Optical strength of the material under conditions of high-power pulsed radiation

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Abstract. The stochastic nature of the laser-induced destruction of transparent materials under the action of high-power pulsed laser radiation was simulated using the Weibull statistical distribution in order to predict the optical strength dynamics of the irradiated surface. Theoretical and experimental studies of the optical strength of glass composites were conducted, taking into account the stochastic properties of the breakdown of nano-scale coatings under the action of a single high-power pulsed laser radiation. Coatings were obtained by sol-gel method. As a radiation source, we used a solid-state laser on a yttrium-aluminum garnet doped with neodymium ions (YAG-Nd laser) which generated laser pulses at wavelength of 1.064 μm with duration of 30 ns with energy of up to 0.15 J and with duration of 300 μs with energy of 1.2 J. The authors proposed an algorithm for determining the optical strength of the irradiated material by the breakdown stress of the material. It is proposed to determine the breakdown stress by comparing the experimental and simulated dependences of stress, temperature, and reliability of the surface of the irradiated material. Based on the proposed measurement technique, experimental studies were conducted and an algorithm was developed for determining the optical strength of coatings.

1. Introduction
Materials on the basis of glasses are widely used in many areas such as optics and optoelectronics [1-9]. The problems of dynamics of such materials irradiated by laser pulses are important [10-22]. The interaction of laser radiation with a substance causes a number of physicochemical, optical, thermal, mechanical processes, including thermochemical and thermomechanical, in the irradiated material [23-41].

In this paper, we consider the results of laser ablation destruction experiments conducted by the authors [11-15, 24-28, 42-45]. The authors used the Weibull statistical distribution [46-49].

The strength of the material, its resistance and the dynamics of destruction under different types of effects is an important factor in the development of many technologies. Many studies have been devoted to the investigation of these properties [50-54]. Among such materials, ceramics and glass are often used, and one of the most important types of effects is high-power laser radiation.

The investigation of the properties of a material as a result of irradiating its surface with laser radiation or obtained by laser spraying is also the focus of attention of many scientists [55, 56]. Hardening materials by laser treatment or the introduction of special additives or by applying thin film coatings on its surface is one of the widely used technological methods for improving the strength properties of a material [57-59].
The issues of strength and prediction of the destruction dynamics of ceramic materials and glass are considered separately in the works of the authors [60], including issues of radiation or optical strength under the action of laser radiation.

The authors of this article conducted a number of studies of the radiation strength of materials (as applied to these experiments, they often use the term "optical strength"), including materials covered with a system of nanoscale coatings under the action of high-power pulsed laser radiation. Various parameters of the process of laser-initiated destruction of materials were studied experimentally, theoretically, and by methods of mathematical modeling [11–15, 24–28, 42–45, 61].

The purpose of this paper is to show an algorithm for applying the Weibull statistical distribution to determine the optical strength of a material and to predict the dynamics of its destruction and time of no-failure operation under conditions of irradiation with powerful laser pulses.

2. Experimental Part

The experimental part of the study was conducted on the samples of glass, applied with oxide single-layer SiO$_2$, TiO$_2$ coatings or multilayer SiO$_2$ and TiO$_2$ coatings using method of sol-gel technology. Figure 1 shows a cross-section of one of the samples coated with a film of silicon dioxide with thickness of 150 nm.

Composite materials on the basis of glass doped with transition metals (Au, Cu) were also considered. These samples were also obtained by the sol-gel synthesis method by introducing gold or copper chlorides into the reaction mixture. In this case, additives were introduced into the sample volume, and not on its surface.

Measurements of refraction and thicknesses of nanoscale films were performed on the HORIBA Jobin Yvon ellipsometer. The refraction indices of SiO$_2$ films were in the range from 1.455 to 1.475 and the TiO$_2$ films ranged from 1.974 to 1.998.

Figure 1. A cross-section of the film sample of SiO$_2$ with a thickness of 150 nm on a glass substrate.

The thickness of the SiO$_2$ films ranged from 58 nm to 171 nm, and the TiO$_2$ films ranged from 126.6 nm to 130 nm. Measurements of threshold values of the laser beam energy density at which the breakdown begins on the surface of the material were taken in experiments on laser ablation destruction of composites. The breakdown phenomenon was recorded by the formation of a laser plasma torch. Experimental studies were conducted on the setup assembled on the basis of [11–15, 26–30, 44–47].
A YAG-Nd laser generated pulses at wavelength of 1064 nm with duration of 20 ns with energy of up to 0.15 J in the Q-switched mode and 300 μs with energy of 1.2 J in the free-running mode, respectively. The structural diagram is presented in Figure 2.

The setup structure includes the sample under study 1, the laser radiation source 2, the system for measuring and changing energy and geometry of the radiation pulse 3, the system for detecting the surface destruction of the sample under study 4, the system for recording and processing information 5. System 3 included calibrated neutral light filters, photodiodes, lenses. System 4 contained an FSD-8 spectrometer with fiber input. System 5 included a personal computer controlling the delay line needed to synchronize the work of the entire laboratory setup, more precisely, to start the recording of the spectrometer relative to the leading edge of the laser pulse. The high-power pulsed radiation of laser 2 was focused by a lens of system 3 onto the surface of sample 1. The breakdown phenomenon was recorded by the presence of a self-emitting torch of the laser plasma and recorded by an FSD-8 spectrometer. The laser pulse energy was controlled by a photodiode with an IKS-1 glass filter. The change in the energy density of the laser pulse in system 3 in the range from 0.1 to 150 J·cm⁻² was achieved both by choosing the focal length of the lens and by attenuating the radiation with calibrated neutral light filters. Standard software was used to process the measurement results. The modes of operation of the spectrometer were regulated using the built-in specialized software. The results of experimental measurements were processed using the appropriate software.

3. The optical strength of the material in the Weibull model
To determine the strength by the mean value of \( x \) from \( N \) measurements on the interval \( \Delta x \), the distribution function is used

\[
f(x) = \frac{1}{N} \frac{\Delta N}{\Delta x},
\]

where \( \Delta N \) is the number of samples with optical strength in the range \( (x, x+\Delta x) \).

In the case of a single-irradiated target, the optical strength of the sample coating will have the form:

\[
r(F) = 1 - p(F) = \exp \left[-\ln 2 \left( \frac{F}{F_{0.5}} \right)^m \right],
\]

where \( F \) is energy density, \( m \) and \( F_{0.5} \) are the exponent in Weibull statistics and the energy density for which the probability of breakdown is 0.5, both calculated from experimental data.

The optical strength of the target with \( N \) laser pulses at different points of the target will be equal to
\[ R(F) = r^N = \exp \left\{ -2 \ln 2 \left[ \sum_{j=1}^{k} \left( \frac{F}{F_{0.5}} \right)^{m_j} \right] N \right\}. \]

With a laser pulse repetition rate \( f \) during time \( t \), the total number of pulses will be \( N = ft \) and, substituting this expression in (6), we obtain the optical strength of the sample during time \( t \):

\[ R(F, t) = \exp \left\{ -2 \ln 2 \left[ \sum_{j=1}^{k} \left( \frac{F}{F_{0.5}} \right)^{m_j} \right] ft \right\}, \]

and the time when reliability \( R \) is achieved:

\[ t = \frac{\ln(1/R)}{f \ln 2 \left[ \sum_{j=1}^{k} \left( \frac{F}{F_{0.5}} \right)^{m_j} \right]}. \]

4. Results
In the experiments, measurements of the values of the threshold energy density \( F_{0.5} \) of laser radiation were taken, at which breakdown begins on the sample surface. The method is described in [1, 2]. The values of the probability curve outside the experimental points are interpolated (Figure 3). At those points where the probability values calculated by interpolation become greater than one or less than zero, they are equated to one and zero, respectively.

![Figure 3. The probability of breakdown \( p \) from the energy density \( F \). Experimental values \((F_i, p_i)\) \((i = 1, 2, \ldots, 9)\) are marked by squares, linear interpolation of these values is marked by solid line.](image)

According to this probability curve, the threshold energy density \( F_{0.5} \) is determined.

5. Conclusion
In a series of experiments, issues related to the determination of the radiation strength of a material irradiated with powerful nano and microsecond laser pulses were considered. In this case, the Weibull statistical distribution was applied, which made it possible to predict the radiation strength of the material and to make assumptions about the presence of various defects in the material. For example, the analysis of the graph \( \ln \left( \ln \frac{1}{1-p} \right) \) on \( \ln y \) from the Weibull distribution makes it possible to identify various types of defects in the material.

Thus, the laser ablation of experimental samples was investigated taking into account the stochastic nature of the material destruction. The breakdown of such samples was studied using the Weibull
distribution. The described algorithm of actions makes it possible to predict the dynamics of the optical strength of the surface of optical materials. This allows simulating the destruction parameters of a substance under the action of pulsed radiation and predict the non-failure operating time of the material in such conditions.

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