THE EFFECT OF MICRO-MACHINING WITH A SINGLE-MODE AND MULTI-MODE FIBER LASER ON THE SURFACE OF DLC COATINGS

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Abstract

The article presents research on the influence of single-mode and multi-mode fiber lasers on the micromachining effects of a diamond-like carbon (DLC) coating surface. DLC coatings are a form of amorphous carbon consisting of sp^2 bonds characteristic of graphene and sp3 bonds found in diamond. Depending on the proportion of these bonds, DLC coatings exhibit different tribological properties. These coatings are commonly used to reduce wear on parts. It has been proven that the texture applied to the surface of these coatings improves their tribological properties under lubrication conditions. The changes in the geometric profile of the obtained groove on the coating surface were analyzed using various parameters of the laser process. A comprehensive characterization of the obtained effects was carried out, namely microstructure, hardness, wear resistance and adhesion of the layer with the substrate. The experimental results showed significant differences depending on the laser beam parameters, indicating that the properties of the DLC layer can be precisely controlled by adjusting the processing parameters. The tests were carried out on DLC a-C:H coatings obtained by PVD magnetron sputtering deposition on stainless steel 1.4034. This research may contribute to the development of a laser surface treatment method to improve wear resistance and durability in applications where DLC layers play a key role, such as in the automotive, tooling, and medical industries.

Keywords: DLC, laser processing, coatings, single-mode laser, multimode laser

1. INTRODUCTION

Diamond-like carbon (DLC) coatings [1] have garnered significant attention because of their remarkable properties, ranging from high hardness and wear resistance to excellent chemical inertness. These attributes make DLC coatings an ideal candidate for a wide array of applications, including but not limited to automotive components, biomedical implants, and aerospace coatings. However, precise control over their surface properties is significant to fully harness the potential of DLC coatings. In recent years, laser micromachining techniques have emerged as promising methods for modifying the surface characteristics of materials with unparalleled precision [2]. Among these techniques, fiber laser micromachining stands out due to its versatility, high processing speed, and ability to achieve microscale precision. Lasers typically comprise three primary elements: a lasing medium, which could be solid, liquid, or gas; a stimulating energy source, often referred to as a pump; and an optical resonator. Inside the laser resonator (the active medium is a gas laser or a solid), depending on its type, design, and configuration, an intense and constant electromagnetic field, the shape of which determines the distribution of the energy of the laser beam across its cross section and is referred to by the acronym TEM (Transverse Electromagnetic Modes).

The beam is divided into two planes perpendicular to each other, and the shape of the beam is described by the letters 'm' and 'n', taking the value of O or 1. Typical beam energy distributions of electromagnetic lasers of industrial lasers used in the industry are (**Figure 1**):

- gaussian distribution, single-mode TEM_{00} type,
- multimode distribution, i.e. several Gaussian distributions partially superimposed on each other, type: TEM_{01} , TEM_{10} and TEM_{11}.

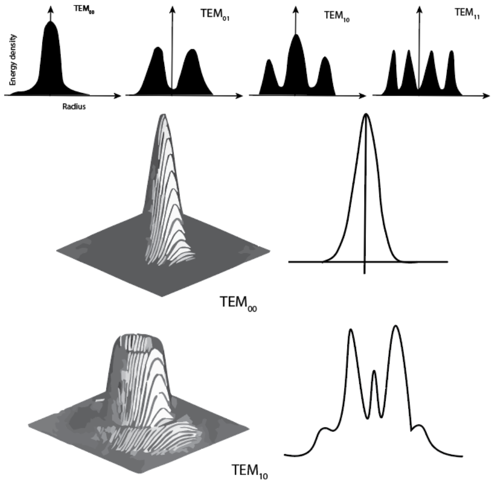


Figure 1 Typical energy distributions at the focal point of a laser beam

The laser beam with single-mode TEM_{00} type focal plane energy distribution is characterized by a high-power density power, concentrated in the axis of symmetry of the laser beam, thus ensuring minimal diameter of the laser beam focus. This is particularly advantageous in laser processes for cutting or perforating objects with small thicknesses and in welding processes using the mesh technique or welding with the liquid metal weld pool technique. In the case of a laser beam with multimode energy distribution (type: TEM_{01} , TEM_{10}, and TEM_{11}), the energy is distributed almost uniformly, but the power densities of the laser beam are much smaller. Multimode laser beam energy distributions are recommended for such processes as welding with weld pool technique, surfacing, alloying, and brazing, and for surface heat treatment, remelting, and heat treatment. This is very important for increasing durability and thus improving quality in the industry, including in terms of corrosion resistance [3, 4] and wear resistance [5, 6]. The obtained results are also important for the automotive industry, both in terms of production [7, 8] and quality control procedures [9, 10]. The geometry of the surface layer resulting from processing is very inspiring for the development of qualitative [11, 12] and quantitative [13, 14] description methods, also in terms of active control of process parameters [15] to obtain the intended surface characteristics.

2. MATERIALS AND METHODS

To perform this study, samples with diamond-like carbon coating of the a-C:H type with W and Cr interlayers were selected. Coatings were deposited on 1.4034 stainless steel with a physical vapor deposition process – sputter deposition at <300°C, while the material substrate temperature was 350°C. The chemical composition of the steel used was as follows (wt%): C: 0.36-0.45; Mn: 0.50-0.80; Cr: 12.0-14.0; Si: 0.60-0.80; Mo: 0.5-0.7; V: 0.2- 0.3; Ni: 0.1-0.60; P: max 0.04, S: max 0.03, other is Fe.

The microstructure of the sample with DLC coating was analyzed with a Joel JSM-5400 scanning electron microscope. The analyses were performed on polished specimens, allowing the thickness of the DLC coating and the thickness of the interlayers to be observed. The thickness of the DLC coating was approximately 4 μm, and the thickness of the entire coating system was approximately 5 μm.

To examine the effect of single-mode and multimode laser beams on the surface of DLC coating, two lasers were selected - single-mode fiber laser SPI G 3.1 20 W and multimode fiber laser SPI G3.1 40 W. The characteristic parameters of these lasers are presented in **Table 1.**

Table 1 Single-mode and multimode laser parameters [16]

	SPI G 3.1 20 W	**SPI 3.1 40 W**
Type	Single-mode fiber laser	Multimode fiber laser
Wavelength (nm)	1064	1064
Average power (W)	20	40
Pulse duration (ns)	9-500	9-250
Pulse energy (mJ)	≤ 0.8	≤ 1.33
Frequency (kHz)	25-500	30-250
Beam quality M^2	<1.3	<4
Pulsed laser beam expander	7x	7x
Beam diameter after beam expander (mm)	8,1	8.1
Galvo system scan head max scanning speed	10,000 mm/s	10,000 mm/s
Lens	F-theta lens 160 mm	F-theta lens 160 mm

Using EzCAD software, a template was made in which five laser beams pass with the same process parameters, such as frequency, power, pulse energy, and pulse length, for five different pulse energy levels to achieve the same pulse energy produced. Then, the quality and width of all the fabricated grooves were examined using a Hirox optical microscope. In **Table 2,** all parameters taken into account are presented.

Table 2 Parameters of the laser micromachining process [16]

	SPI G 3.1 20 W	**SPI 3.1 40 W**
Pulse energy level	20%, 25%, 30%, 35%, 40%, 45%, 50%	6%, 7.5%, 9%, 10,5%, 12%, 13,5%, 15%
Calculated pulse energy	32 μJ, 40 μJ, 48 μJ ,56 μJ, 64 μJ	
Scanning speed [mm/s]	750 mm/s	
Pulse duration	30 ns	
Frequency	30 kHz	

In (**Figure 2**) the distribution of energy density in the laser beam cross section for single-mode and multimode fiber laser is presented. It can be observed that the power density of a multimode laser beam is much more widely distributed than that of a single-mode laser, which results in the laser radiation affecting a larger area.

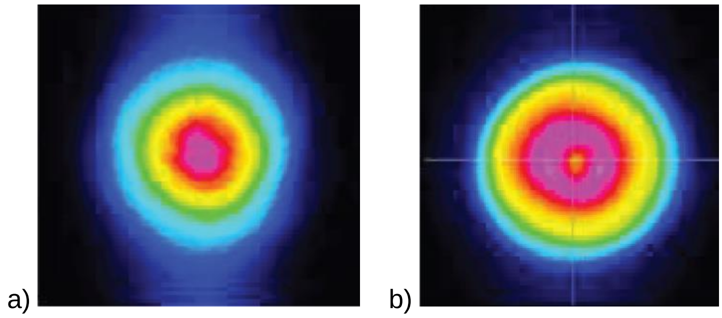


Figure 2 Distribution of energy density in the laser beam cross-section:
a) For single-mode laser SPI G 3.1 20 W, b) for multimode fiber laser SPI 3.1 40 W

3. RESULTS AND DISCUSSION

All passages were examined with an optical microscope. The pulse energy that provides the best results (not removing all coatings - groove depth smaller than 4 µm) is 32 µJ, which corresponds to 20% of the declared pulse energy in the case of a 20 W single-mode laser and 6% of the pulse energy for a multimode laser when parameters such as pulse duration, frequency, and scanning speed are constant and determined.

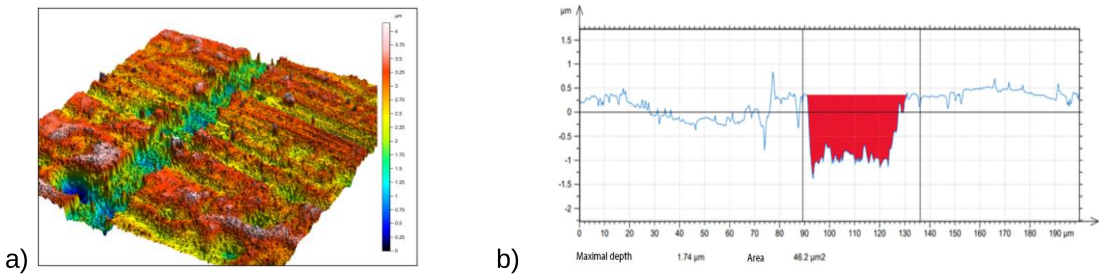


Figure 3 Topography of the groove created with the 20 W single-mode laser (a) and shape and depth of the groove made with the 20 W single-mode laser (b)

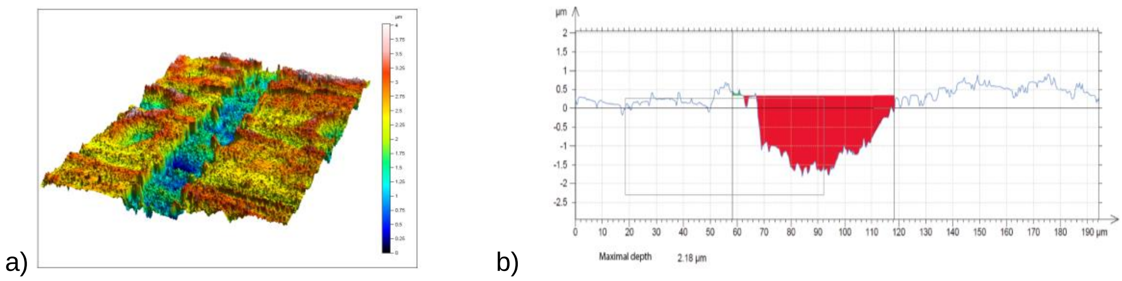
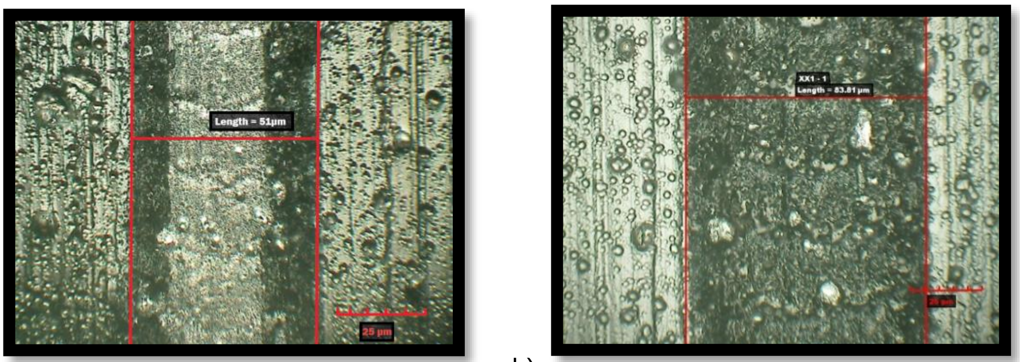


Figure 4 Topography of the groove created with the 40 W multimode laser (a) and shape and depth of the groove made with the 40 W multimode laser (b)

Figure 3 and **Figure 4** present the topography and the shape of the groove made with optimal parameters for single-mode and multimode lasers, respectively. The maximum depth of the groove for 20 W was 1.74 µm, and for 40 W was 2.18 µm.

Figure 5 presents the average width of the groove created with a single-mode and multimode laser. As shown, the average width of the groove was 51 µm for the single-mode laser and 84 µm for the multimode laser. This shows that with the same optical equipment installed, parameters, and the same focus of the beam, the multimode laser produces a wider groove, and therefore, the laser beam has a greater diameter.



a) b)

Figure 5 The width of the groove made with (a) 20 W laser and (b) 40 W laser

4. CONCLUSIONS

- The width of the groove after micromachining with the same parameters differs when a single-mode or a multimode laser is used.
- The groove created with a multimode laser is wider and is about 84 um.
- The groove created with a single-mode laser is narrower and is about 51 um.
- The DLC coating was not completely removed after laser treatment, and therefore, the coating was not damaged and retained its anti-wear properties.

Although numerous studies have demonstrated the transparency of DLC coatings to visible and infrared light, with absorption primarily occurring in the UV spectrum, this research highlights the potential for surface modification of this material using a highly concentrated laser beam, specifically with a wavelength of 1064 nm.

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