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MODELING LASER PROCESSING OF MATERIALS

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Abstract. *In the paper, modeling of the interaction of laser radiation with substance is carried out using the example of acrylic glass with the help of COMSOL Multiphysics 5.5 software package. For a long time, the complexity of the phenomena occurring during the laser impact on the material made it possible to select processing modes mainly experimentally. Thanks to the programs working with the finite element method, a model of the passage of laser radiation through a block of dielectric material was created in this work. A graphic distribution of heat on the surface was obtained, as well as an isotherm of the depth of heat distribution inside the material. The possibility of modeling laser processing of materials by the finite element method has been proven.*

Key words: *modeling, laser heating, CO_2 laser, laser radiation, finite element method, COMSOL Multiphysics, heat transfer in solids.*

Introduction

The use of lasers for processing of materials has been known to mankind for more than a dozen years. A laser beam is a stream of coherent, monochromatic light. Thanks to this, it is possible to localize laser radiation in a small spatial volume. In combination with the pulse mode of operation, this allows the realization of power densities at which non-linear optical effects are observed and evaporation and optical breakdown of substance occur [1, 2]. For a long time, the complexity of the phenomena occurring during the laser impact on the material made it possible to select processing modes mainly experimentally. The analysis of the thermal processes taking place at the same time and the programs used require in-depth physical knowledge, as well as large computing power, hence they have not become available to many researchers. But technology does not stand still. The development of microelectronics has led to the fact that computing machines, whose capacities are sufficient for serious problems of modeling physical processes and complex mathematical formulas, have become available. Thanks to the programs working with the finite element method, interactive modelling of complex objects becomes possible [3].

Analysis of publications

Interaction of laser radiation with highly absorbing materials in a wide range of light flux densities is well described by the thermal model, according to which the entire process as a whole can be conditionally divided into several stages: light absorption and energy transfer to thermal vibrations of the solid grid; heating of the material without destruction; destruction of the material by the ablation mechanism; cooling after the end of interaction [2, 4].

Even the first experiments on the influence of laser radiation on materials, conducted in the 60s of the last century, showed that laser heating in its physical essence does not differ from other types of heating. As with any other heating, the temperature is an unambiguous characteristic of the thermal action, and the heating itself consists in increasing the amplitude of thermal vibrations of the grid. Heat transfer in a solid is carried out by mechanisms of thermal conductivity, of which electronic thermal conductivity is the main one for metals and strongly degenerate semiconductors, and grid thermal conductivity is the main one for nonmetals.

Laser heating can be accompanied by changes in the optical and thermophysical properties of the material, its thermal expansion, as well as phase transitions in the solid state and melting. In some cases, heating can activate diffusion processes in a solid and some chemical reactions on its surface and in near-surface layers. Thus, the heating of materials by laser radiation is accompanied by the usual well-studied phenomena.

At the same time, high heating and cooling rates and large spatial temperature gradients determine the features of laser heating. They can and do lead to significant differences in the flow of thermal processes stimulated by laser exposure.

An important role in laser heating is played by changes in the optical properties of the substance, since the amount of heat generated and its spatial distribution directly depend on the values of the absorption capacity and absorption coefficient. The formation of feedbacks in the optical parameters of the material surface, which change during laser exposure, introduces fundamental features in the course of ongoing processes.

The stage of heating materials by laser radiation is the main one when studying the physical essence of technological operations carried out without destroying the material, for example, heat treatment, diffusion, etc. For operations of laser processing of materials associated with the destruction and removal of some of their parts, the heating stage is preliminary, but at the same time quite important, since its analysis allows us to determine the conditions of the beginning of destruction [2, 3].

The technique of modeling mechanical failure mechanisms has been around for a long time. When designing structures, it is necessary to find the stress distribution, or stress field, in order to identify potentially dangerous areas. Sometimes, in order to find out if the specified gaps between structural parts are broken, you need to calculate the movement only at certain points in the system. In some cases, especially if the load and behavior of the structure depend on time, the designer needs to calculate the total distribution of displacements, or the displacement field. For the calculated stress field, the equilibrium conditions must be met at each point, and the displacements must be continuous (i.e., the compatibility conditions must be met). The main difficulty that arises in this regard, not to mention the aspects of solving the selected equations, is to decide whether these equations can adequately reflect the design requirements. Moreover, the complexity of the structure geometry, as well as the nature of loads and material properties must be taken into account in these calculations. To get a sufficiently accurate solution, a large number of factors must be taken into account.

The advent of electronic computers has radically changed the situation in the field of solving such problems using partial differential equations. Finite-difference methods are also used, in which differential equations are approximated using discrete values of quantities given at selected points. The advantage of these methods stems from the long history of their development, which resulted in the appearance of convergence theorems. In addition, the algebraic equations used in these methods, which need to be solved numerically, often have a particularly simple form.

The finite element method is an analytical procedure that has been intensively developed over a relatively short period of time. The key idea of the method in analyzing the behavior of structures is as follows: a continuous medium (the structure as a whole) is modeled by dividing it into regions (finite elements), in each of which the behavior of the medium is described using a separate set of defined functions representing stresses and displacements in the specified region. These sets of functions are often given in a form that satisfies the conditions of continuity of the characteristics they describe in the entire environment. In other cases, the selected sets of field functions do not provide continuity and, nevertheless, make it possible to obtain satisfactory solutions. However, unlike completely continuous models, there is no complete confidence in the convergence of the solution. If the behavior of the structure is described by a single differential equation, then an approximate solution of this equation can be obtained either by the finite element method, or by using the technique of series expansion or finite difference schemes. If the design is inhomogeneous and consists of a large number of individual structural elements, the behavior of each at this is described by its own differential equation, then as a rule, in this case only the finite element method can be directly applied.

Along with these alternative methods of numerical solution of applied problems of structural mechanics, the finite element method should be used to construct and solve a system of algebraic equations. The specific advantages of the method are the convenience of forming equations and the ability to represent completely irregular and complex structures and load conditions [5].

Quite a lot of finite element application software packages are known, in which the program itself divides the modeling space into finite elements (triangles, rectangles, tetrahedra, parallelepipeds, etc.). You just need to build a model, enter the material properties and limit conditions, run the calculation and display its results in numerical and graphical form. The entire analysis process is quite clear, as a rule, it is accompanied by graphic constructions on the computer screen.

Goal and problem statement

The aim of the study is to simulate the interaction of laser radiation with substance on the example of acrylic glass using a COMSOL Multiphysics 5.5 software package. To achieve this goal, the following tasks were set: 1) checking the possibilities of modeling the surface treatment of a non-metallic substance with a laser beam; 2) creating a model of the passage of laser radiation through a block of dielectric material using the COMSOL Multiphysics package; 3) determining the depth of the engraving line; 4) showing that this model allows adjusting the parameters of laser processing of certain materials.

Development of an application for testing the possibility of modeling laser heating

All finite element programs can be divided into two groups: programs specifically designed for calculating magnetic fields, and general-purpose programs that use the finite element method to solve many scientific and technical problems. Programs of the first group (ELCUT) are easy to learn, but, as a rule, are designed to calculate only two-dimensional fields, which greatly narrows the range of tasks that are assigned to them. Programs of the second group (ANSYS Multiphysics, Maxwell, COMSOL Multiphysics) have much greater capabilities.

COMSOL® Multiphysics® is a powerful solver program that runs on Finite element (FEM) and partial differential equation (PDE) systems. The basic COMSOL Multiphysics software package has eight additional modules that extend the basic features of the program [3].

In this paper, the main task is to create a program to test the feasibility of using the COMSOL® Multiphysics® 5.5 package for laser processing of materials (in this case, nonmetals).

The research material was acrylic extrusion glass. Acrylic organic glass is an amorphous polymer of methyl ester of methacrylic acid: it has a high transparency for visible and ultraviolet rays; it is well formed, processed, glued; it is characterized by oil, gasoline and water resistance. In the IR region of the spectrum, it has almost zero transmission coefficient (fig. 1).

This gives us the right to model the laser beam not as an electromagnetic wave, but as a surface heat source with Gaussian propagation [5]. Modeling can be done using the "Heat Transfer" module. The "Heat Transfer" module included in the COMSOL Multiphysics® software product allows you to analyze heat transfer by thermal conductivity, convection, and radiation. The Heat Transfer module contains a complete set of tools for performing thermal calculations and analyzing the impact of thermal loads.

To ensure the efficiency of laser processing, maximum radiation absorption is required, so we chose the CO_2 laser with a wavelength of 10.6 microns.

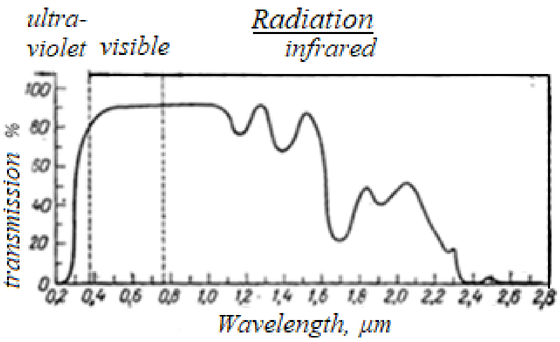


Fig. 1. Coefficient of radiation transmittance for polymethylacrylate depending on the wavelength [1]

Other laser processing parameters (power of 10W, focusing spot diameter of 1 mm, travel speed beam speed of 40 mm/s) is typical for a standard StoLaser Standard 4030 Mini installation.

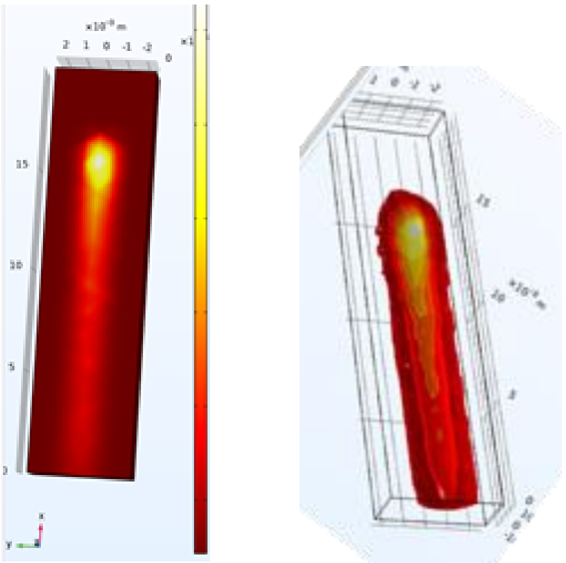
The main characteristics of the material taken into account by the program are density, heat capacity and thermal conductivity, as well as absorption capacity.

At the beginning of model development, a workspace with the necessary elements must be created for this task. The first stage is the choice of measurability of the modeling space. You can create from a point (0D) to a full-fledged three-dimensional model (3D). In this case, creating a three-dimensional model seems to be right.

After this the physical modules to be used in the program must be chosen. As mentioned above, the model will perceive the laser beam as a surface heat source, so only the Heat Transfer module, node Heat Transfer in Solids will be used. The interface allows selecting the names of basic variables (in this case, temperature).

After that, the model research mode is selected. Since the laser beam moves along the object in a certain amount of time, you need to use the Time Dependent mode. Geometric parameters of the sample are also set.

After the calculations are completed, the program will automatically create the necessary basic drawings that show the calculated data. In this case, it is a surface temperature graph and an isothermal contour (Fig. 2). Both images are synchronized with the time of exposure, so you can see the temperature change on the surface, as well as the movement of the laser beam during the processing time.



a b

Fig. 2. Surface temperature (a) and isothermal contour graph (b) in 0.4 s after the treatment started

In order to find out the exact values of the parameters, as well as to build graphs based on them, you need to add the "Probe" function, which will read this data and add it to the tables. As can be seen from the temperature values, it is higher than the ablation temperature of organic glass. This means that in real-world conditions with these settings, the laser will perform glass engraving (Fig. 3).

Fig. 3. Acrylic glass engraving performed according to the specified modes

The depth of the engraving can also be determined by an isothermal graph.

Conclusions

1. The created model allowed us to test the possibilities of modeling surface treatment of a non-metallic substance with a laser beam.

2. COMSOL package allows us to develop the created model, for example, to add calculations of surface deformation as a result of material evaporation thanks to the Deformed Geometry mathematical interface, and also to create a full-fledged program with its own graphical interface thanks to the built-in Application Builder program editor.

3. Using the "Probe" function, we can determine the depth of the engraving line. Using the analytical functions, we can adjust the frequency of laser radiation.

4. This model makes it possible to adjust the parameters of laser processing of certain materials.

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Моделювання процесів лазерного оброблення матеріалів

Анотація. Проблема. *Складність явищ, що відбуваються під час лазерного впливу на матеріал, протягом тривалого часу уможливлювали переважно експериментальний вибір режимів оброблення. Аналіз теплових процесів, що мають місце в цьому разі, і використовувані програми вимагають глибоких знань фізичних явищ, а також широких можливостей обчислювальної техніки, тому вони стали недоступні багатьом дослідникам.* ***Метою дослідження*** *є моделювання взаємодії лазерного випромінювання з речовиною на прикладі акрилового скла за допомогою програмного комплексу COMSOL Multiphysics 5.5.* ***Методика.*** *Матеріалом для досліджень слугувало акрилове екструзійне скло за ГОСТ 17622-72 і ГОСТ 10667-99. Успішне лазерне оброблення потребує максимального поглинання випромінювання, тому для досліджень обрали* CO_2*-лазер з довжиною хвилі 10,6 мкм. Інші параметри лазерного оброблення (потужність 10 Вт, діаметр точки фокусування 1 мм, швидкість переміщення променя 40 мм/с) типові для установки StoLaser Standard 4030 Mini.* ***Результати.*** *Основним завданням у поданій роботі є моделювання взаємодії лазерного випромінювання з речовиною на прикладі акрилового скла за допомогою пакета програм COMSOL Multiphysics 5.5. У роботі досліджено особливості та характер взаємодії лазерного випромінювання з акриловим склом методом скінченних елементів, а також за допомогою програмного комплексу COMSOL, який працює за цим методом. Експериментально створено програму моделювання процесу взаємодії лазерного променя з матеріалом, у цьому разі неметалевим. Отримано графічний розподіл тепла на поверхні, а також ізотерму глибини розподілу тепла всередині матеріалу.* ***Наукова новизна.*** *У роботі за допомогою пакета COMSOL Multiphysics створено модель проходження лазерного випромінювання крізь блок діелектричного матеріалу. Доведено можливість моделювання лазерного оброблення матеріалів методом скінченних елементів.* ***Практичне значення****. Розроблена модель може бути використана у виборі режимів лазерного оброблення різних матеріалів.*
Ключові слова: *лазерний нагрів,* CO_2*-лазер, лазерне випромінювання, метод скінченних елементів, COMSOL Multiphysics, теплообмін у твердих тілах.*

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