The temperature field during laser ablation of glass composites at high temperatures

O V Mkrtychev¹ and V G Shemanin²

¹ Novorossiysk Branch of the Shukhov Belgorod State Technological University, Mysknakskoye Shosse 75, Novorossiysk, Krasnodar Region 353919, Russia
² Novorossiysk Polytechnic Institute of the Kuban State Technical University, Karl Marx 20, Novorossiysk 353900, Russia

E-mail: oleg214@ya.ru

Abstract. The authors were performed computational experiments on laser ablation of glass composites. The heat equation was solved by the method of moments. After study of the subthreshold approximation \( l \ll 1 \text{ cm} \) and \( T_s \ll T_a \) (\( l \) is the heating typical size, \( T_s \) is the surface temperature, \( T_a \) is the typical ablation temperature), the task was to consider another boundary approximation, when \( T_s \gg T_a \). This task is important for studies at extreme values of energy density of the laser radiation. If we proceed from the meaning of the adopted approximations, this one describes the dynamics of the temperature field in the target at the initial stages of interaction of low-temperature laser radiation with the very hot target material. Being a mathematically correctly obtained solution, this system gives you the ability to build interesting hypotheses of the interaction of radiation and matter.

1. Introduction

The problems of the laser ablation of materials are considered by many authors [1–4] because of the great role of this phenomenon in theoretical and practical problems. The authors of paper [5] consider the physical mechanisms of laser destruction associated with the photoionization of absorbing inclusions, thermal ionization, thermochemical reactions with the formation of absorbing products, and mechanochemical reactions with the formation of excited particles. The authors of [6] consider the melting-crystallization model taking into account the kinetics of phase transformations on the basis of the Kolmogorov’s equation. The paper [7] analyzes the thermal, hydrodynamic, and photophysical ablation model, as well as the gas dynamics of three-dimensional vapor expansion during laser ablation. The thermoelastic laser destruction of transparent dielectrics, related both to absorbing inclusions and to their own mechanisms of destruction, is analyzed [8]. The authors of [9] based on the Maxwell’s equations consider the dynamics of the temperature field in the target and the dynamics of the plasma torch. In papers [10–12], various problems of laser ablation are studied for different ranges of the radiation pulse duration. The paper [13] deals with laser ablation destruction of materials within the framework of the thermal model. The authors [13–18] performed computations on laser ablation of glass composites with sol-gel coatings to confirm the experimental data. In particular, the dynamics of the thermal field in the matter of the irradiated material was investigated. For this, a thermal ablation model was used [5, 7]. The heat equation was solved by the method of moments [13]. The positive aspects of the method of moments include the ability to take into account the...
dependence of thermophysical parameters on temperature. The disadvantages of the method of moments include the absence of a single solution for different types of such dependence. This actually means that for each of functional dependences of the thermophysical parameters, it is necessary to carry out anew the calculations on the entire algorithm of the method of moments.

The purpose of this work is to obtain the functional dependences of the surface temperature of the irradiated glass composites and the depth of heating on time for different ranges of change in the parameters of the problem in the framework of the thermal ablation model [7]. The novelty of the work lies in obtaining new numerical solutions for comparison with the results of other authors.

2. Evaluation

We consider irradiation of samples of glass composites obtained by the method from [18]. The numerical solution of the heat equation by the method of moments is considered in detail in [13]. First, the solution was simplified for small values of the parameters

\[ l \ll 1 \text{ cm} \quad \text{and} \quad T_a \gg T_s, \]

where \( l \) is the heating typical size, \( T_a \) is the typical ablation temperature, \( T_s \) is the surface temperature. This is the so-called subthreshold approximation, when the surface temperature is much lower than the ablation temperature. The adequacy of the obtained results was estimated in comparison with the works of other authors and from general principles [5–7, 19–21].

The solution is given for simplicity in one of the special cases (for constant thermophysical parameters and constant intensity of laser radiation) and has the form

\[ \dot{T}_s = \frac{I_s \alpha}{c_p} - \frac{1}{2} \frac{\alpha \kappa (T_s - T_0)}{I c_p}, \quad \dot{l} = \frac{1}{2} \frac{\kappa}{c_p} \frac{\alpha l}{l} \]

or, after transformation

\[ \Delta \dot{T}(t, T_s, l) = \frac{1}{2} \frac{\alpha \kappa}{c_p} \frac{2 I_s l - \kappa \Delta T}{\kappa l}, \]

\[ \dot{l}(t, l) = \frac{1}{2} \frac{\kappa}{c_p} \frac{\alpha l + 1}{l}, \]

where \( \Delta T = T_s - T_0 \) is the growth of the target temperature \( T_s \) over its initial value \( T_0 \); \( \kappa \) is the thermal conductivity, \( c \) is the heat capacity, \( \rho \) is the target density, \( I_s \) is the intensity of the absorbed laser radiation at the laser ablation front and \( \alpha \) is the absorption coefficient.

Dynamics of temperature fields in a substance for a given solution (1) at the following values of parameters: \( \alpha = 4.25 \times 10^5 \text{ cm}^{-1} \), \( T_0 = 300 \text{ K} \), \( T_a = 15700 \text{ K} \), \( \kappa = 2.11 \times 10^{-2} \text{ W cm}^{-1} \text{ K}^{-1} \), \( c = 0.96 \text{ J g}^{-1} \text{ K}^{-1} \), \( \rho = 1.42 \text{ g cm}^{-3} \). For different intensities \( I_s \), it is presented in figure 1. In experiments [13] pulses with \( \Phi = 10 \text{ J cm}^{-2} \) and \( t_1 = 10 \text{ ns} \) were used, \( I_s = 10^8 \text{ J cm}^{-2} \text{ s}^{-1} \) (where \( I_s, \Phi \) and \( t_1 \) are related by \( \Phi = I_s t_1 \)), other values of \( I_s \) were taken for numerical modeling and comparison of results of calculations.

After investigating the subthreshold approximation within the framework of this problem, it was decided to consider another boundary approximation when \( T_s \gg T_a \). Such a problem, although different from the problems considered by authors [5, 6], is important for research in the field of the extreme values of the energy density of laser radiation. The solution, in the particular case, has the form

\[ \Delta \dot{T}(t, T_s, l) = -\frac{1}{2} \frac{\alpha \kappa T_s}{c_p} l, \]

\[ \dot{l}(t, l) = \frac{1}{2} \frac{\kappa}{c_p} \frac{1}{l}. \]

The solution (3) and (4) shows that the temperature of the irradiated surface decreases with time, while the rate of change in the length of the heating region is constantly decreasing. If we proceed from the meaning of adopted approximations, this system of equations describes
Figure 1. Dependence of the irradiated surface temperature on time for different values of the absorbed radiation intensity.

the dynamics of the temperature field of the target at the initial stages of interaction of low-temperature laser radiation with a much hotter target material. Being a mathematically correct solution (but not a physically), which confirms the first subthreshold approximation (1) and (2), this system (3) and (4) makes it possible to construct interesting hypotheses of the interaction of radiation and matter. And, in any case, the receipt of such solution indicates that the thermal model in this temperature range does not work.

3. Conclusion
A thermal ablation model was used to numerically simulate the propagation of the thermal field in the irradiated material. The numerical solution of the heat equation by the method of moments confirmed that the thermal model adequately describes the laser ablation process under the condition that the speed of laser ablation obey the laws of the kinetics of thermal evaporation. In practice, this means that adequate results can be obtained in the range of values $T_a \gg T_s$.

References
[1] Volkov N B, Maier A E and Yakovets A P 2003 Tech. Phys. 75 1–9
[2] Abrasimov S A, Bazhulin A P, Bokhakov A P, Konov V I, Krasyuk I K, Pashinin P P, Ral’chenko V G, Semenov A Yu, Socyk D N, Stuchebryukhov I A, Fortov V E, Khishchenko K V and Khomich A A 2014 Quantum Electron. 44 530–4
[3] Geras’kin A A, Khishchenko K V, Krasyuk I K, Pashinin P P, Semenov A Yu and Vovchenko V I 2009 Contrib. Plasma Phys. 49 451–4
[4] Krasyuk I K, Pashinin P P, Semenov A Yu, Khishchenko K V and Fortov V E 2016 Laser Phys. 26 094001
[5] Manenkov A A and Prokhorov A M 1986 Phys. Usp. 148 179–211
[6] Zhvavyi S P 2000 Tech. Phys. 70 58–63
[7] Anisimov S I and Luk’yanchuk B S 2002 Phys. Usp. 45 292–324
[8] Kaludkevich V M, Manenkov A A and Pokotilo I L 1997 Quantum Electron. 24 944–8
[9] Bulgakova N M, Zhukov V P and Meshcheryakov Yu P 2013 Appl. Phys. B 113 437–49
[10] Agranat M B, Anisimov S I, Ashitkov S I, Ovchinnikov A V, Kondrat’ev P S, Sitnikov D S and Fortov V E 2006 Pis’ma Zh. Eksp. Teor. Fiz. 83 592–5
[11] Anisimov S I, Zhakhovskii V V, Inogamov N A, Nishikhara K, Petrov Yu V and Khokhlov V A 2006 Zh. Eksp. Teor. Fiz. 130 212–27
[12] Arnold N, Luk’yanchuk B and Bityurin N 1998 Appl. Surf. Sci. 127–129 184–90
[13] Shemanin V G and Mkrtchyan O V 2018 Tech. Phys. 88 643–8
[14] Atkarskaya A B, Mkrtchyan O V and Shemanin V G 2012 Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika 55 238–9
[15] Atkarskaya A B, Mkrtchyan O V, Privalov V E and Shemanin V G 2014 Opt. Mem. Neural Networks 23 265–70
[16] Shemanin V G and Mkrtchyan O V 2015 J. Phys.: Conf. Ser. 653 012012
[17] Mkrtchyan O V and Shemanin V G 2015 Proceedings of the RAS Ufa Scientific Centre 2 5–10
[18] Mkrtchyan O V, Privalov V E and Shemanin V G 2015 St. Petersburg Polytechnical University Journal: Physics and Mathematics 1 82–6
[19] Gus’kov K S and Gus’kov S Yu 2001 Quantum Electron. 31 305–10
[20] Zehan L, Juan D, Yuanan Z, Yueliang W, Yuxin L and Jianda S 2015 Opt. Express 23 14774–83
[21] Gao X, Feng G, Han J, and Zhai L 2012 Opt. Express 20 22095