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LASER SURFACE MODIFICATION OF MATERIALS

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Abstract. To develop any process of laser technology, you need to solve 3 problems: 1) What are the properties of the interaction of laser radiation with matter must be selected to achieve the goal (resonant – non-resonant, absorption-scattering, photo- or thermal absorption, heating, hardening, melting, softening, evaporation, decomposition, coagulation, etc.); 2) What type of laser source should be used to achieve this goal (wavelength, operation mode – continuous or pulse-frequency, power, pulse duration, transverse energy distribution in the beam, coherence, monochromaticity, polarization, etc. taking into account the reliability, stability of the process and its value, and how to calculate and verify these parameters ?; 3) What are the requirements for the transverse and longitudinal shape of the beam and what opto-mechanical, opto-electronic and other systems are needed to solve this problem? Successful solution of these problems hardens the high quality of the result of the application of laser technology of materials processing.

The aim of this work is to show the effectiveness of laser surface treatment of materials on their micromechanical properties.

The surface of the samples was treated with laser radiation using a pulsed neodymium laser YAG: Nd. Vickers microhardness measurements were then performed.

The surface of silicon carbide was irradiated with a laser beam with different technical parameters. The micromechanical characteristics of the treated samples were studied and their comparison with the source material was made. Suggestions for laser modification of mechanical properties of superhard materials are made. Alloying of aluminum with titanium nitride impurities by pulsed laser irradiation was performed. A significant increase in microhardness in the field of laser fusion of titanium nitride nanopowder into the aluminum matrix was revealed. We have thus shown that laser treatment of structural and functional materials is an effective method of controlling their properties.

A set of experimental studies, in particular, structural, optical, and magnetic, will be conducted to physically substantiate the established results. In this paper, we have expressed our views, citing well-known literature sources.

Keywords: pulsed laser irradiation, microhardness, crack resistance, aluminum, titanium nitride, silicon carbide.

Introduction

The achievements of industry in any developed society are invariably associated with the achievements of technology of structural materials and alloys. The quality of processing and productivity of products are the most important indicators of the level of development of the state.

Materials used in modern structures, in addition to high strength characteristics must have a set of properties such as increased corrosion resistance, heat resistance, thermal conductivity and electrical conductivity, refractory, as well as the ability to maintain these properties in long-term work under load.

Industrial processing of materials has become one of the most widely used areas of lasers, especially after the advent of high-power lasers.

The advantages and prospects of using lasers in mechanical engineering are determined not only by progress in the field of laser technology, but also by skillful, scientifically sound selection of optimal for each application processing conditions, laser modes and parameters of its radiation.

During hardening, the surface of the material quickly heats up and cools down without melting. When glazing, a thin layer of melt is formed, which, when cooled, forms a surface of various structures (with low porosity and such microstructural characteristics that cannot be obtained by conventional methods).

Problem statement

The efficiency of electronic devices, especially those operating in extreme conditions (high temperatures, aggressive environments, radiation), significantly depends on increasing the speed, energy saving and reliability of solid-state element base, including its ability to work long-term in harsh operating conditions.

Increasing the strength and ductility enhances the resource-saving potential of metals and alloys, expands the scope of their rational application.

One of the most common structural materials, what has valuable properties, is aluminum and its alloys. The main disadvantage of aluminum is low strength. Therefore, improving its strength characteristics is an important and urgent task.

Silicon carbide (SiC), in turn, has chemical stability, high strength and resistance to elevated temperatures and ionizing radiation. However, it is characterized by significant fragility, which requires adjustment of its micromechanical characteristics.

One of the ways to improve the performance of structural and functional materials is to treat the surface with laser radiation, which we tried to implement in this work.

Review of Modern Information Sources on the Subject of the Paper

Laser processing of materials is not yet a stable and sophisticated section of the theory and practice of processing materials with concentrated energy flows. However, significant progress has been made in the development of the theoretical foundations of the processes of influence of powerful light fluxes on materials and in the practical applications of these processes [1–6].

The high speed of heating and cooling, provided by the high power of laser radiation, allows you to change the microstructure of the surface of metals and ceramics. At laser hardening there is a local hardening of a thin near-surface layer only in places of the details which are subject to wear, and higher hardness of a surface is provided. This is due to the high cooling rate and, consequently, the decrease in the size of the metal crystals and the increase in the density of dislocations. Laser surface treatment increases its resistance to corrosion, because the rapid cooling of a thin molten layer on crystalline materials forms amorphous layers, vitreous surface layers, thin dendritic structures, etc. [7–11].

Polycrystalline diamonds, polycrystalline cubic boron nitrides and tungsten carbides are considered difficult to process due to their excellent mechanical (hardness, strength) and wear-resistant properties. The authors [12] have shown significant progress in the use of lasers for texturing these solid and superhard materials with high and reproducible quality.

Surface treatment with femtosecond laser pulses with a high repetition rate in the presence of gaseous sources of nitrogen and carbon leads to the formation of stable coatings with nitrides and carbides [13].

In [14], to increase the hydrophobicity of the surface, laser treatment of sintered silicon carbide surfaces was performed. Indentation studies have shown a decrease in crack resistance, which the authors attribute to an increase in microhardness.

Objectives and Problems of Research

The aim of this study is to study the possibilities of laser treatment of materials on their micromechanical properties. Based on the goal in the work solved the following tasks:

1. Develop a scheme of the technological process and select the optimal operating parameters of the laser for alloying the aluminum surface with metals and alloys using laser irradiation. Experimentally evaluate the mechanical properties of alloyed areas by measuring Vickers microhardness.
2. Irradiate the surface of silicon carbide with a laser beam with different technical characteristics. Investigate changes in the micromechanical properties of silicon carbide due to laser irradiation.

Main Material Presentation

In this work, the hardening of the aluminum surface was carried out by the method of pulsed laser melting of titanium nitride powder. An aqueous suspension of titanium nitride powder was prepared and applied in a thin layer to the aluminum surface. After drying, the surface was treated with a pulsed neodymium laser YAG:Nd (Fig. 1). Operating parameters of the installation are as follows: power density 100 MW/mm^2, pulse energy 0.5 J, wavelength λ = 1.06 mm, pulse duration: in the mode of modulated quality factor – 20 ns; in free generation mode – 200 μs; beam cross section – 3 mm.

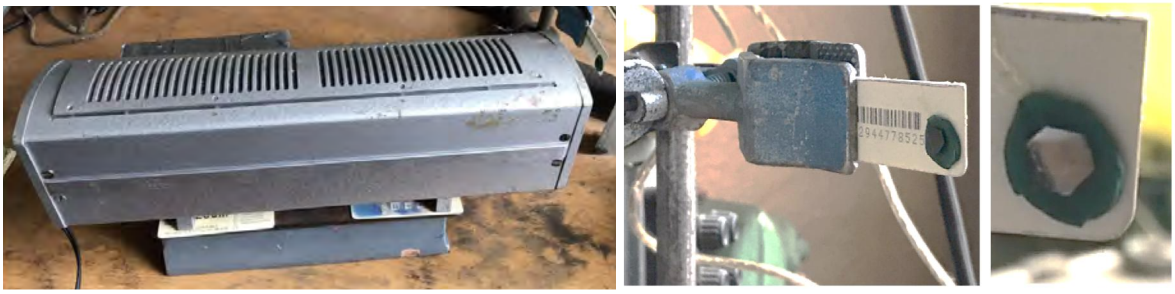

Fig. 1. Laser YAG: Nd and placement of the test sample

A lapping is a technological process of finishing treatment, during which there is performed a removal of stock from the surfaces with a help of abrasive materials placed on the working surfaces of the laps. The principal diagram of lapping flat surfaces is presented i Craters are observed in the places of laser action on the surface of aluminum samples (Fig. 2). It was in these craters that Vickers microhardness was determined (Fig. 3). Measurement of microhardness was performed on a microhardness tester DMT-3.

Fig. 2. Craters on the surface of aluminum are formed by pulsed laser treatment

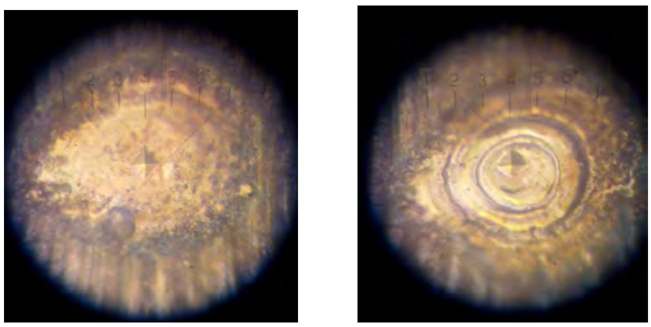

Fig. 3. Impressions of the indenter in the crater, which is formed by pulsed laser treatment of the aluminum surface

Microhardness was determined by the formula

$$H_{\mathrm{m}} = \frac{P}{F_{\mathrm{ind}}} = 2\frac{P}{d_a^2}\sin\frac{\alpha}{2} = 1{,}854\frac{P}{d_a^2}, \text{ [GPa]} \qquad (1)$$

where P is the load on the indenter, H; α = 136° angle at the top of the diamond pyramid; d_a is the average size of the diagonal of the imprint, mm.

The experimental method selected the optimal load on the indenter of 70 g. Due to the clarity of the image of the indenter fingerprint and a significant number of measured fingerprints (not less than 20), the error of microhardness did not exceed 3 %.

According to the results of Vickers microhardness measurements, it was found that the microhardness at the sites of titanium nitride nanopowder melting is 721 MPa, and at the initial surface of aluminum 368 MPa. That is, the fusion of titanium nitride powder into the aluminum matrix by pulsed laser treatment leads to an increase in microhardness almost twice.

To physically substantiate the detected effect, it is necessary to conduct a set of experimental studies. For now, we can only express some considerations. The microstructure of the composite layer consisted of dispersed TiN particles in an aluminum matrix. The mechanism of increasing the microhardness in the composite layer is due to both grain grinding and increasing the dispersion of TiN nanoparticles. It should be noted that both the laser power and the scanning speed must be carefully selected to achieve increased microhardness, improve microstructural homogeneity and uniformity of dispersion in the composite layer.

The efficiency of electronic devices, especially those operating in extreme conditions (high temperatures, aggressive environments, radiation), significantly depends on increasing the speed, energy saving and reliability of solid-state element base, including its ability to work long-term in harsh operating conditions. One of the materials on the basis of which it is possible to produce electronic devices that meet these conditions is silicon carbide (SiC). It has chemical stability, high resistance to elevated temperatures and ionizing radiation, the possibility of its doping with acceptor and donor impurities. All this is of interest to SiC developers of the solid state electronics component base in a number of leading countries [15].

Currently, most of the work in the field of SiC materials science and devices on this material is performed in the United States. In Europe, active work is being carried out in Germany, France and Sweden. In Asia, the leader is Japan. Also, work is underway to improve the properties of silicon carbide. One of such directions is reinforcement of SiC by diamond particles, as diamond is significantly superior to SiC in its characteristics (Table 1) [16].

Table 1

SiC and diamond properties

	SiC	Si/SiC	Diamond
Density	3.0	3.1	3.5
Modulus of elasticity, GPa	350	400	110
Hardness, GPa	25	30	100
Thermal conductivity, W/(m·K)	80	150	500–2000
TCLE, 10^{-6}/K	4	4	1.5

It is assumed that the reinforcement of SiC with diamond particles leads to a composition with a unique set of mechanical, physical and operational properties and ensures their effective use as structural materials.

Fig. 4. Formation of a plasma torch

Fig. 5. Sample SiC after exposure to a laser beam (5 points)

Another area of modification of SiC properties is laser processing. In our case, the surface of the sample was treated with a laser beam of different intensity. The formation of a plasma torch testifies to the qualitative interaction of the laser with the surface of the sample (Fig. 4).

After irradiation on the surface of the sample, even the naked eye can observe the action of the laser beam (Fig. 5).

The next task was to investigate the change in microhardness of the SiC sample after irradiation. The measurements were performed on a clean SiC surface and in five craters formed after laser irradiation (Fig. 5).

The results of measurements on a clean surface are presented in Fig. 6.

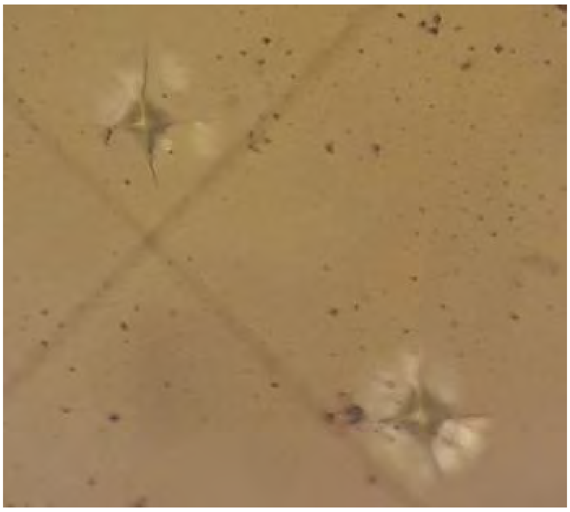

Fig. 6. Indenter prints on a clean SiC surface

As can be seen from Fig. 6, not only indenter prints are formed, but also cracks along the diagonals of the prints, which indicates the fragility of the material. The magnitude of the cracks can be used to estimate the amount of fragility.

Next, we tried to determine the microhardness directly in the craters. This proved to be quite a difficult task, as the surface of the sample in the craters after the action of the laser beam had an uneven and granular structure. This is well illustrated by Fig. 7. Therefore, we observed not quite clear and irregularly shaped prints. However, due to the large number of impressions (15–20 in each crater) and measurements of their diagonals, we were able to estimate the value of microhardness and compare with the original sample.

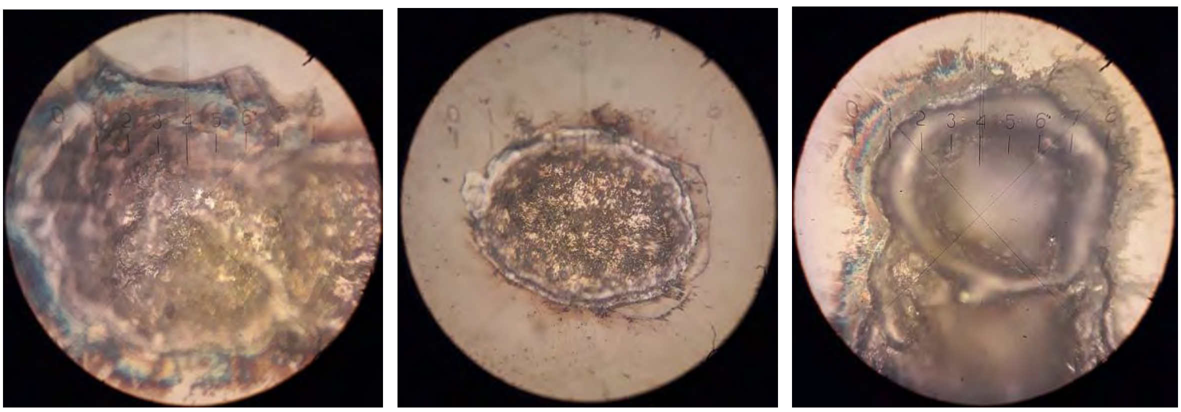

Fig. 7. Laser-formed craters on the SiC surface

The coefficient of brittleness of fracture (crack resistance) of pure SiC can be determined by the formula [17]

$$K_c = 0.0089 \cdot \left(\frac{E}{H}\right)^{2/5} \cdot \frac{P}{a\sqrt{l}} \text{ [MPa·m}^{1/2}\text{]}, \quad (2)$$

where E is the Young's modulus (for SiC 390-420 GPa), take 400 GPa; H – microhardness according to Vickers; l is the length of the crack; a – half the length of the diagonal of the imprint.

According to the results of measuring the length of cracks, we obtained their average value l = 7.2 μm. Substituting all the values in formula (2), we calculated the coefficient of crack resistance of silicon carbide.

Thus, the determined values of microhardness and crack resistance of the studied sample SiC, respectively, are: H_V = 27.8 GPa, K_c = 2.9 MPa·m$^{1/2}$, which is in good agreement with the literature data [18]. According to these values, you can set the sintering technology of silicon carbide. In particular, it is sintering in the solid phase. After exposure to laser irradiation, there is a slight decrease in the microhardness of SiC (H_V = 26.4 GPa), but the absence of cracks along the diagonals of the prints indicates a significant increase in its crack resistance.

Conclusion

It is shown that the introduction of titanium nitride powder into the aluminum matrix by pulsed laser irradiation of the surface leads to an increase in microhardness of aluminum almost twice, which can be explained by both grain grinding and increasing dispersion of titanium nitride nanoparticles.

It is established that after the effect of laser irradiation on the surface of silicon carbide there is a slight decrease in its microhardness, but a significant increase in crack resistance, which may be of great practical importance.

Therefore, the properties of structural and functional materials, in particular such superhard materials as silicon carbide, can be modified by the influence of laser irradiation.

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