Investigation of the influence of various exposure modes of laser radiation on physico-mechanical characteristic of alloy samples

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Abstract. The influence of various regimes of the action of laser radiation on the physicomechanical characteristics of metallic samples is considered in the article. A study was carried out to study the effect of the character of the laser treatment on the surface of metallic samples to increase their resonant vibration frequencies. Periodic micro- and nanostructures on the surface of molybdenum, which were obtained as a result of laser femtosecond action, were also investigated.

1. Introduction
The rapid development of laser technology that promotes the appearance of femtosecond lasers has led to the development of the use of ultrashort laser pulses to study the fundamental mechanisms of interaction of radiation with matter in order to use this phenomenon in various technologies. This is due to a number of advantages, the impact of such impulses on the substance leads to its ultrafast heating, which allows achieving high quality materials processing, and gives new opportunities for studying fast processes in a solid under the influence of powerful energy flows [1].

With the help of femtosecond laser radiation, high-precision reproducible processing of materials without structural defects becomes possible, which is explained in principle by other ablation mechanisms.

The uniqueness of the conditions for the ablation of a substance by femtosecond pulses provides important aspects: during the time of the action of the laser pulse, the heat removal from the heated zone is negligible, whereby the laser energy absorbed by the substance is localized in a certain area, the size of which can be controlled; the ablation of the target material occurs after the end of the laser pulse, which eliminates the energy loss due to absorption of ablation products in the plasma [2]. There is a wide class of problems associated with the surface modification of opaque materials, where also features of femtosecond interaction are manifested in comparison with longer pulses, for example, the creation of laser-induced periodic surface structures.

The use of laser radiation energy for surface modification of the structure of the material makes it possible to significantly improve the performance characteristics of products, in particular the elements of microelectronic products and specialized radio engineering devices operating under severe conditions of exposure to vibrations and temperature changes [3].

Depending on the character of the laser action on non-transparent materials, it is possible to initiate various physicochemical processes that contribute to structural and phase changes, modification of the treated surface, the formation of hybrid metal, metal-ceramic, ceramic coatings and complex alloys.
Thus, the change in the local properties of the surface of the processed material, depending on the type of treatment, makes it possible to change the vibrational and thermal conductivity characteristics, locally improve the mechanical properties and resistance to various physical influences on the elements of semiconductor and hybrid products, in particular microelectronic integrated circuit boards [4].

2. The experimental change in the resonant frequencies of the samples using the methods of local laser exposure

To increase the resonant frequency of vibrations of a cantilever fixed samples, we used the methods of local laser exposure, in particular of local laser strengthening, local laser welding, laser scribing (removal of a section of the material).

As materials for processing various grades of steel (stainless steel 50, 40X, 20X13) with a thickness of 0.5 to 1 mm were used. Table 1 shows the content of iron and chromium in the initial samples.

| Sample number (steel grade) | 1    | 2 (20X13) | 3 (20X13) | 4 (40X) | 5 (50) | 6 (50) | 7 (20X13) |
|-----------------------------|------|-----------|-----------|---------|-------|-------|-----------|
| Fe                          | 86,4 | 97,5      | 85,5      | 97,8    | 95,9  | 96,6  | 85,5      |
| Cr                          | 13,0 | 1,3       | 13,7      | 0,9     | 2,9   | 2,3   | 13,9      |

Various processes of laser surface treatment are implemented in modes that do not cause material destruction. The laser thermal hardening processes are based on structural and phase changes in the material that occur due to ultra-high rates of its heating and subsequent cooling by the localized area of irradiation. Figure 1 schematically presents the processes of laser exposure to samples.

![Figure 1](image)

**Figure 1.** A schematic representation of the processes of laser action
To increase the resonance frequency of oscillations, the surface of the samples was structured by exposure to femtosecond and nanosecond laser pulses. Femtosecond laser system has the following parameters: the average power of 0.01-1.5 W, pulse repetition rate of 10 kHz, pulse duration of 300 fs, spot size in the exposure area of 50 microns. Nanosecond laser system: average power 0.1-10 W, pulse repetition rate 10 kHz, pulse duration 100 ns, spot size in the processing area 30 microns.

As the structure created on the surface, extended grooves were formed on the surface of the entire sample. The depth varied in the range of 100-200 μm, the width of the order of 50-80 μm. During the experiment, changes in the geometric features of the sample were not recorded. Characteristic changes in the form of bends and other deformations characteristic of some laser processing modes were not observed.

The surface of the obtained samples was studied using an optical microscope, and the resonance frequency of vibrations was measured on a vibrating table. This method is characterized by high requirements for processing equipment, high processing time and has not led to significant changes in the resonant frequencies.

The next method for increasing the resonant frequency of oscillations was local laser thermal hardening, which is characterized by the creation in the field of laser radiation of the material area having different physical and mechanical properties from the main material. Surface treatment of the samples was carried out using a continuous laser system with radiation parameters: the average power of 1-200 W, spot size in the processing area of 50 microns. Local laser hardening was performed by forming "tracks" on the sample surface. Laser exposure was carried out both in the mode of melting the surface and in the mode without melting the surface.

For this type of treatment is characterized by the formation of significant stresses in the material, which in turn led to the deformation of the sample, so the treatment was carried out with a rigid fixation of the sample in a special holder. This approach is necessary to preserve the geometric characteristics of the sample during processing, as when changing the location of the treated surface, as a result of bending, there is a shift of the treated surface relative to the focus point, which leads to a change in the processing mode. As a result of processing on the one hand the sample is strongly bent towards the treated surface, which indicates the formation of high internal stresses in the structure of the material. Stress compensation was performed by processing the sample from the opposite side. It was possible to save the shape of the sample after processing.

The surface of the obtained samples was studied using an optical microscope, the end microsections were made, and the resonant frequency of vibration was measured on the vibrating table.

Increasing the resonance frequency of vibrations of the metal plate is also possible by forming a layer of another material on the surface with different properties. Foams, gels, porous bodies with a low oscillation frequency and high viscosity of the structure are widely used, which contributes to a significant damping of exciting vibrations due to intrastructural interactions of the nodes. A number of experiments were carried out on the formation of local metal compositions on the surface of the test sample (BrAZhN10-4-4 powder was used).

Continuous and millisecond laser systems were used in laser cladding experiments. The parameters of the continuous laser system were given above. The millisecond laser system has the following parameters: average energy from 0.1 to 35 J in pulse, repetition rate of pulses is 20 Hz, pulse duration is 2 ms, spot size in processing area is 0.5-2 mm.

The powder layer (100±10 μm) was applied to the surface of the processed sample. Further, laser radiation was processed with parameters that contribute to the formation of a uniform roller of the deposited material on the surface of the sample. The formed layer has good adhesion resistance.

The surfaces of the end microsections were investigated by optical microscopy, which studied the distribution of the material, the structural transformation of the powder composition, both on the surface and on the border with the base material of the sample.

Modes of processing and changes of own resonant frequencies depending on the composition of the material and the type of exposure to laser radiation are listed in Table 2. The table shows the
parameters of laser processing: power, speed and density of laser beam scanning on the surface, as well as the distribution of the treated areas on the surface of the sample.

**Table 2.** Comparison of the resonance frequency

| Sample number | The resonance initial frequency, Hz | Laser processing | The resonance frequency after treatment, Hz | The change in the resonant frequency of oscillation, % |
|---------------|------------------------------------|------------------|---------------------------------------------|-------------------------------------------------|
| 1 -1          | 53,5                               | 280 fs, 100-750 mW, f=10 kHz, 10 lines/mm, 1 mm/s | 53,1 | -0,75 |
| 2 -1          | 37,1                               | 1 line, 2 sides, 100 W, 15 lines/mm, 1000 mm/s | 36,0 | -2,96 |
| 2 -2          | 38,0                               | 1 line, 2 sides, 100 W, 15 lines/mm, 1500 mm/s | 36,75 | -3,29 |
| 2 -3          | 35,2                               | 1 line, 2 sides, 100 W, 15 lines/mm, 500 mm/s | 34,3 | -2,56 |
| 3 -1          | 43,0                               | 5 lines, 1 side, 50-150 W, 15 lines/mm, 500 mm/s | 45,2 | 5,12 |
| 3 -2          | 46,3                               | 2 lines, 2 sides, 50 W, 15 lines/mm, 500 mm/s | 45,6 | -1,51 |
| 3 -3          | 45,5                               | 4 lines, 2 sides, 50 Br, 15 lines/mm, 500 mm/s | 46,0 | 1,10 |
| 3 -4          | 44,9                               | 1 line, 2 sides, 100 W, 15 lines/mm, 500 mm/s | 45,0 | 0,22 |
| 3 -4          | 46,8                               | 1 line, 2 sides, 100 W, 15 lines/mm, 250 mm/s | 48,0 | 2,56 |
| 4 -1          | 36,2                               | Surfacing of powder BrAZhN 10-4-4, 1 line 90*5 mm | 40,0 | 10,50 |
| 5 -1          | 34,0                               | 2 lines, 2 sides, 50 W, 15 lines/mm, 500 mm/s | 32,5 | -4,41 |
| 5 -2          | 36,2                               | 1 line, 2 sides, 50 W, 15 lines/mm, 500 mm/s | 35,0 | -3,31 |
| 5 -3          | 38,0                               | 4 lines, 2 sides, 50 W, 15 lines/mm, 500 mm/s | 37,2 | -2,11 |
| 6 -1          | 34,2                               | 1 line, 2 sides, 100 W, 15 lines/mm, 1000 mm/s | 32,8 | -4,09 |
| 6 -2          | 35,0                               | 1 line, 2 sides, 100 W, 15 lines/mm, 750 mm/s | 33,7 | -3,71 |
| 6 -3          | 36,2                               | 1 line 2 sides, 100 W, 15 lines/mm, 1250 mm/s | 33,9 | -6,35 |
| 7 -1          | 45,7                               | 2 lines, 2 sides, 50 W, 15 lines/mm, 250 mm/s | 48,2 | 5,47 |
| 7 -2          | 46,9                               | 2 lines, 2 sides, 50 W, 15 lines/mm, 500 mm/s | 47,3 | 0,85 |
| 7 -2          | 47,9                               | 2 lines, 2 sides, 75 W, 15 lines/mm, 500 mm/s | 48,9 | 2,09 |
| 7 -3          | 47,5                               | 2 lines, 2 sides, 100 W 15 lines/mm, 500 mm/s | 49,8 | 4,84 |
To study the structural changes in the field of laser processing, the end sections were made and metallographic studies were carried out.

Figure 2 shows the results of sample 3 processing (laser power 50-150 W). As a result of local thermal hardening, intensive melting of the material did not occur, there are no traces of redistribution of the material masses as a result of convective motion in the bath of the melt on the thin section, a dendritic structure is formed, needle crystals of growth are clearly visible, developing in the direction of rapid cooling (deep into the material). This exposure mode allows to obtain local quenching structures.

![Figure 2. The end section of the sample 3-1: a, b - different areas of the track.](image)

In the process of laser exposure, structures corresponding to local hardening of the material are formed (judging by the characteristic recrystallization). In place of the formed tracks there is some "bulge" formed as a result of changes in the structure of the material.

Figure 3 shows the result of surfacing bronze powder brand BrAZh10-4-4 on the surface of the steel plate 40x. In the process of exposure to laser radiation, a continuous coating was formed, cracks and pores in its structure are absent, light areas are likely to be the released phase of the aluminum alloying additive.

![Figure 3. The end section of the sample 4-1: a, b - different areas of the track.](image)

Figure 4 shows micrographs of the end section of sample 6-3. The cross section of the hardened tracks is expressed by two main zones, in the central region there is a structure corresponding to the intensive redistribution of the main material and chromium coating in the melt bath, around which there is a hardening zone without melting. The formed central region is slightly prone to etching due to the significant content of chromium. As a result of exposure to laser radiation, the sample was released due to a large thermal effect.
Figure 4. The end section of the sample 6-3: a, b - different areas of the track.

Figure 5 shows the end section of sample 7-1. The hardening structure is poorly expressed, is a light stripe on the gray surface of the sample. The structure is very weakly expressed needle crystals formed as a result of rapid cooling. This mode of processing was the most optimal in terms of increasing the resonant frequency of own oscillations.

Figure 5. The end section of the sample 7-1: a, b - different areas of the track.

As a result of the work carried out with the use of various laser systems, modes of action and the initial images of steels, the most significant increase in the intrinsic resonance frequency of oscillations is introduced by local laser surfacing of materials, as well as local laser heat-hardening without melting. In this case, an increase in the values of the resonant oscillation frequency with laser cladding more than 10%, with laser heat-hardening without melting more than 5% was obtained.

3. The formation of laser-induced periodic surface structures (LIPSS)
Laser-induced periodic surface structures are a universal phenomenon that can be observed on almost any material, after exposure to linearly polarized laser beams, especially when using femtosecond laser radiation. Over the past few years, research activities in the field of LIPPS have increased significantly, since their generation in a one-stage process provides an easy way to nanostructure and functionalization of the surface for the control of optical, mechanical or chemical properties, many works are devoted to this direction [5-7].

The most widely used theory of LIPPS formation is due to the interference of the influencing radiation and the excited surface electromagnetic wave (SEW) or, in other words, the plasmon-polariton model (PPM). The period of such structures depends on the wavelength of the applied laser radiation and the angle of incidence, and the tracks formed in the irradiation zone are aligned with the orientation of the plane of polarization of the laser radiation. Structures whose period is more than half
the wavelength is called "Low-Spatial-Frequency LIPSS" (LSFL). Structures with periods less than half the wavelength are called "High-Spatial-Frequency LIPSS" (HSFL).

As a radiation source, a femtosecond laser system with laser radiation parameters was used: a radiation wavelength of 1029 nm; the pulse duration is 300 fs; pulse repetition rate 10 kHz, pulse energy 150 μJ.

The sample was a round plate of molybdenum. Before proceeding directly to the experiment, the plate was polished on the polishing disk and degreased.

The general scheme of the developed experimental setup for obtaining surface periodic structures is shown in Figure 6.

The femtosecond laser system (1) generates laser radiation, which primarily falls on the polarization attenuator (2) used to regulate power values. Further, the radiation is reflected from the blind mirror (3) and enters the portal-periscope system (4) in which the dichroic mirror (5) is located, which transmits the laser radiation to the focusing cylindrical lens (6). Next, the beam hits the molybdenum target (7), which is located on the moving three coordinates of the table (8). Also used is a surveillance system consisting of a camera (9), backlight (10), the light from which, passing through the beam splitter (11), extends in the direction of the focusing lens, as well as in the opposite direction, passing through the filter (12) and enters the camera matrix.

The studies of the formed periodic surface structures resulting from the action of femtosecond laser radiation were made on the basis of the obtained images from a scanning electron microscope Quanta 200 3D. The best parameters at which surface-periodic structures are formed are the values of the number of pulses \( N = 255 \) and the average radiation power \( P = 1500 \) mW. The LIPSS obtained with these parameters can be seen in Figure 7.
Figure 7. SEM Image of the obtained structures on the surface of molybdenum by exposure to femtosecond laser radiation with a pulse number of 255 and an average power of 1500 mW.

The best value of speed of movement of the specimen, wherein the formed surface-periodic structures, was the value of speed equal to 1 mm/s. The Image of the obtained structures and their periods can be seen in Figure 8.

Figure 8. SEM image of the obtained structures at a speed of 1 mm/s
4. Conclusion

Thus, in this paper we study the effect of the character of laser treatment on the surface of metal samples, in order to hang their resonant oscillation frequencies. The metallographic analysis of the surface of the processed samples is made; the study of the end sections of the processed samples is carried out. The paper compares the effectiveness of different methods of laser exposure to increase the resonant oscillation frequencies. These methods can significantly improve the performance of products, in particular structural elements of products of microelectronic production and specialized radio devices operated under severe conditions of vibration and temperature changes. As a result of the experiments, it is concluded that a significant increase in the intrinsic resonance frequency of oscillations is introduced by local laser deposition of materials, as well as local laser thermal hardening without melting.

The paper also discusses the formation of surface periodic structures (LIPSS) using femtosecond laser radiation. These structures can be used in various fields, for example, can be used for the formation of antireflection coatings, as well as in medicine.

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