structures correlated with the Sbi values. The Svi index for all the investigated surfaces with the parallel structures showed no changes for different LIPSS, meaning that it did not significantly contribute to the friction coefficient changes.

An increase in the Sci values decreased the friction coefficients for the samples with the cross-like structures using the engine oil and the cutting tool oil (figure 3). There is also a dependence between the friction coefficient with the Svi value: that the lower Svi the lower friction coefficient. Thus, it can be presumed that liquid retention parameters are decisive for the friction test condition of the cross-like structures.

The change in the aforementioned behavior of the samples with cross-like structures occurred when the test speed and the friction path increased by 3 times (from 5 cm/s to 15 cm/s) and by approximately 4 times (from 450 m to 2000 m), respectively. It was found that the lower Sbi correlated with the lower friction coefficient. The effect of the Sci decreased. According to the tests results at low test speeds using the cutting tool oil, smaller contact areas (i.e., the lower Sbi values) corresponded to lower friction coefficients. However, at the test speed of 15 cm/s, the indicated dependence for parallel structures was not completely retained, namely, the maximum friction coefficient corresponded to the highest Sbi, but the smallest Sbi value corresponded to the structure obtained using the laser pulse energy, E of 6.2 μJ, where CoF = 0.05. The sample irradiated at E = 1.5 μJ has the lowest friction coefficient of 0.04. This happened due to the close Sbi values and friction coefficients, in other words, the detected difference was insignificant. Similar dependences were found for the cross-like structures.

4. Conclusion

The chosen 3D spatial roughness parameters can be used to predict the tribological properties (friction coefficient) for wear-resistant coatings with LIPSS in the friction conditions with lubricants. The functional parameter of roughness determining the surface valley fluid retention, Svi played the major role, when the engine oil was used. Differences in the dependence of the influence of the functional parameters of roughness on the friction coefficients under the friction conditions in the engine oil and the cutting tool oil can be apparently explained by the different viscosity of lubricants and the type of the additives used in them. Structures with smaller contact areas were better in the case of using the cutting tool oil, i.e. when the surface bearing index Sbi demonstrated the lowest values.

Acknowledgments

The study was carried out with a grant from the Russian Science Foundation (project No.19-79-00295).

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