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LASER RADIATION INTERACTION WITH SOLIDS

A short overview of basic problems connected with high power laser radiation interaction with solids is presented. Physical phenomena occurring during absorption of laser beam energy in solid, basic fields of application of lasers, and mathematical model of the conversion of light energy into heat are described. There are also many examples of numerically calculated temperature fields in solids caused by the interaction of laser radiation of different parameters (different power densities and interaction times), which are the results of investigation of the laser interaction with solids. These investigations have been conducted in the Institute of Heat Engineering for several years.

Nomenclature

a – thermal diffusivity
c_p – specific heat
C_m – latent heat (heat of melting)
I – intensity of absorbed radiation
q – heat flux
Q – power density of laser radiation
R – reflectivity
T – temperature
t – time
x, y, z – spatial coordinates
α – surface heat transfer coefficient
β – absorption coefficient
δ – thickness of slab
ε – emissivity
λ – thermal conductivity
ρ – mass density
σ – Stefan-Boltzmann constant
τ – time of interaction
τ_R – relaxation time

INTRODUCTION

The study of laser interaction with solids, including laser produced plasmas, is one of the fastest growing fields of present-day physics. It has brought numerous innovations in material treatment, such as quality changes, welding, cutting, drilling, and related to high-power beam weapons. The very important and exciting field of application of high power laser beams is the safe production of clean nuclear fusion energy.

Especially in the last decade, several research projects, costing hundreds million dollars, have been established in the main research centres in the world. The main goal of these projects is to develop high power lasers and investigate phenomena of laser radiation interaction with materials. In the Institute of Heat Engineering, Warsaw University of Technology, similar investigations, concerning laser interaction with solids, are being conducted for more than 15 years.

The main purpose of this paper is to present some problems connected with the application of high power laser in different fields of human activities.

In section 1 we present the latest achievements in development of very high power laser system. Then we describe the physical phenomena occurring during laser radiation interaction with solids. In the last part of the chapter we show some examples of fields of application of high power lasers.

Section 2 is devoted to the modelling of heat transfer phenomena connected to the interaction of laser beam energy with solids. Both analytical and numerical approaches to that problem are presented.

In section 3 we show some results of numerical simulation of heat transfer in a bulk during laser interaction. These are the results of the investigations conducted in the Institute of Heat Engineering. They refer to both the classical application of lasers (laser material processing) and the special conditions connected with the extremely short pulses (non-Fourier effects).

In the last section we summarise the problems associated with the description and applications of high powers laser interaction with solids.

1. HIGH POWER LASER INTERACTION WITH MATERIALS

1.1. Lasers for laser material processing and plasma generation

From the viewpoint of material processing and nuclear fusion (plasma generation) the main properties of lasers are power density and also time of duration (for pulse lasers).

Presently the most commonly used lasers for high-power application and research are:

- the neodymium laser (Nd:YAG or neodymium glass); its wavelength is 1.064 μm and duration can be from continuous operation (cw) to pulses of a length 170 fs (0.17 ps);
- carbon dioxide laser (CO_2); wavelength is 10.6 μm, possible cw and pulse operation.

In different fields of applications the following types of lasers are also used:
- Free Electron Lasers (FEL),
- hydrogen fluoride lasers (HF),
- photochemical iodine lasers,
- excimer lasers, e.g. KrF,
- X-Ray lasers.

The development of high power laser technology during the last decade is quite significant. This is due to very intensive research connected with laser nuclear fusion. Below we present some examples of laser systems of the highest power, which were developed for use in nuclear fusion experiments [1]:
- ANTARES system (CO_2 laser) – pulses duration is 100 ps, power is 100 TW (10^{14} W),
- NOVA lasers (Nd:YAG) – pulses duration is 100 ps, power is 125 TW,
- DELFIN system (Nd:YAG) – pulses duration is 0,1 ns with energy 50 J,
- PHEBUS – pulses of 1 ps, energy of 1 pulse of a row of 1 kJ (power is 10^{15} W),
- ISKRA-5 (photochemical iodine laser) – 35 kJ energy in pulses of a length 0,25 ns,
- hydrogen-fluoride (HF) lasers – 3 kJ energy in pulses of 30 ns duration,
- AURORA (KrF excimer lasers) – 1.3 kJ energy in pulses of 5 ns duration.

Lasers with such extreme powers and duration times allow to reach, after focusing in vacuum, the power intensities up to 10^{23} W/m^2. This is 20 orders of magnitude brighter than the sunlight power density at the earth. This also implies strange different approach to the analysis of thermophysical processes occurring during interaction of such energy fluxes with materials.

1.2. Physical phenomena accompanying laser interaction with solids

During the interaction of the laser with solids a variety of physical processes occur. These are heating, melting and vaporization. At sufficiently high power densities, the laser may interact with the plume, thereby creating the plasma. In this case plasma cloud shields the surface from the incoming laser light, and the process of interaction is much more complicated.

Mechanism of absorption of electromagnetic energy in solids mainly depends on the kind of material, i.e. metal or nonmetal. In metals absorption of electromagnetic field occurs by photon-electron interactions with free or bound electrons. These interactions raise the energy state of the electrons in the conduction band and the mechanism is the same as for classical thermal conduction. The excited electrons collide with lattice phonons and with other electrons or give back their radiation by spontaneous emission. Thermal equilibrium is established very quickly since the mean free time of electrons in conductor is 10^{-13} s [2]. The process of conversion of energy of electromagnetic field to heat is shown in Fig. 1.

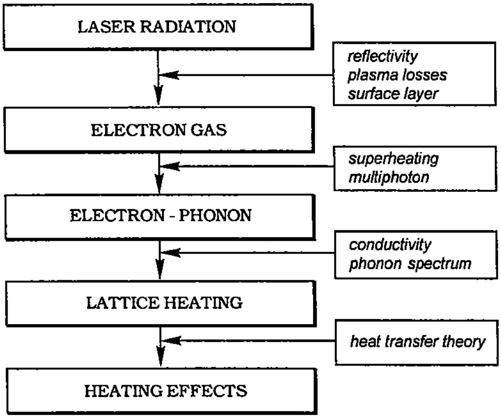

Fig. 1. Scheme of the conversion of laser (electromagnetic wave) energy into heat [10]

Dielectric materials are usually transparent for laser radiation, because the photon-phonon interaction can occur only when the energy of photon is equal to the excitation energy for phonon. Only for ultraviolet radiation (excimer lasers), where electron excitation can occur, absorption is much higher.

The absorbed power density, together with the pulse duration and reflectivity of the surface, determines the absorbed energy density. Energy absorption depends on a wide variety of physical and chemical properties of the target material, the main of them are thermal diffusivity, vapor pressure and optical absorbance. These properties govern the depths of penetration of the laser light and thermal front, and consequently of the maximum surface temperature and density of the vapor just above the surface. The reflectivity of a surface is a function of the material, nature of surface, the level of oxidation, temperature, wavelength and power density of incident radiation. Reflectivity falls dramatically with the increase of the incident power density, time of exposure and temperature.

At low power densities, the interaction has essentially thermal character in the sense that the material is heated, melted and even removal rate of material

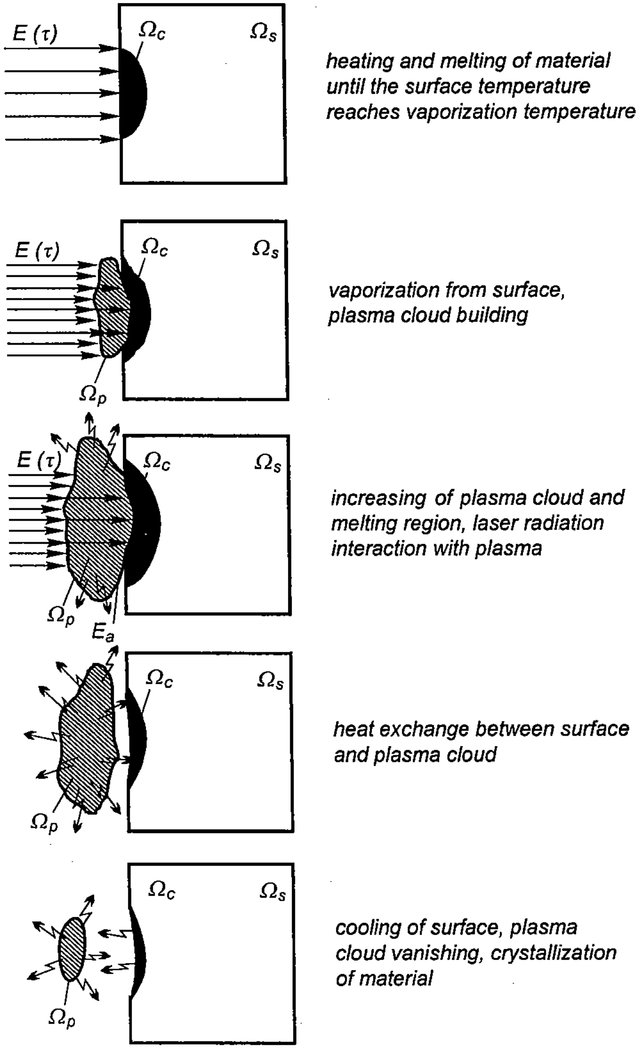

Fig. 2. Basic effects caused by high power laser [10]

follows the vapor pressure. For higher power densities delivered in pulse times on the order of tens of nanoseconds (typical of excimer lasers) a variety of other, nonequilibrium, mechanisms assume greater importance than thermally driven emission. These are generally of the „explosive" type involving emission of large masses of material rather than individual molecules. One of these mechanisms to be proposed is as follows. Rapid, initially thermally-driven vaporization creates a back pressure on the surface. This pressure can contain the hot liquid surface and prevent farther vaporization, producing superheating liquid. As the pulse ends, the vapor escapes and rapid nucleation of vapor bubbles in the superheated liquid leads to explosive release in the form of ejected droplets [3].

Successive phases of the interaction of laser beam with solid are shown in Fig. 2.

1.3. Fields of application of high power lasers

Laser as a source of electromagnetic radiation, possessing an extremely high power density, is a very useful tool in a wide range of human activities. Other characteristics of laser radiation, such as monochromacity and coherence allow better collimation and focusability to the laser beam, thus making more effective its manipulation by optics and its concentration in a very small focusing spot, where the power density can reach extremely high values, up to 10^{23} W/m^2 [1]. In other words, laser provides a localized, mainly surface heat source, which allows to heat the surface to very high (4000÷5000 K), but controllable temperatures.

Presently, high power lasers are in common use in the filed of material processing. This includes surface processing, cutting, drilling and welding [6, 7]. For melting or annealing lasers (both pulsed and cw) with power densities from $10^7 \div 10^8$ W/m^2 are used. Welding require lasers of higher power – about 10^{10} W/m^2. And for cutting power density of focused laser beam should be about 10^{12} W/m^2 (especially for cutting with vaporization, which is necessary for not melted materials, such as wood, graphite).

In cutting, to reduce needed power density, different phenomena, other than vaporization, are used. These are:

- melting and blowing,
- explosive ejection of material (ablation),
- burning in reactive gas,
- thermal stress cracking or controlled fracturing.

For pulse laser interaction both heat affected zone is very small, and cooling rate is high. This allows to use pulse lasers in surface treatment, e.g. surface hardening.

Pulsed laser vaporization is a promising method for producing thin films of refractory materials (for use in integrated circuits) and high-T_c superconducting ceramics. In these applications targets of bulk material are vaporized in vacuum and deposited as films on suitable substrates [3].

Pulsed laser heating provides a useful method for studying the kinetic and thermodynamic aspects of vaporization process that cannot be achieved using standard heat sources. For example:

- to simulate high temperature (3000°C) in nuclear reactor core during a severe accident,
- to simulate rapid energy deposition on plasma facing components (constructed of refractories such as graphite, silicon carbide, tungsten) which is a result of disruption of thermonuclear plasma in tokamak-type fusion reactors,
- to simulate heating and vaporization of heat shields (fabricated of graphite components) which are used in space vehicles as a heat insulation.

2. MODELLING OF LASER INTERACTION WITH SOLIDS

Laser interaction with solids, in specific cases such as welding or cutting, is a multiparameter problem. The principal variables are the substrate thermophysical properties, the total energy input, power distribution and diameter. Therefore, the experimental investigations of such problems are very difficult and expensive. Alternatively, mathematical modelling can be used instead of experimental investigations. In addition, it allows to estimate some unmeasurable parameters.

Taking into consideration the model of absorption of light by metals (section 1), a heat source in a thin surface layer occurs during the interaction of a laser beam. The spatial distribution of this source can be estimated on the basis of Bouguer law, which describes the changes of the intensity of a beam in solid

$$I(z) = I_0 \exp(-\beta z) \tag{1}$$

For metals absorption coefficient β is $10^7 \div 10^8$ m^{-1}, and the thickness of the layer in which almost the whole energy of light is converted into heat is of the row of 10^{-7} m. As it was proved in [4], it is necessary to consider volumetric heat source only for very short pulses, i.e. shorter than $10^{-7} \div 10^{-8}$ s. When interaction of laser of a duration longer than $10^{-7} \div 10^{-8}$ s is considered, boundary condition based on the surface absorption can be used do describe the absorption of laser energy

$$Q(1 - R(T)) = -\lambda \operatorname{grad} T \tag{2}$$

Similar problem occurs for the case of description heat transfer in the irradiated body. For nanosecond and longer interactions, a Fourier heat conduction equation of the form

$$\rho \frac{\partial (c_p T)}{\partial t} = \operatorname{div}(\lambda \operatorname{grad} T) \tag{3}$$

gives good enough results. But presently there are many fields of application, where picosecond and shorter laser pulses are used. In these cases the time of interaction is of the row of relaxation time, i.e. time of energy conversion between electrons and phonons. Due to a very short interaction time, and very high gradients of temperature, Fourier law is not valid in these circumstances. This is because Fourier equation has a parabolic form, which implies a paradox of infinite speed of propagation of heat pulses. To avoid this disadvantage, some different models of heat conduction are proposed [8]. Heat transfer equation of a hyperbolic type is one of the most often used. It has a form

$$\frac{\partial^2 T}{\partial t^2} + \frac{1}{\tau_R}\frac{\partial T}{\partial t} = c^2 \nabla^2 T \tag{4}$$

Where c is a speed of heat propagation, $c^2 = a/\tau_R$. Equation (4) is based on the following equation for the heat flow q, proposed by Cattaneo and Vernotte

$$\tau_R \frac{\partial q}{\partial t} + q = -\lambda \nabla T \tag{5}$$

As during high power laser interaction change of phase occurs (melting, vaporization), it is necessary to take into account energy balance on a moving interface. This is a Stefan condition, which for the case of melting has the following form

$$\lambda_l(\boldsymbol{n}\,\mathrm{grad}\,T)|_l - \lambda_s(\boldsymbol{n}\,\mathrm{grad}\,T)|_s = \rho C_m \boldsymbol{v}\boldsymbol{n} \tag{6}$$

Boundary and initial conditions complete the mathematical model of heat transfer in solids during laser interaction. For relatively long pulses (microsecond and longer) and continuous action the surface boundary condition is given by energy balance

$$q(1-R) = -\lambda\left(\frac{\partial T}{\partial z}\right)_s + \alpha\left(T_s - T_\infty\right) + \varepsilon\,\sigma\left(T_s^4 - T_\infty^4\right) \tag{7}$$

Presented model is not valid for the case, when intensive vaporization occurs. Then a cloud of plasma is created, and conversion of laser radiation energy with solid is much more complicated. Apart from that fact, as absorbtivity and thermal properties of materials are strongly dependent upon temperature, the thermodynamic problem of laser heating is nonlinear. It is very difficult to find close form of the solution of this problem, therefore analysis of specific heat transfer problems are simplified to suit the particular process (e.g. welding, hardening and so on).

A large number of investigations have been made with the object of obtaining data for heat transfer during laser interaction with solids. There is a range of numerical and analytical methods which have been developed for calculating the thermal history associated with laser interaction.

Analysis of heat transfer problems during laser interaction, particularly when analytical methods are used, is associated with the necessity of introducing some simplifying assumptions. Additional conditions to the mathematical model, which are the most often used, are summarized in [5]. There are:

- constant thermophysical properties of target material,
- one dimensional heat transfer,
- point or line heat source for multidimensional heat flow,
- uniform distribution of energy radiation in the laser beam,
- heat losses from the surface not considered,
- surface absorption for very short pulses,
- heat of fusion (for melting and vaporization) not considered,
- absorption of laser radiation by plasma cloud, and heat transfer between plasma cloud and surface not considered.

Analytical solutions of such simplified models do not give the most accurate results, but they can be used for qualitative analysis of thermal changes occurring during laser interaction. For quantitative analysis numerical techniques are much more precise. In the next chapter we present some chosen results of numerical simulation of laser interaction with solids of different type.

3. LASER PROCESSING – NUMERICAL SIMULATION OF HEAT TRANSFER PROBLEMS

Mathematical model, presented in the previous section, can be solved numerically by standard methods (e.g. elementary energy balances method with a finite difference numerical discretization and explicit temporal discretization scheme). In our investigation of the problem of heat transfer during laser interaction with solids, we prepared some computer programs for simulation of different types of interaction, i.e. with reference to different fields of application of high power laser radiation.

We solved either two-dimensional (for axial symmetry problems) or three-dimensional (in general) heat conduction problems. Different absorption models (surface or volumetric) were also considered. In each case temperature dependent thermal properties, and change of phase processes were taken into consideration. In addition we solve hyperbolic heat conduction equation with different boundary conditions to show possible non-Fourier effects, which can occur during short laser pulse interaction with solids.

In these programs the principal output is the time variation of the temperature field in the body, although the location of interface surface (melting front) and temperature gradients can be extracted.

3.1. Laser beam interaction with metals

Simulation of temperature fields in metals during laser beam interaction is very important from the viewpoint of laser material processing. In our work we calculate temperature distribution, melted zone and temperature gradients for the case of millisecond laser pulse interaction [9]. Different metals (of different thermal properties), and pulses of different shapes were investigated. In Fig. 3 distance between melting front and surface during laser interaction for selected materials is presented. Dashed line shows the shape of laser pulse under consideration. Fig. 4 shows temperature gradients (dT/dx, [K/m]) near surface during laser pulse interaction.

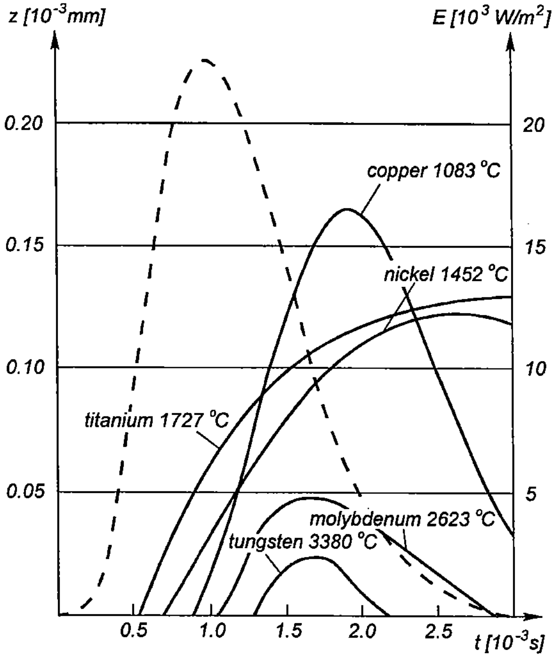

Fig. 3. Position of melting front on an axis of laser beam during laser pulse interaction; dashed line depicts the temporal shape of laser pulse, Gaussian power distribution in the cross section of beam is considered

As a result of this investigation a strong dependency of thermal diffusivity on temperature time history was observed. For the same laser pulse heating process (i.e. temperature distribution, heat affected zone, size of melted region) in different materials has a substantially different character. The shape of laser pulse is also a very important parameter, which should be taken into consideration in laser material processing [5].

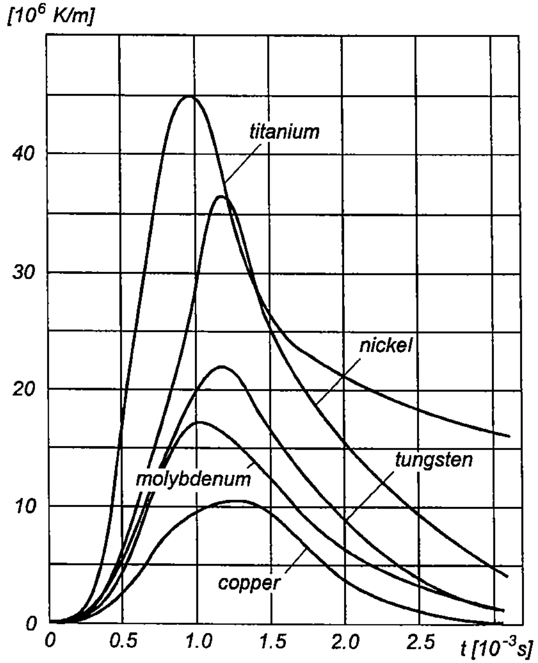

Fig. 4. Gradients of temperature near surface during laser pulse interaction; the same laser pulse as shown in Fig. 3

3.2. Laser beam interaction with multilayer structures

In some fields of laser applications, such as microelectronics, laser lithography, it is very important to know the effects of high power flux interaction with thin (thickness of microns) films. In our work we consider the laser interaction with thin metallic layers deposited on non-metal material [10]. For these cases, additional boundary condition for the interface between layers is needed in mathematical model. Because both very thin layers and very short pulses (nanosecond duration) were considered, a model of volumetric absorption of laser energy was used.

In the following Figures we present selected results of calculated temperature fields in multilayer structures. Here temperature distribution and melted regions in a structure consisting of copper and tungsten layers deposited on quartz (SiO_2) are shown. As it is visible, some complex processes can occur in such interaction, e.g. melting of internal copper layer (Fig. 5). Effects of this kind can lead to the destruction of such complex structures. Figure 6 shows the temperature distribution in various multilayer structures.

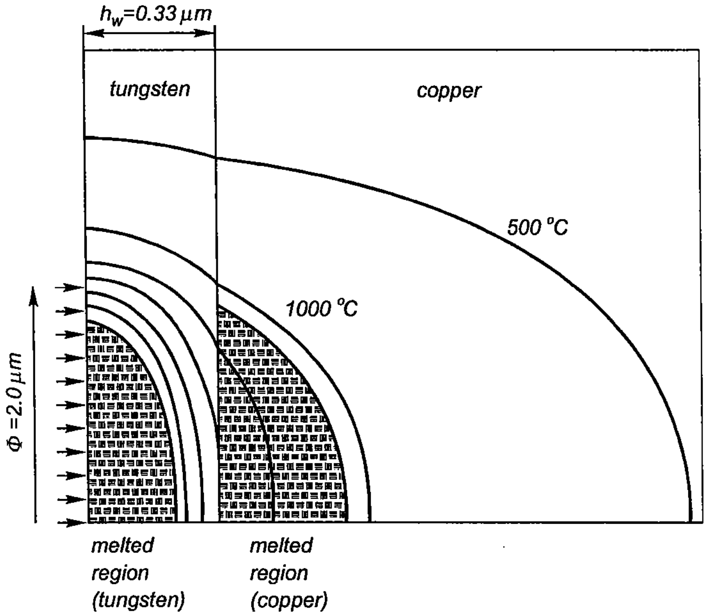

Fig. 5. Temperature distribution in a complex structure (copper and tungsten layers deposited on SiO_2) at the end of laser pulse interaction; pulse duration is 35 ns, its maximum power density is $0.96 \cdot 10^{12}$ W/m^2; isolines from 500 to 3000°C, step 500°C

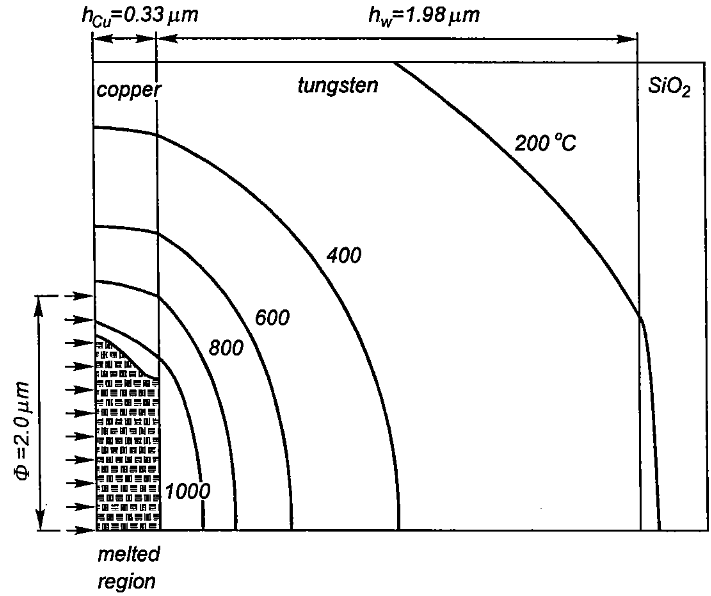

Fig. 6. Temperature distribution in a complex structure (tungsten and copper layers deposited on SiO_2) at the end of laser pulse interaction; pulse duration is 35 ns, its maximum power density is $0.48 \cdot 10^{12}$ W/m^2

3.3. Non-Fourier effects during short laser pulse interaction with solids

In many works hyperbolic heat transfer equation (4) is considered as a mathematical model of some real processes, including interaction of short laser pulses [8, 12, 13]. In our investigations we analysed the thermophysical processes which occur when wave equation is used to solve heat conduction problem.

The wave character of heat propagation is visible especially when heat conduction in both thin films and multilayer structures of thin films of different materials is taken into consideration. In [12] a lot of results of temperature calculation in such structures, consisting of copper and graphite layers, are presented. Here we show, as an example, some selected results.

In Fig. 7 temperature profiles inside a copper layer subjected to a step change of temperature of both sides are presented. In this special boundary

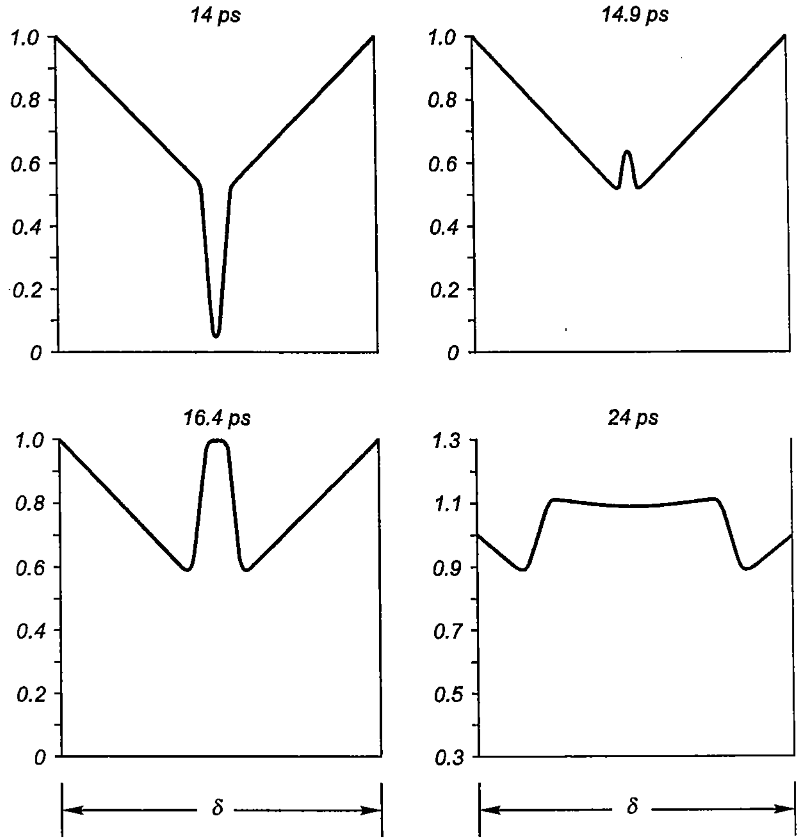

Fig. 7. The temperature distribution in a copper layer of thickness $1.0 \cdot 10^{-7}$ m subjected to a step change of temperature on both sides

condition, due to wave character of heat propagation, temperature inside a layer can exceed its both boundary and initial values – in the Figure it is visible for time $t > 16$ ps. This is a result of reinforcement from two waves travelling from both sides of a layer.

According to the constitutive equation (5) heat flux, as a solution of hyperbolic equation, may be considered as a sum of two components [12]:

– Fourier's component

$$q_\lambda = -\lambda \operatorname{grad} T \tag{8}$$

– relaxation component

$$q_\tau = -\tau_R \frac{dq}{dt} \tag{9}$$

In Fig. 8 these heat flux components distribution near the front of moving thermal front is presented. This is a solution of hyperbolic equation with the following boundary conditions: constant temperature on a left surface (400 K), no heat exchange with environment on the right surface for time $t > 0$. Initial temperature of a slab is 300 K.

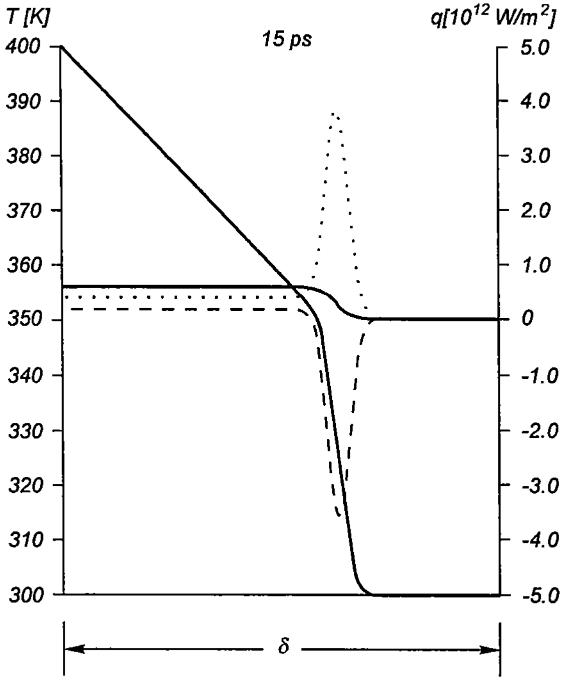

Fig. 8. The calculated temperature and heat fluxes distribution in copper flat plate; thick solid line – temperature, solid line – total heat flux, dashed line – relaxation part of heat flux, dotted line – Fourier's flux

3.4. Computer simulation of laser material processing

The three dimensional quasi-steady state heat transfer model for laser material processing with a moving heat source was developed [14]. In order to develop the model, the process is physically defined as follows: a laser beam, having a defined power distribution, strikes the surface of a plate of infinite length, but finite width and thickness moving with a uniform velocity in the x-direction (Fig. 9). The incident radiation is partly absorbed according to the value of reflectivity. Some of the absorbed energy is lost by radiation from the surface and by convection from both upper and lower surfaces. The rest energy is conducted into the plate. In addition, the model allows temperature-dependent thermophysical properties of material.

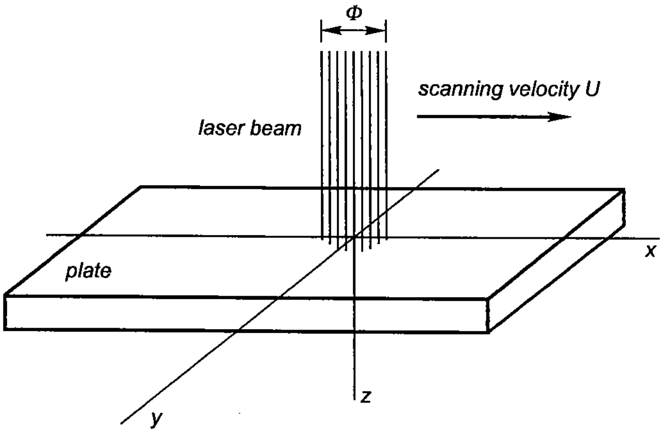

Fig. 9. A flat plate subjected to a moving heat source

This model can be used for the following purposes:

- to predict the temperature profile,
- to predict maximum speed of laser processing (e.g. welding),
- to predict the melted zone or heat affected zone (for the case of heat treatment),
- to predict the effect of geometry dimensions of the plate (e.g. thickness) and other parameters (reflectivity).

Fig. 10 shows an example of the results of numerical simulation of laser material processing. The results, in graphic form, consist of two parts: on the upper part the temperature distribution inside solid in x-y cross-section, the temperature on the surface along x-axis and the main parameters of the laser surface processing are presented. On the lower part the 2-D surface temperature and temperature distribution on the surface (isolines) are presented. The melted region is marked by dotted field.

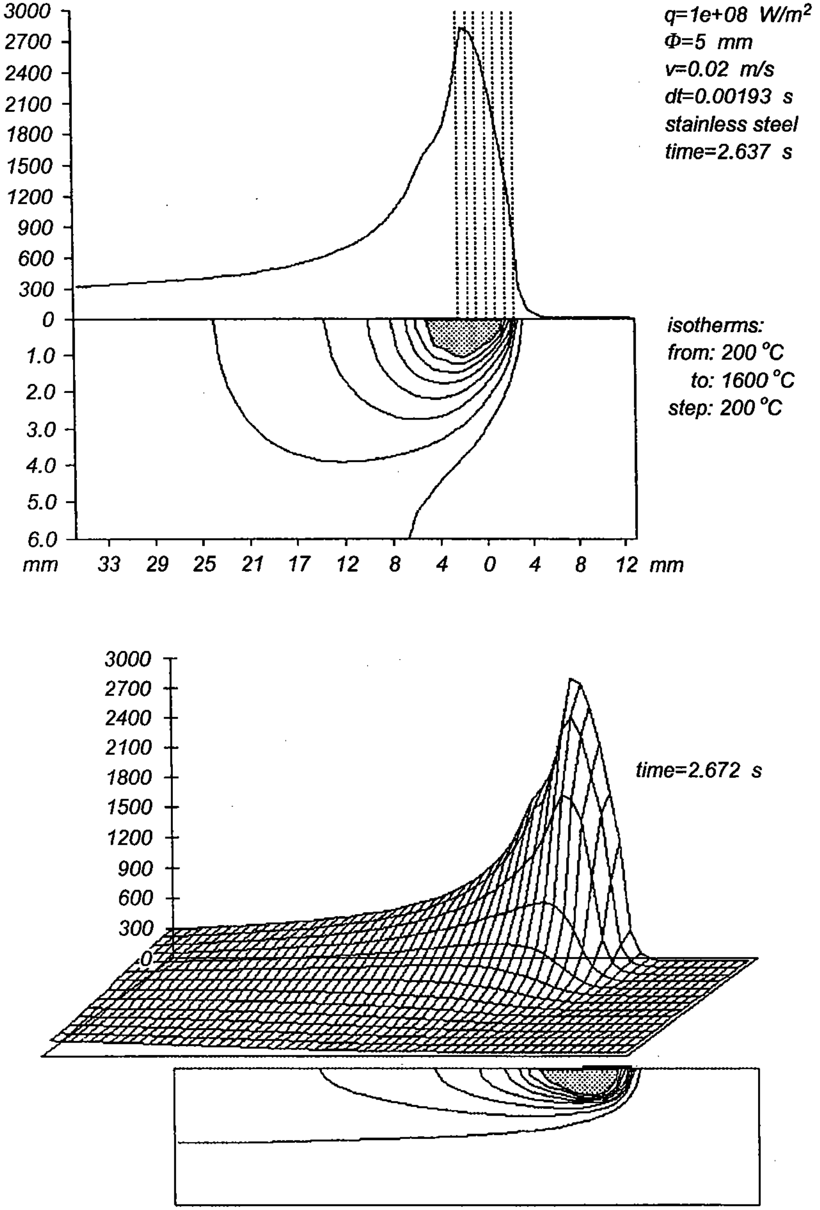

Fig. 10. Temperature distribution in stainless steel plate during laser beam interaction with velocity 0.02 m/s

CONCLUSIONS

Lasers offer the broad processing advantages: localization of thermal treatment in three dimensions, and thus, freedom form wafer degradation due to homogenous, lengthy, high temperature processing. Lasers allow processing to be carried out in either the solid or the liquid phases by choice of the laser power, wavelength, time scale and geometry and the material properties, geometry and starting temperature. The most exciting prospects for lasers, as a new tool in technology, are the unique materials and structure and the ways of fabricating, e.g. thin films deposition, elimination of extended defects, the growth of single crystals.

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ODDZIAŁYWANIE PROMIENIOWANIA LASEROWEGO NA CIAŁA STAŁE

Streszczenie

W pracy przedstawiono podstawowe problemy związane z oddziaływaniem energii promieniowania laserowego o dużej mocy na powierzchnię ciał stałych. Omówiono zjawiska fizyczne występujące w czasie absorpcji energii promieniowania laserowego. Podano dziedziny zastosowań laserów dużej mocy oraz przedstawiono model matematyczny procesów wymiany ciepła w ciałach stałych w czasie oddziaływania wiązki promieniowania laserowego. Praca zawiera przykłady numerycznego określania pola temperatury dla przypadków oddziaływania promieniowania laserowego na powierzchnię metali i struktur wielowarstwowych, wyniki symulacji numerycznej procesów obróbki laserowej, jak również wyniki obliczeń pól temperatury przy uwzględnieniu modelu falowego przewodzenia ciepła. Przedstawiane rezultaty są wynikiem badań prowadzonych w Instytucie Techniki Cieplnej w okresie ostatnich kilkunastu lat.

ВОЗДЕЙСТВИЕ ЛАЗЕРНОГО ИЗЛУЧЕНИЯ НА ТВЕРДЫЕ ТЕЛА

Краткое содержание

В работе обсуждены основные вопросы, связанные с воздействием лазерного излучения на твердые тела. Представлены физические явления, выступающие при поглощении энергии лазерного излучения, и возможности практического использования лазеров большой мощности, а также подана математическая модель процессов теплообмена в твердых телах при воздействии лазерного излучения.

Во второй части показаны результаты численного определения полей температуры в металлах, в тонких металлических пленках на неметаллической основе, а также результаты численного моделирования процессов лазерной обработки материалов. Представлены также результаты расчетов температурного поля, учитывая волновую модель теплопроводности.