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REGULAR ARTICLE

Interaction of Laser Radiation (UV) with Materials

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The interaction of laser radiation with matter is considered. Marking of non-metallic materials requires heating below the softening point, heat treatment requires heating to temperatures above the phase transformation temperature, laser cutting of metals occurs with heating above the melting point, and engraving occurs above the melting or evaporation point. The choice of a laser for a certain type of processing is determined by the specific impact of laser radiation on a given material and the characteristics of the technological task at hand. Laser radiation in the UV range with a wavelength of $\lambda = 355$ nm, which can be obtained through third harmonic generation, is increasingly used in industry.Recommendations are provided for the use of low-power pulsed UV lasers for marking, engraving, cutting of metallic and non-metallic materials and surface hardening of steels. The paper presents the results of a study of the effect of laser radiation wavelength on metal engraving. The studies show that engraving with a beam with a radiation wavelength of $\lambda = 0.355$ µm allows obtaining a high-quality image without melting the surface. Due to the fact that radiation with a wavelength of $\lambda = 0.35$ µm is equally well absorbed by metals and dielectrics, UV-lasers can be used for separation operations in microelectronics, for example, for cutting flexible printed circuit boards with high quality. Reducing the diameter of the focus spot of the UV-laser compared to the focus of the CO_2-laser makes it possible to reduce the radiation power and perform better cutting. Comparison of thermal strengthening of steels by volume hardening, laser hardening with melting, laser hardening by UV-radiation showed high efficiency of hardening by UV-radiation. Laser processing in the UV-range is rationally used for local surface hardening of fuel equipment parts, cutting tools.

Keywords: Lasers with radiation in the UV-range, Third harmonic, Laser cutting, Laser marking, Laser hardening.

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1. INTRODUCTION

The basis of laser industrial technologies is the thermal or physico-chemical effect of radiation on the material being processed. Under the influence of radiation absorbed by the material, various thermophysical processes can take place on its surface and in the volume [1-3].

The process of interaction of laser radiation with matter can be schematically imagined as follows: absorption of light by the surface, transfer of energy into the depth of the material due to thermal conductivity, heating of the material below or above the temperature of phase transformations, melting and destruction of the material through the emission of melt and evaporation, cooling of the material after the end of exposure to light. In the case of heating below the temperature of phase transformations (melting and evaporation), there is no stage of destruction of the material. Thus, when developing any technological process implemented with the help of a laser, it is necessary to take into account the thermophysics of laser heating. Most of the technological processes using a laser are based on the thermal effect of its radiation, that is, the main condition is the need to heat the affected object to a given temperature. The choice of a laser for carrying out a certain type of processing is determined by the specifics of the effect of laser radiation on this material and the specifics of the given technological task. Heating below the softening temperature is suitable for marking non-metallic materials because the main mechanism is photochemical. Depending on the expected result, heat treatment requires heating to temperatures above the temperature of phase transformations (below or above the melting temperature). Laser hardening when heated above the temperature of phase transformations, but below the melting temperature, i.e. hardening from the solid state, allows strengthening of steel products while preserving the geometric characteristics of the surface, which is very important for precision parts, for example, parts of fuel equipment [4-7].

Laser cutting of metals occurs when heated above the melting temperature, and engraving – above the melting or vaporization temperature. Therefore, the main characteristic of the laser used in such technologies is its

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power. For pulsed lasers, the power in the pulse and the average power are considered, which depends on the duration and frequency of the pulses, as well as on the coherence, directionality, monochromaticity and polarization of the radiation [8-14].

The nature of the described processes, and therefore the result of this interaction of matter and radiation, largely depend on the absorption coefficient of the material at the wavelength of laser radiation.

Traditionally, laser sources emitting near-IR (solid-state and fiber lasers) and far-IR ranges (CO_2-lasers) are used in industry for processing materials. The choice of source type depends on the radiation absorption coefficient of a particular material at a certain wavelength: the absorptive capacity of metals decreases with increasing wavelength (Fig. 1), for non-metals this dependence is more complex (Fig. 2) and is characterized by high absorption in the far IR- and for some materials and UV-ranges [15-16].

Therefore, metal processing using fiber (λ = 1.53-1.56 and 1.064 μm) and solid-state Nd:YAG or $Nd:YVO_4$ lasers with a wavelength of λ = 1.064 μm is more efficient than processing with a CO_2-laser with a wavelength of λ = 10.6 μm [9-11]. The use of radiation with an even shorter wavelength, for example, UV, is limited by the low power of UV-lasers or their high cost [17].

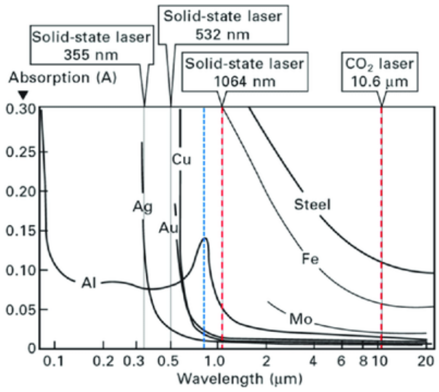


Fig. 1 – The absorption coefficient of some metals depending on the wavelength of radiation [8]

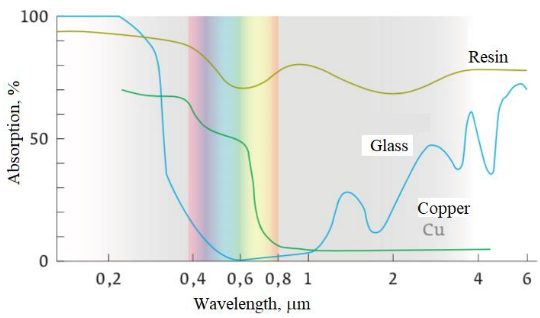


Fig. 2 – Absorption spectrum of materials mainly used for printed circuit boards [8]

Laser radiation of the UV-range can be obtained due to the generation of the third harmonic, which is implemented as a cascade process. Frequency tripling is a process of nonlinear frequency conversion, where the resulting optical frequency is three times the frequency of the input laser beam.

Non-linear optical phenomena are used to generate the third harmonic (355 nm) in a diode-pumped solid-state laser. The generation is implemented according to the following scheme: the main wavelength λ = 1064 nm excites the second harmonic with λ = 532 nm (the corresponding green region of the spectrum) on the first non-linear crystal of potassium titanyl phosphate ($KTiOPO_4$). Potassium titanyl phosphate crystals are physically and chemically inert and have high nonlinear optical efficiency. These nonlinear crystals are most often used to double the radiation frequency of solid-state lasers. Then the radiation of the main and second harmonics is combined on the second nonlinear crystal, as a result of which the third harmonic with a wavelength of 355 nm is emitted at the output.

Lasers with radiation in the UV-range are increasingly used in industry due to a number of advantages – high accuracy of processing, high quality of the processed surface, the ability to process both metallic and non-metallic materials, and a small zone of thermal influence [18-28].

2. VICORISTANT OF ULTRAVIOLET LASER PULSES FOR MARKING

Laser marking is the application of text and graphic images to the surface of a product under the influence of high-intensity laser radiation. Marking of parts, units or the final product allows the manufacturer to control the volume of manufactured products, their quality and promote their trademark. One of the methods of product marking is engraving – removal of a part of the material under the action of focused radiation. Engraving is most often applied to metal (usually to products made of carbon and stainless steel), ceramics, organic glass and acrylic. In this case, a layer of material is removed: up to 0.5 mm for artistic or 3.5 mm for deep engraving.

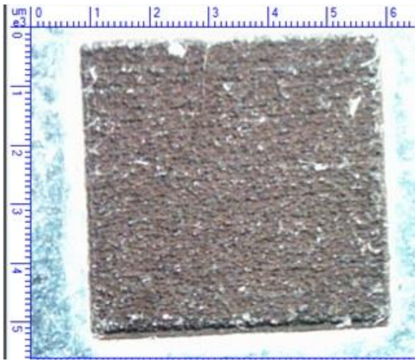
The marking becomes clearly visible because the incident light is scattered in the channels near the unmarked material. The technology has found wide application in all branches of production. In microelectronics it is used for marking blanks and products at all stages of development and production, for example, for silicon wafers.

The work investigated the effect of laser radiation wavelength on metal engraving.

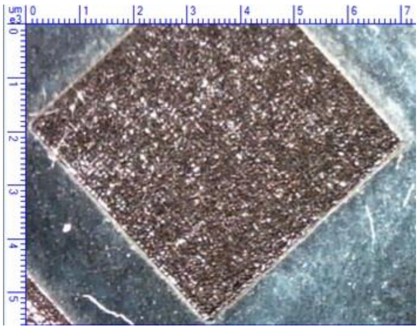
As a result of experiments using a Nd:YAG laser (λ = 1.06 μm), surface engraving with partial melting was performed. Fig. 3 shows the appearance of a surface processed at an average power of 17 W and a processing speed of 5 to 20 mm/s. The pulse frequency varied from 20 to 2 kHz.

Comparison of the relief of samples processed in different modes shows that changing the parameters within the studied limits allows one to obtain a rough image with melting using an engraving unit based on a Nd:YAG laser.

In this work, laser processing was also carried out using a solid-state $Nd:YVO_4$ laser with diode pumping (initial wavelength λ = 1.06 μm) and a nonlinear crystal, with a power of 5 W and a radiation wavelength of λ = 0.355 μm, (τ = 10 ns). The radiation frequency was 50 kHz, the focal spot diameter was 75 μm and 150 μm. The wavelength of 0.355 μm is provided by third harmonic generation.

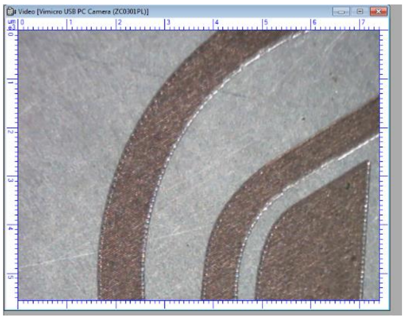


a

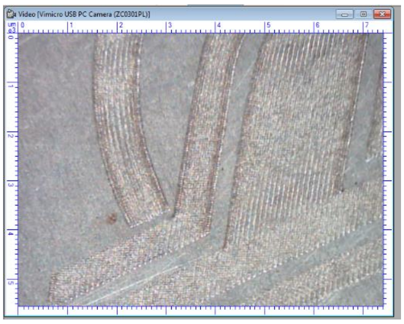


b

Fig. 3 – Surface relief under different processing modes: a – pulse frequency 4 kHz, processing speed 5 mm/s, b – pulse frequency 12 kHz, processing speed 20 mm/s



a



b

Fig. 4 – Laser engraving with different diameters of the focusing spot: a – 75 μm, b – 150 μm

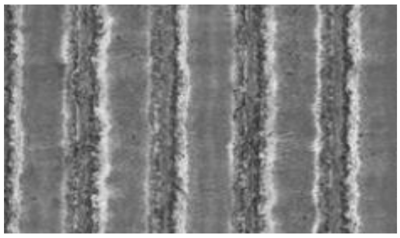
The conducted studies show that engraving with a beam with a wavelength of radiation $\lambda = 0.355$ μm allows obtaining a high-quality image without melting the surface (Fig. 4).

Under the same conditions, the image is affected by the diameter of the focusing spot.

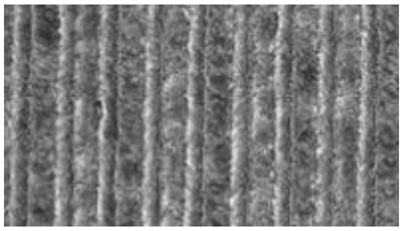
An important processing characteristic is also the scanning interval, which determines the distance between the processing lines, the so-called resolution. Fig. 5a shows the result of laser processing when scanning a metal surface with a resolution of 20 lines/mm.

In this case, the pattern of each line is created independently of the others, and the final image is formed sequentially – line by line. To create a film of uniform color, the line thickness must vary between 20 and 50 μm. In this image, obtained using a scanning electron microscope, the surface of the original material is visible between the scanning lines, but it is not noticeable to the naked eye.

During laser processing, such a scanning mode is possible, in which the lines of movement of the laser beam will overlap (Fig. 5b).



a



b

Fig 5 – Laser engraving with resolution: a – 20, b – 30 lines/mm

In this case the resolution is 30 lines/mm. The color of the processed surface is more uniform than when scanning with a resolution of 20 lines/mm.

Scanning with overlapping lines gives a more contrasting marking, but the outer lines differ in color from the others due to the smaller amount of energy falling on the remaining area of the laser-processed surface.

Laser marking of polymers is used for almost all classes of commercial plastics. Marking can be based on the thermal (Fig. 6) or photochemical effect (Fig. 7).

Marking can be done not only by evaporation of the material, but also by decolouration under the influence of ultraviolet radiation (Fig. 7). In this case, the third harmonic of laser radiation is also used.

For thermal marking, CO_2-lasers of the TEA type are used quite effectively, the radiation of which is equally well absorbed by almost all types of polymers. These lasers are most effective in cases where high productivity is required, and high image accuracy is not a determining requirement.

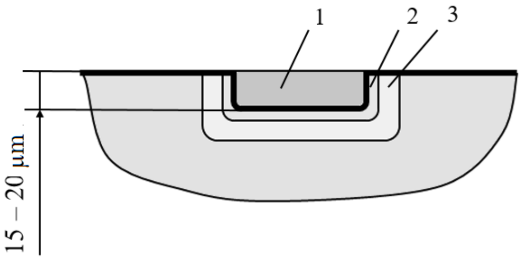


Fig. 6 – Surface layer of a part after marking based on the thermal effect: 1 – groove obtained as a result of heating, melting and evaporation of the material, 2 – zone of charring of the material, 3 – zone of the material with a partially changed structure

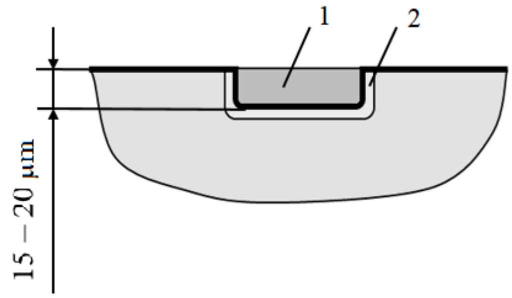


Fig. 7 – Surface layer of the part after ultraviolet laser marking: 1 – zone of material with changed color, 2 – zone with minor structural changes

Intense ultraviolet radiation discolors almost all modern polymer materials – under the action of the laser beam, a white marking is formed on a dark field. Polymers colored white (the main pigment is TiO_2) acquire a silver-gray marking due to the reduction of titanium ions.

3. CUTTING WITH LASER RADIATION IN THE UV-RANGE

Cutting is one of the first operations using lasers. The main mechanism of metal destruction during cutting is melting and displacement of the melt from the processing zone by a jet of auxiliary gas. For such processing, massive and reliable fiber lasers are usually used, the radiation of which is practically not absorbed by dielectrics.

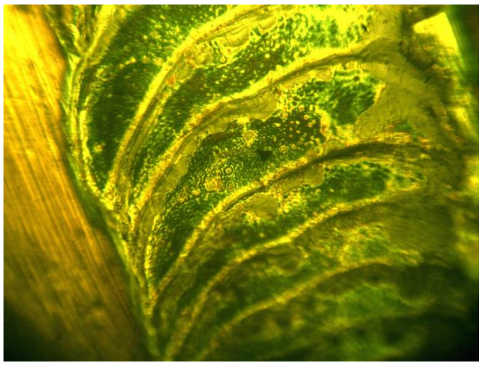
The absorption of laser radiation by dielectrics is due to the presence of vibrational degrees of freedom of the crystal lattice, impurities, defects, intermolecular vibrations, etc. Dielectric materials absorb CO_2-laser radiation well at a wavelength of $\lambda = 10.6$ μm, but IR-lasers remove material by intense local heating, which results in carbonization products, charred edges, and high thermal stresses. A comparison of cutting dielectrics with radiation of different wavelengths shows that when cutting with a CO_2-laser there are traces of carbonization of the material, while with UV-cutting there is a clean, even cut edge [3, 8].

Due to the fact that radiation with a wavelength of $\lambda = 0.35$ μm is equally well absorbed by metals and dielectrics, UV lasers can be used for separation operations in microelectronics. Laser cutting with a UV-laser allows for high-quality cutting of flexible printed circuit boards. Reducing the diameter of the UV-laser focusing spot compared to the focusing of a CO_2-laser allows for lowering the radiation power and producing higher-quality cutting. In addition, CO_2-laser radiation is completely reflected by metals, which makes it impossible to cut flexible printed circuit boards with metal elements.

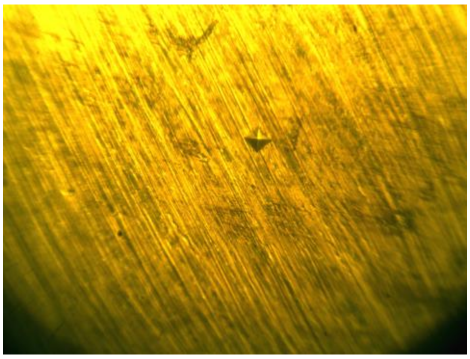
4. THERMAL STRENGTHENING BY ULTRAVIOLET LASERS

The basis of the laser hardening process is rapid heating to the phase transformation temperature (melting temperature or lower, but higher than the austenization temperature) of the surface layer of the metal, followed by rapid cooling due to thermal conductivity. Laser hardening can be used for all types of steel and provides higher hardness than traditional volumetric hardening. More often, processing without melting is used while maintaining the initial roughness $R_a = 0.16\text{-}1.25$ μm. The depth of the hardened metal layer is determined by the amount of permissible wear.

Hardening with solid-state laser radiation (mode 2) results in surface melting (Fig. 8a). Hardening with UV-radiation does not cause surface melting or deterioration of its quality (Fig. 8b).



a



b

a – mode with reflow, b – without reflow

Fig. 8 – Steel ШХ15 after laser hardening with UV-radiation

In this work, the studies were carried out on 40X and ШХ15 structural steels and P9 tool steel. The hardened layer was controlled by microhardness, which was measured on a PMT-3 device by pressing a standard tetrahedral diamond pyramid with a load of 100 g. The following modes were studied: bulk hardening with cooling in water (1), hardening with a beam of an ND:YVO_4-laser with $\lambda = 1.06$ μm (2) and hardening with a beam of an Nd:YVO_4-laser with $\lambda = 0.355$ μm (3). The radiation power density was $q = (0.8\text{-}0.9) \times 10^4$ W/cm^2.

Results of studies of volume and laser hardening of steels 40X, ШХ15 and P9 are shown in Fig. 9.

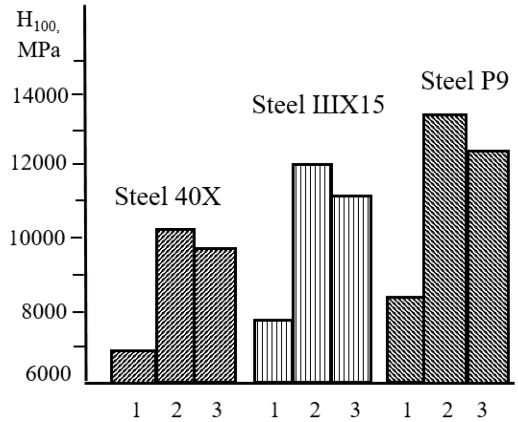


Fig. 9 – Microhardness of steels after various types of hardening: 1 – bulk hardening; 2 – laser hardening with melting; 3 – laser hardening with UV-radiation

On the one hand, melting hardening provides maximum hardness, which is the purpose of surface hardening (mode 2). But on the other hand, it has a negative effect on the surface condition operating under friction conditions.

The microhardness of samples after hardening with UV-radiation is lower (mode 3) than from the liquid state, but much higher than after bulk hardening. This indicates the effectiveness of laser hardening with UV-radiation. Laser hardening in the UV-range is rationally used for local surface hardening – cylinder liners, teeth of cutting tools, individual surface areas of fuel equipment parts, etc.

CONCLUSION

The choice of a laser for a certain type of processing is determined by the specifics of the effect of laser radiation on a given material and the features of the technological task.

For marking non-metallic materials, heating is used below the softening point, heat treatment requires heating to temperatures above the phase transformation temperature, laser cutting of metals occurs when heated above the melting point, and engraving – above the melting or evaporation temperature.

Laser radiation of the UV range with a shorter wavelength ($\lambda = 355$ nm), which can be obtained due to the generation of the third harmonic, is increasingly used in industry.

Recommendations are presented for the use of low-power pulsed UV lasers for surface hardening of steels, marking and cutting of metallic and non-metallic materials.

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Взаємодія лазерного випромінювання (УФ) з матеріалами

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Розглянута взаємодія лазерного випромінювання з речовиною. Для маркування неметалевих матеріалів використовують нагрівання нижче температури розм'якшення, термічна обробка потребує нагрівання до температур вище температури фазових перетворень, лазерне різання металів відбувається при нагріванні вище температури плавлення, а гравірування – вище температури плавлення або випаровування. Вибір лазера для проведення певного виду обробки визначається специфікою впливу лазерного випромінювання на даний матеріал і особливостями поставленого технологічного завдання. Все більше використання в промисловості знаходить лазерне випромінювання УФ-діапазону з довжиною хвилі $\lambda = 355$ нм, яке можна одержати за рахунок генерації третьої гармоніки. Надані рекомендації з використання малопотужних імпульсних лазерів УФ-діапазону при маркуванні, гравіруванні, різанні металевих та неметалевих матеріалів та поверхневому гартуванні сталей. В роботі наведені результати дослідження впливу довжини хвилі лазерного випромінювання на гравірування металів. Проведені дослідження свідчать, що гравірування променем з довжиною хвилі випромінювання $\lambda = 0{,}355$ мкм дозволяє одержати якісне зображення без оплавлення поверхні. Завдяки тому, що випромінювання з довжиною хвилі $\lambda = 0{,}35$ мкм однаково добре поглинається металами і діелектриками, УФ-лазери можуть застосовуватися для роздільних операцій в мікроелектроніці, наприклад, для різання гнучких друкованих плат з високою якістю. Зменшення діаметру плями фокусування УФ-лазеру у порівнянні з фокусуванням СО2-лазеру дозволяє знизити потужність випромінювання і проводити більш якісне різання. Порівняння термічного зміцнення сталей об'ємним гартуванням, лазерним гартуванням з оплавленням, лазерним гартуванням УФ-випромінюванням показало високу ефективність гартування УФ-випромінюванням. Лазерну обробку в УФ-діапазоні раціонально застосовувати для локального поверхневого зміцнення деталей паливної апаратури, різальних інструментів.

Ключові слова: Лазери з випромінюванням УФ-діапазону, Третя гармоніка. Лазерне різання, Лазерне маркування, Лазерне гартування.