The optical strength of the glass nanocomposites at laser ablation

V G Shemanin[1] **and O V Mkrtychev**[2]

[1] Novorossiysk Polytechnic Institute of the Kuban State Technical University, Karl Marx 20, Novorossiysk 353900, Russia

[2] Novorossiysk Branch of the Shukhov Belgorod State Technological University, Rubin 5, Novorossiysk 353900, Russia

E-mail: vshemanin@nbkstu.org.ru

Abstract. The results of theoretical and experimental study of the nanocomposites laser ablation have been used to predict its optical strength dynamics under laser irradiation. A practical application of statistical regularities observed in the laser ablation destruction of materials using Weibull–Gnedenko three-parameter statistics has been proposed.

1. Introduction

Laser ablation of materials is studied in many works that explore different aspects of laser radiation's interaction with matter [1–3]. The authors of this article examine the possibility of predicting the dynamics of glass nanocomposites' laser destruction. The nanocomposites were the glass substrate coated with the surface oxide nano film. Such a film's laser ablation destruction threshold energy density values dependences on the optical and chemical properties were the subject of our earlier works [4, 5]. This work goal is experimental and theoretical study of glass nanocomposites laser ablation destruction using Weibull–Gnedenko's statistics for its optical strength prediction [6, 7].

A statistically random distribution of micro defects on the surface of the material determines the statistical nature of material's strength and, therefore, the threshold laser destruction will depend on the characteristics of defects in the volume of interaction (absorption coefficient and its temperature dependence, the size of the defect), the probability of one or another defect in this volume, as well as from statistical fluctuations of laser radiation. The most widely in the analysis of the strength of brittle materials, including glass, used Weibull–Gnedenko's model, based on the principle of "the weakest link" and considering the structure of the material as a chain, the strength of which is determined by the least durable part.

In the case of three-parameter Weibull–Gnedenko's statistics the probability density function (differential distribution function) has the form

$$f_{wbl}(x) = \begin{cases} \dfrac{c}{b}\left(\dfrac{x-a}{b}\right)^{c-1} e^{-\left(\frac{x-a}{b}\right)^{c}}, & x \geq a, \\ 0, & x < a, \end{cases}$$

where $f_{wbl}(x) \geq 0$, $x \geq a$, $c > 0$, $b > 0$, $-\infty < a < \infty$. Value a named by argument position (time of risk-free operation), b—the scale parameter (characteristic time) and c—the

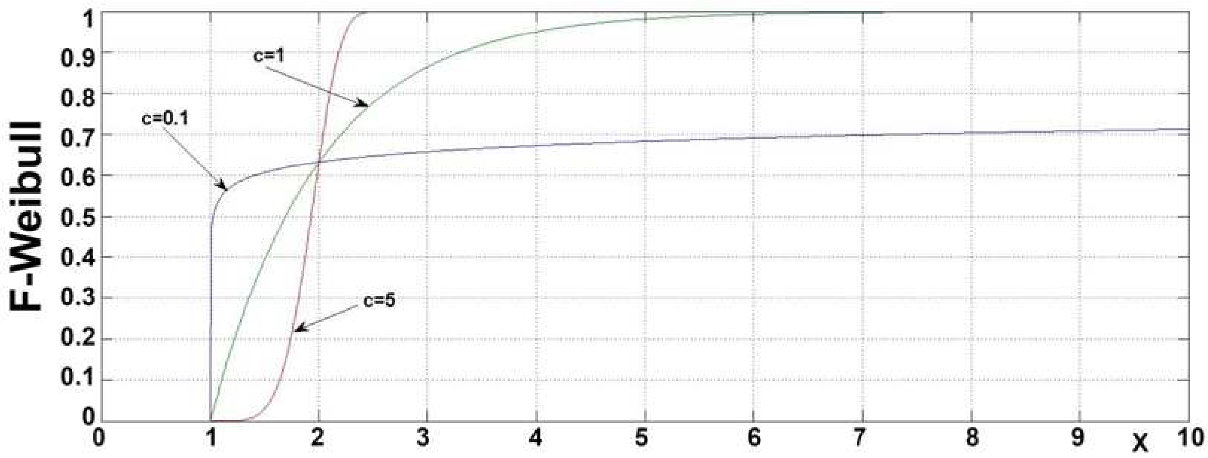

Figure 1. The graph of the cumulative distribution function of the Weibull–Gnedenko at $a = b = 1$ and different c.

form parameter (angular coefficient). The parameters a and b have the same dimension as a random variable x, and the form parameter c is dimensionless value.

After the estimation of parameters of the Weibull–Gnedenko's statistics, one can evaluate a variety of reliability features. In particular, to calculate the distribution function bounce (usually denoted as $F(t)$). The corresponding cumulative, otherwise the integral, function of the Weibull–Gnedenko's statistics has the form:

$$F_{wbl}(x) = 1 - e^{-\left(\frac{x-a}{b}\right)^c}.$$

Graphs of this function for various combinations of parameters are shown in figure 1.

The reliability function is calculated according to the formula:

$$R(x) = 1 - F_{wbl}(x) = e^{-\left(\frac{x-a}{b}\right)^c}.$$

Two-parameter Weibull–Gnedenko's statistics obtained from the three-parameter one under the condition of equality to zero of the position's parameter $a = 0$, that is:

$$f(x) = \begin{cases} \frac{c}{b}\left(\frac{x}{b}\right)^{c-1} e^{-\left(\frac{x}{b}\right)^c}, & x \geq 0, \\ 0, & x < 0. \end{cases}$$

2. Experimental

The samples of the float glass with dimensions of $50 \times 50 \times 3$ mm served as substrates. The sols containing oxide (SiO_2 or TiO_2) in the amount of 2 mass. % in the film-forming solution were taken for studies. The threshold laser density values F at which the film breakdown on the sample surface begins were measured at the laser ablation station in [5, 8]. The measurement method carried out was described in detail in [4, 9, 10]. Two YAG-Nd laser pulse duration of 20 ns and 300 mks were used in this measurements.

Let us assume that the irradiated material is homogeneous medium with a single type of defects randomly distributed over the volume or the surface of the sample. I.e. the probability of laser destruction $p(F)$ is determined by the defects of one kind, and one-parameter Weibull–Gnedenko statistics can be applied, for example, to determine according to the analyzed characteristics of laser destruction from Weibull's module. Thus, in the simplest case, when the probability of laser destruction is determined by the defects of one kind on the surface of the sample, for which the probability of failure can be described by the exponential function of the type [4]

$$p\,(F) = 1 - e^{-\rho(F)A} = 1 - e^{-kAF^m},$$

where $\rho\,(F) = kAF^m$—the average surface/volume defects concentration defined as in [10], and A—the area exposed to laser radiation with energy density F, k—constant and m—factor determined below. Knowing the area of impact of the laser beam when the laser destruction is possible to determine the concentration of defects and then calculate the probability of failure for the actual values of the energy density of the beam used in a particular experiment

$$p\,(F) = 1 - e^{-\ln 2\left(\frac{F}{F_{0.5}}\right)^m}.$$

The graph of $\ln\left(\ln\frac{1}{1-p}/\ln 2\right)$ from $\ln\left(F/F_{0.5}\right)$ will schedule a direct proportionality factor m equal to the index of exhibitors in Weibull–Gnedenko's statistics. The analysis of the experimental data confirms that the slopes of direct repeated many times because of a faulty mechanism of laser ablation and Weibull–Gnedenko's statistics adequately describes the process of laser ablation and allows to estimate the probability of failure of the polymer sample at a given energy density of the laser pulse.

Reliability (in our case this function is the nano film optical strength of the coating details) in this case is defined as the probability function of the breakdown of the target depending on the energy density of the incident radiation:

$$R\,(F) = 1 - p\,(F) = e^{-\ln 2\left(\frac{F}{F_{0.5}}\right)^m},$$

where $F_{0.5}$—if the breakdown energy density value at the probability level of 0.5.

The results of studies using Weibull–Gnedenko's statistics related to a single irradiation of the sample, can be used to predict the optical strength of the sample when it is repeated irradiation of pulsed laser radiation. If the repetition rate of the laser pulses is equal to f, then after time t the total number of pulses is equal to $N = ft$, and substituting this expression into the last formula, we obtain the optical strength of the sample at time t:

$$R\,(F,t) = e^{-\ln 2\left(\frac{F}{F_{0.5}}\right)^m ft},$$

According to the optical strength of R on time t for values of the energy density of the incident radiation $F = 5$, 30 and 35 J/cm^2 in the nanosecond range is shown in figure 2. And figure 3 is constructed according to the optical strength of R on time t for values of the energy density of the incident radiation $F = 50$, 100.17 and 150 J/cm^2 in the microsecond range.

The parameters $F_{0.5}$ and m are determined from the results of experiments [4, 5, 10], and the repetition rate of laser pulses f is an input parameter. Thus, the use of Weibull–Gnedenko's statistics allows us to predict the optical strength of the polymer of the target during the time t, which is a pulsed radiation with a pulse repetition frequency f. The time when the sample is achieved reliability R, considering from time $t = 0$, can be determined by the formula:

$$t_R = \frac{1}{f}\frac{F_{0.5}^m}{F^m}\frac{\ln\left(1/R\right)}{\ln 2}.$$

So for one of the samples irradiated with pulses of nanosecond range, while the values of density of the incident radiation $0.1\ldots0.5\ldots1.0\ldots2.0\ F_{0.5}$ J/cm^2 ($F_{0.5} = 30.21$) the lifetime of the sample is approximately equal $14.427\ldots2.885\ldots1.443\ldots0.721$ s.

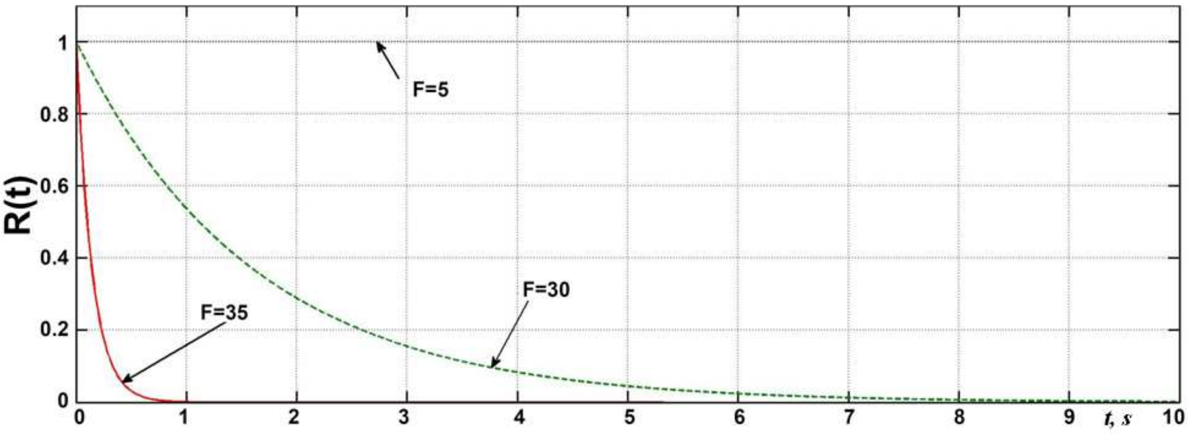

Figure 2. Graphs of the optical strength of R on time t, values for the energy density of the incident radiation $F = 5$, 30 and 35 $\mathrm{J/cm^2}$ in the nanosecond range.

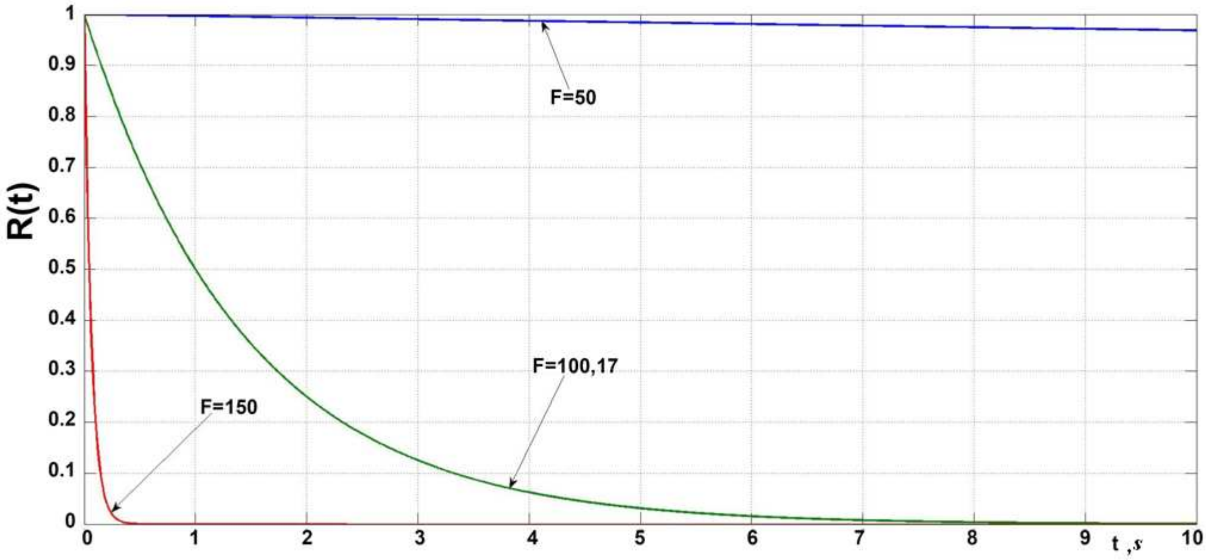

Figure 3. Graphs of the optical strength of R on time t, values for the energy density of the incident radiation $F = 50$, 100.17 and 150 $\mathrm{J/cm^2}$ in the nanosecond range.

The results can be used to predict the optical strength of glass nanocomposites. For example, if the irradiation of a sample with $F_{0.5} = 30.21$ $\mathrm{J/cm^2}$ and $m = 15.65$ pulses in the nanosecond range with a repetition rate of $f = 1$ Hz, we want to obtain the lifetime of the sample for more than one month ($t \approx 10^7$ s), when the optical strength $R = 0.5$, the density of the incident radiation should be no more than 10.78 $\mathrm{J/cm^2}$.

Thus, experimental and theoretical studies of glass nanocomposite's laser ablative destruction's stochastic nature allowed us to develop a procedure for predicting these material's optical strength using Weibull–Gnedenko's statistical distribution.

References

[1] Christy F A, Manikandan D, Manikandan P and Aravazhi S 2012 *J. Chem. Pharm. Sci.* **5** 1

[2] Kwang-Ryul K, Byong-Deog C, Jun-Sin Y, Sung-Hak C, Yong-Ho C, Dong-Soo S, Dong-Ho B, Myung-Chang K and Young-Keun J 2009 *Trans. Nonfer. Met. Soc. China* **19** 189
[3] Sola D and Pena J I 2013 *Materials* **6** 5302
[4] Atkarskaya A B, Mkrtychev O V, Privalov V E and Shemanin V G 2014 *Opt. Mem. Neural Net. (Information Optics)* **23** 265
[5] Atkarskaya A B, Mkrtychev O V and Shemanin V G 2012 *Izv. Vuzov. Fizika* **8/2** 238
[6] Weibull W 1951 *J. Appl. Mech.* **18** 293
[7] Madjoubi M A, Bousbaa C, Hamidouche M and Bouaouadja N 1999 *J. Eur. Cer. Soc.* **19** 2957
[8] Mkrtychev O V 2012 *Izv. Vuzov. Sev.-Kav. Reg.* **4** 36
[9] Runkel M 2012 *SPIE OEmag.* **5** 48
[10] Voronina E I, Efremov B N, Privalov V E, Charty P V and Shemanin V G 2009 *Tech. Phys.* **79** 143