Measurement of laser-induced dynamic structures on the surface of materials in a real time scale

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Abstract. The processes induced by laser radiation in the region of its interaction with matter are characterized by a high development rate and exclude direct contact of measuring detectors in the interaction region. The opportunity of structural adjustment of the irradiated surface of the material requires recording the temporal characteristics of these dynamic processes, which essentially determine the structural surface phase transitions in a heterogeneous medium. Therefore, for their diagnostics the highly sensitive, non-contact and inertialess registration methods are preferred.

In [1], a scheme was proposed for obtaining a brightness-enhanced magnified image of an object using a medium with a high gain. In practice, this approach was first implemented in [2].

The main advantage of the use of brightness amplifiers based on active media of metal vapor laser in optical diagnostic channel systems is that the brightness amplifier acts as a narrow-band selective filter. The active medium of a brightness amplifier amplifies the radiation passing through it many times, but only in a narrow frequency band corresponding to its own gain profile of the active

1. Introduction
The processes induced by laser radiation in the region of its interaction with matter are characterized by a high development rate and exclude direct contact of measuring detectors in the interaction region. In addition, the possibility of structural adjustment of the irradiated surface of the material requires recording the temporal characteristics of these dynamic processes, which essentially determine the structural phase transitions. Therefore, for their diagnosis, highly sensitive, non-contact and inertialess registration methods are preferred.

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medium. As a result, if the sounding of the studied object is carried out in reflected light using radiation from such an active medium of the brightness amplifier, then the radiation carrying useful information at the receiving device significantly exceeds the brightness of various background / spurious illumination. A system of requirements for brightness amplifiers for optical systems is formulated [3-5].

The registration of laser-induced processes on the surface of various materials using a CVL-10 copper vapor brightness amplifier is presented in many works, for example [6–12].

The problem is that the distance from the processing surface to the input lens of the laser monitor is fixed, which is inconvenient in the study of technological processes of laser processing of various materials. An optical harness allows one to study the processes of interaction of laser radiation with the surface and in cases of a rather arbitrary arrangement, both in space and remotely from the laser monitor.

In this paper, for the first time, the question of the possibility of transmitting and recording dynamic laser thermal hardening processes with the corresponding characteristics of the spatial structure on the surface of an object when transmitting an image through a fiber-optic system / optical bundle under real-world multi-beam exposure of a power laser to an object (such multi-beam / waveguide lasers is most effective for technological applications [13]).

However, in this case, a problem arises with the depth of field of the image when registering the dynamics of the laser thermal hardening process. An analysis of possible solutions to this fundamental problem is presented in this article.

2. Methods

Experimental studies of the processes occurring in the field of interaction of laser radiation with the surface of the sample are carried out according to the following procedure. The laser monitor is configured to observe the surface of the test sample. The adjustment can be performed both with visual control - in this case, on the screen or display, an image of the surface of the material with a distinctly visible surface relief is observed (Figure 1), and as far as the maximum of radiation reflected from the sample and amplified by an active medium of a copper vapor laser of copper atoms. To improve the contrast, both classical optical methods for eliminating glare and computer methods for subsequent image processing are used [4].

After setting up the laser monitor, the radiation of the power laser (solid-state YAG laser (λ = 1,06 μm) and / or the waveguide CO2 laser (λ = 10,6 μm), and / or the matrix of laser semiconductors (λ = 0,81 μm), and / or a fiber continuous laser (λ = 1,07 μm)), and the alignment of the power and probe / diagnostic channels of the installation is performed jointly. Moreover, the alignment accuracy of the axes is not worse than 0,02 mm. The area of influence of radiation from a power laser can be easily identified by a decrease in the reflectivity (darkening) of the sample surface and by the destruction of the initial microrelief. The intensity of the radiation acting on the surface of the sample and the duration of exposure depend on at what stage and in what mode the interaction of laser radiation with the material should occur.

Indeed, under the influence of laser radiation, the optical characteristics of the irradiated material change, which leads to a change in the reflectivity of the surface of the sample under study, and also surface structures of various nature arise, causing a change in the reflection pattern. These changes in the reflection conditions lead to a change in the recorded image of the interaction zone of laser radiation with the surface of the sample and are determined by computer processing.

To do this, the obtained images are digitized (the brightness level of each image element is converted into the corresponding digital code) and in this form are recorded in the computer's memory. As a result, arrays of codes are formed in the computer's memory. When subtracting from the base array (corresponding to a specific image frame) another array (corresponding to the previous image frame), only digital information about the changes that occurred on the surface of the sample remains.

The advantages of the experimental scheme under discussion in the study of high-temperature processes that develop when laser radiation interacts with materials under the conditions of spurious
illumination from an erosion plume (it screens the area of influence) were clearly shown during a comparative experiment in which copper vapor laser radiation reflected from the surface of the material, was divided in half by a beam splitter, and part of the radiation was directed into the recording chamber bypassing the active medium of the x copper. This channel is a conventional standard projection optical system with a laser as a light source. The optical paths in both channels were almost the same and the image was recorded by the camera with the same magnification. Then, radiation from a power laser was directed to the sample, the intensity of which gradually increased. At a radiation intensity of the power laser of the order of 4·10⁵ W/cm², the erosion plume developed so strongly that its luminescence completely shielded the interaction region of laser radiation with the surface of the material. This did not allow her to be observed. On the image of the interaction region obtained in the channel with a brightness amplifier, this had no effect.

In our case, a frame capturing the state of the surface at a certain point in time of the action of the laser beam of the power laser gives a qualitative picture of the conditions of light reflection in this interaction region. A detailed study is carried out on the spatial distribution of the brightness of the resulting image, built along the selected axis. In this case, the spatial resolution is determined both by the capabilities of the optical system of the laser monitor, and by the capabilities of the used computer equipment and software [14, 15].

By changes in the brightness distribution of the image, changes in the conditions of reflection of the probe radiation, which are the result of changes in the surface conditions of the material under the influence of laser power, are tracked. Thus, it is possible to identify the moment of appearance of the transition region arising from the interaction of laser radiation with matter, to monitor the dynamics of its expansion, to register the appearance of a thermal front, melting front, oxide fronts, etc.

To conduct experiments on the subject of this article, a laser projection microscope (LPM) was modernized with an optical bundle included in the probing channel. A schematic diagram of an experiment with an optical bundle is shown in Figure 1.

![Figure 1. Scheme of a laser projection microscope with a fiber / optical bundle.](image)

As a laser projection microscope (LPM), a brightness amplifier on copper vapors CVL-10 was used with the following characteristics: length of the active element 1 = 0,8 m, diameter d = 18 mm, unsaturated gain coefficient α = 0,14 cm⁻¹; emitting at a wavelength λ = 510,6 nm, the spatial resolution of the recorded image is of the order of 10 μm, the temporal resolution of the registration system is not worse than 1 ms.

CVL-10 copper vapor laser radiation focuses on the surface of the optical bundle using a lens with a focal length of 125 mm and an antireflection coating of 400 – 700 nm.

In addition, to measure the temperature of the treated surface, a high-temperature micropyrometer is used that meets the following requirements [16, 17]: range of controlled temperatures from 2000 °C to 5000 °C; time resolution no worse than 0,5 ms.

The problem is that an object located in the plane of the test object is not static, that is, its position relative to the optical axis of the entire system changes. Indeed, during laser processing of a surface on which a source / area of influence of powerful laser radiation is necessarily present, depending on the
chosen laser processing scheme, there is always mutual movement of an object, a LPM and a source of powerful laser radiation.

In the simplest model experiment on thermal hardening of the flat surface of a metal material, the following scheme was implemented: the object (the processed surface) and the whole LPM circuit are stationary during the experiment; the processing beam of the power laser with the help of a robotic arm moves at a constant speed through the field of view with the image of the surface in a straight path. The registered dynamic process is saved in an avi file. At the same time, we demonstrated the visualization of the surface of the material and recorded its fusion during the experiment.

Unfortunately, such a simple approach is not common in modern laser technologies, where the movement of a powerful laser beam relative to a stationary (in the laboratory coordinate system) workpiece, as a rule, occurs along a complex curved path.

Therefore, it is necessary to ensure the synchronous movement of two laser beams: a powerful one – a power laser acting on the surface, and a probe laser beam. If we proceed from the assumption that high-power laser radiation is delivered to the corresponding treated surface by the optical head using optical fiber, then it seems natural to use fiber technologies for transmitting images to the CVL as well. This is shown in Figure 3, where an optical harness is introduced into the circuit, which serves to transfer the image from one end to another, as well as an additional lens system (lens 1 and lens 2). The lens system builds an image of the subject plane (plane of the test object) on the right end of the optical bundle. The tourniquet transfers the image to its left end in a 1:1 scale. Further, the image of this end is transferred by the lens into the CVL-10 active medium with the same magnification and displayed on the screen of a laser projection microscope. Due to the mechanical flexibility of the fiber bundle, the lens is no longer mechanically rigidly connected with the rest of the LPM and can be rotated at an arbitrary angle within a certain range.

The paper used a fiber-optic bundle with the following characteristics: the calculated numerical aperture of 0.5; resolution of 8-15 mm\(^{-1}\). An optical wedge (refractive angle \(\theta = 4^\circ\)) is glued to the end of the optical bundle to reduce the reflection of radiation.

In the general case, the registration of dynamic processes in real time requires not only a modification of the optical registration scheme itself, but also the use of more advanced / modern models of high-speed brightness amplifiers at induced transitions in metal vapors [18-20].

3. Results and Discussion
First, the standard / simplified circuit shown in Figure 1 was assembled and tested, but without an optical bundle and lens system (lens 1 and lens 2). As a lens, a standard laser kit lens with a focal length \(f \sim 70\) mm and a relative aperture of \(\sim 1:3\) was used. The test object is a plate of polished stainless steel, onto which strokes with a certain amount per millimeter (from 1.75 to 10 strokes per millimeter) are applied by laser engraving.

The resulting image of a part of the test object is shown in Figure 2. As you can see, the image is of good quality, the borders of the rectangles are clear, the contrast is high (one fragment of a rectangle with a border is shown).

![Figure 2. The image of the test object on the LPM screen in the plane of the best focusing (number of strokes per millimeter 2.5).](image-url)
The depth of field was experimentally determined for the surface paintwork surface of the processed object. To do this, the test object was mounted on a table with precision feed, after which the rotation of the differential screw set the best sharpness and the best image contrast (Figure 2). Further, the test object was removed from the set plane of the best image until the contrast almost disappeared. The following picture was visually recorded: the image contrast is small, small details (previously seen) are indistinguishable. As a result of these measurements, it was obtained that the depth of field is ± 200 μm.

Such a shallow depth of field makes it difficult to use such a simplified diagram (Figure 3) provided that it works to register dynamic processes. If the movement is made by some mechanical system (for example, using a robot manipulator), which always moves along a program-defined path with a certain error, the question arises of the ratio of this error and the magnitude of the depth of field of the used LPM. However, the actual data on how accurately the distance between the object and the lens is maintained during the operation of the robotic arm is difficult to evaluate, since its manufacturer usually does not provide the necessary information for this. According to our estimates, in practice - this value is comparable to the depth of field. Therefore, in this situation, obtaining a high-quality image of the investigated dynamic surface is problematic.

One of the simplest ways to improve the situation with the depth of field parameter is to use longer telephoto lenses. Indeed, an experiment with a longer telephoto lens (f ~ 100 mm) led to an increase in depth by approximately 2 times. This value itself makes sense in comparison with the scale of those inhomogeneities on the surface of the workpiece that need to be visualized during their transformation under the action of radiation from a power laser.

Figure 3 presents the dynamics of changes in the machined steel surface in a real experiment on heat hardening under conditions of moderate power of a power laser. Here, for example, the successive stages (1-4) of the modification of the steel surface under the influence of a multi-beam CO₂ laser with a power of P = 743 W are shown; scanning speed of the laser beam over the surface of the sample V = 5 mm/s; in this case, the temperature of the sample in the irradiation zone is T = 884° C, and the structural phase transformations occurred during times t₁ = 0,147 s (the beginning of the process – picture 1) and t₂ = 0,154 s (completion of the process – picture 4) after the start of irradiation.

Figure 3. Dynamic image of the processed surface in real time.

Next, experiments were carried out with the inclusion of an optical bundle in the circuit (Figure 1). A lens with a focal length f = 125 mm. After the optical bundle for focusing radiation on the test
object, an optical system consisting of one lens or two lenses was installed. Focal lengths of 50 mm and 200 mm.

Figure 4 shows the image of the test object obtained on the CVL screen using an optical bundle. The test object was located at the end of the optical bundle. The number of strokes per millimeter 5 – Figure 4a; the number of strokes per millimeter 2.5 – Figure 4b.

![Figure 4a](image1.png) ![Figure 4b](image2.png)

**Figure 4.** The image of the test object on the LPM screen located at the end of the optical harness: a) 5 strokes per millimeter; b) 2.5 strokes per millimeter.

When transmitting an image through an optical fiber, the image contrast decreases. Figure 5 shows an image of a test object located at the end of an optical bundle with the addition of immersion fluid between the bundle and the test object. Glycerin was used as an immersion fluid. The number of strokes per millimeter 5.

![Figure 5](image3.png)

**Figure 5.** The image of the test object on the LPM screen located on the end of the optical harness (using immersion liquid).

The image contrast in this case increases. Figure 6 shows the image of the surface of a test object located after a lens with a focal length of 50 mm installed at a distance of 100 mm from the end of the bundle.

![Figure 6](image4.png)

**Figure 6.** The image of the test object on the LPM screen located at a distance of 100 mm from the focusing system.

The surface image has a low contrast. Part of the radiation involved in imaging is lost when passing through an optical bundle and lens.
To calculate the capabilities of the monitor when transmitting images of the surface of the sample processed by laser radiation through an optical bundle, the ZEMAX computer program was used. Without going into details, suffice it to say that it allows modeling and analysis in the design and selection of various optimal schemes of optical systems, including with optical harness.

In particular, we are talking about the calculation of the optical system after the optical bundle in front of the test object. In the work, a two-lens condenser was calculated, the use of which improves the quality of the resulting image. The following system parameters in the probing channel are considered: radiation wavelength 510 nm; lens diameter 30 mm; distance between lenses 40 mm; lens thickness 6 mm; the radius of curvature of the lens 1 -58.576 mm; radius of curvature of the lens 2 58.576 mm; distance from fiber to lens 69.714 mm; optical fiber diameter 0.6 mm; focal length 80.265 mm; diameter of the focal spot 0.468 mm; glass refractive index 1.568151. The results presented one of the stages in the search for acceptable solutions for image visualization through an optical fiber / bundle and are preliminary with the gradual complication of the optical image input circuitry for use in real laser technology.

The next stage of research is to determine the capabilities of the proposed system for transmitting dynamic images in the case of moving both a power laser beam and the target itself (this happens in a real technological process in production), but for a real laser technological complex being developed when it is used for specific modes thermal hardening.

More specific information should be determined by the power laser actually used for technological processes and its corresponding characteristics. In our case, we are talking about the development of new highly effective technologies to dramatically increase the wear resistance of critical engineering parts based on a robotic universal intelligent laser complex with real-time hardening diagnostics. This complex is still at the stage of our development and bringing / testing of its parameters to the required values for certain technological modes of laser thermal hardening.

4. Conclusions

The paper analyzes the operation of the monitoring system for the process of laser surface treatment of materials in real time, designed to visualize laser-induced dynamic processes directly during laser surface treatment of the object. The basic physical principles of its operation and the existing problems, as well as the prospects for overcoming them under various conditions of specific laser thermal hardening processes, including using computer simulations to find optimal optical designs and modes.

Despite the complexity and requirements for fine-tuning the presented monitor, it is, nevertheless, of exceptional importance in the implementation of special operations in laser thermal hardening of critical parts of complex and precise engineering, especially 3D products of different sizes and purposes.

In standard laser thermal hardening tasks at moderate power laser powers (especially for large-sized products of a simple profile), this monitor provides redundant information, requires more detailed measurements with appropriate high-level software and analytical software, and raises the total cost of the technological process being implemented when commercializing the laser complex for real-world tasks production.

In this case, you can use another, simpler, alternative method for solving the visualization problem using the standard spectral filtering method, based on the fact that in the violet part of the spectrum for various materials (Al, Cu, Fe, Ti), and if not taken into attention to titanium – even in the blue part of the visible range, the laser torch makes a very small contribution. Therefore, if you illuminate the treatment area with a violet semiconductor laser (nominal wavelength 405 nm) and observe the image through an interference filter tuned to a given wavelength, you can expect that the image can be recorded using a typical video camera. Such a system is quite commercially acceptable both in price / quality format and for production conditions. Our preliminary demonstration tests showed the reality of this approach (at least for laser cutting).
However, in the microprocessing of local areas of 3D products with a complex profile, the use of this monitor can give fundamental advantages in terms of the controllability of the process directly during its implementation and the achievement of the required / record processing accuracy.

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