ALGORITHM FOR CALCULATION OF THE POWER DENSITY DISTRIBUTION OF THE LASER BEAM TO CREATE A DESIRED THERMAL EFFECT ON TECHNOLOGICAL OBJECTS

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Abstract

Based on the use of methods for solving the inverse problem of heat conduction, we developed an algorithm for calculating the power density distribution of the laser beam to create a desired thermal effect on technological objects. It was shown that the redistribution of power density of moving distributed surface heat sources can adjust the temperature distribution in the treated zone. The results of thermal processes calculation show the ability of the developed algorithm to create a more uniform temperature field across the width of the heat affected zone. Equalization of maximum temperature values is achieved in the center and on the periphery of the heat affected zone with an increase in the width of the regions, where required temperature is reached. The application of diffractive optical elements gives an opportunity to obtain the required properties of treated materials in the heat affected zone. The research performed has enabled parameters of the temperature field in chrome-nickel-molybdenum steel to be adjusted for laser heat treatment. In addition to achieving uniform temperature conditions across the width of the heat affected zone, the proposed approach allows the increase of the width of the isotherms of the temperature fields; this provides an opportunity to process a larger area per unit time at the same laser beam power.

Keywords: laser beam, power density distribution, formation, moving heat source, material, thermal effect.

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Introduction

Laser beam machining is a progressive process for improving of parts properties and service characteristics. The feasibility and advantages of the use of lasers in material processing process steps are determined by the possibility of non-contact, strictly dosed intensive supply of energy to the product surface. Laser technologies are used to process remote and local areas of parts in the absence of vibrations and other negative effects on the material. These and other significant advantages leads to greater potential of using laser processing of the present time as well as in the future.

Achievements in the study of the physical characteristics of laser beam processing are reflected in numerous papers and monographs [1 – 3], and experience in the application of laser equipment in the production of various products technologies, which were described in detail in reference books [4 – 6]. For technological lasers used for the material processing the following is true. At the treatment of materials by laser irradiation is absorbed portion of the incident energy that leads to formation the heat source on the surface or in volume of the object, the energy and space-time characteristics of which are determined by the parameters of laser beam. The heat from the source is distributed in the volume of the object, causing it heating. Numerous published experimental results show that the most important factor, that make influence on the formation of the physical and mechanical properties of materials and performance of products under laser irradiation, is a temperature in the treatment zone. However, virtually there are no information and recommendations for the implementation of an existing capacity control of energy spatial distribution input into the processed material. Mismatch in distribution of the heat flow on the surface of thin-walled parts leads to the formation of various defects, such as burnout, coarse-grained structure, local melting and warpage of blanks due to uneven heat across the width of the heat affected zone, this occurs already in the processing stage. For large volume parts the following defects are typical: uneven distribution of mechanical properties across the width of the heat affected zone; uneven working depth; local melting; increased brittleness of the product due to overheating of the central and insufficient hardness due to underheating in the peripheral regions of the heat affected zone. However, to prevent these defects, efficiently processed materials are commonly used, instead of those that better fulfill required material properties after laser beam treatment.

Different laser optical systems are used to laser beam shaping [6 – 8], but none of them can provide a simultaneous combination of properties such as the creation of a desired distribution of laser power density, concentration of the laser beam power within a treatment zone having a specific shape and high reliability. Diffractive optical elements (DOEs) can be used to create the required distribution of laser radiation intensity [9 – 12]. In this case, it is appropriate to use new approaches that can take into account the specifics of creating a predetermined specific heat flow through surface of object.

The study of thermal processes allows to identify common relations and the main areas for improvement of technological processes of material processing with concentrated energy flows. It is known that lasers' effects on opaque materials in a wide range of flow densities, up to $10^{13}\ \mathrm{W/m^2}$, is satisfactorily described by the thermal model [13–15]. The required material properties under laser irradiation are achieved by a corresponding change of the thermal state. The nature of thermal processes is determined by the thermophysical characteristics of processed materials (e.g., thermal conductivity, specific heat capacity, surface heat transfer coefficient), absorption state of their surfaces, laser-beam parameters (e.g., laser power density, cross-sectional laser intensity distribution, geometrical parameters), and laser beam irradiation time [16, 17]. However, in the above Refs. a calculation of the power density distribution of the laser beam to create a desired thermal effect on technological objects was not performed. It is appropriate to use new approaches that can take into account the specifics of creating a predetermined temperature field in technological objects for the development of laser materials processing technology. The most effective processing modes are determined only when the inverse heat conduction problem solved. That provides opportunity by given values of temperatures in the object to determine the specific heat flow through this surface. Prerequisites for the use of this approach have been formulated in [18]. But the iterative algorithm for calculating the power density was not designed.

The objective of this paper is to develop the algorithm for calculation of the power density distribution of the laser beam to create a desired thermal effect on technological objects and determine advisability of laser beam shaping by DOE for laser treatment with creating the required set of properties of metallic materials in a heat affected zone.

Power density distribution of the laser beam to create a desired thermal effect on technological objects

The boundary conditions of the second kind of the heat equation includes power density distribution of applied heat flow. The problem of determination this distribution is not always well-posed, because its solution is not always uniquely and stable. There is known algorithm [19] for ill-posed problems, based on the narrowing the range of possible solutions by the use of additional assumptions regarding the unknown function. This process is known as regularization. The most common way to solve such problems is to iterative method described in detail in [19], its principle is in solving of the direct problems with iterations at each step. The condition for the end of the iterations is in coincidence with the required accuracy and the obtained in the temperature fields *k*- iteration of defined discrete temperature values at the points of the object. The condition of constancy in time of the heat flow is satisfied by well-posed formulation of the source determination inverse problem of heat conduction, because after a certain time the temperature field at interior points of the object is regularizing [19, 20]. As an additional condition the temperature data are given at chosen points of the domain.

Numerical integration of the heat equation is implemented taking into account the temperature dependences of the thermophysical characteristics of processed material and the absorption coefficient of the surface, which are defined in the form of tabulated values or appropriate functions at certain temperatures [21, 22]. The nonlinear heat conduction problem is considered for the calculation of the heating process of a metallic material by a moving rectangular-shaped heat source. The calculation is made for the technological object moved with a constant angular velocity ω in the positive direction of $O\varphi$ axis, respectively, in the coordinate system (ρ, φ, z) placed in centre of the heat source with the power value Q. The length of the heat source is set perpendicularly to the path of the laser spot on the surface of the processed material. Fig. 1 shows the geometric representation of the computational domain.

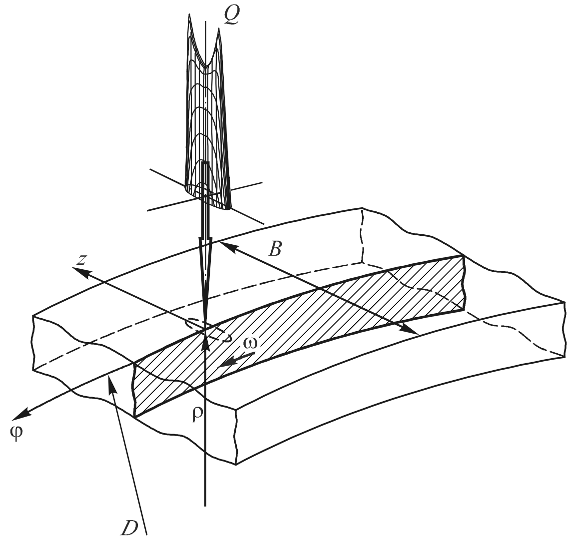

Fig. 1. The geometric representation of the computational domain: B, D – width and diameter of the researched object, respectively

The assumption is made that the heat source, with specified geometry and spatial intensity distribution, represents the surface source and take an area φ on the technological object. In the rest of the surface, nonlinear conditions of heat exchange with the surrounding environment are defined. The distribution of power density is defined by the equation for the rectangular-shaped heat source that provides an opportunity to ensure the conditions of solution uniqueness. Below, $q(\varphi, z)$ is presented in the form of the equation:

$$\begin{aligned} q(\varphi,z) = {} & q_0 (a_{n_1}\bar{z}^{2n} + a_{n_1-1}\bar{z}^{2(n-1)} + \ldots \\ & \ldots + a_2\bar{z}^{4} + a_1\bar{z}^{2} + a_0)\cdot \\ & \cdot(b_{n_2}\bar{\varphi}^{2m} + b_{n_2-1}\bar{\varphi}^{2(m-1)} + \ldots \\ & \ldots + b_2\bar{\varphi}^{4} + b_1\bar{\varphi}^{2} + b_0)\ \nu(\varphi,z), \end{aligned} \quad (1)$$

where q_0 – the intensity of the laser beam in the centre of the focal spot; $\bar{z} = z/(10^{-3}\,\mathrm{m})$; $\bar{\varphi} = D\sin\varphi/(2\cdot 10^{-3}\,\mathrm{m})$ – in dimensionless coordinates; $a_{n_1}, a_{n_1-1}, \ldots, a_2, a_1, a_0$; $b_{n_1}, b_{n_1-1}, \ldots, b_2, b_1, b_0$ – are coefficients of polynomials where n and m are integers; $\nu(\varphi, z)$ – additional function.

The set of temperature values at the points of object is determined in accordance with the required change in its thermal condition. At the first step it is advisable to calculate the distribution of laser power density, which provides the desired maximum temperature of thermal cycles of the object points at a given depth by the width of the heat affected zone.

Structural transformations caused by laser action are determined not only by the maximum temperature, but also by composition of heating, holding at a certain temperature and cooling [4–6], i.e. by thermal cycle. Therefore, based on identified temperature field changes on the surface and within material volume it is important to define the conditions to achieve favorable thermal cycles to produce the desired properties of impact object. The correction of spatial-temporal characteristics of laser action is also needed in order to ensure the required temperature modes.

Calculation of distribution of laser power density to formation a desired thermal effect on technological objects, is conducted in the following order:

1. Maximum advisable temperature $T_{\max}$ at the object surface setting, corresponding to the projected technological process. Enter the initial value of distribution of laser power density $q(\varphi, z) = q(\varphi, z)_1$.

2. Determine the value of the heat source angular velocity ω, at which the maximum surface temperature of the technological object does not exceed $T_{\max}$: $\max T_\varphi|_{\rho=D/2} \le T_{\max}$.

3. Initiate the values of the required maximum temperature at a given depth h of technological object across the width of the heat affected zone: $\max T_\varphi|_h$.

4. Execute the calculation of maximum temperatures values $\max T_\varphi|_h$ at a given depth h of technological object across the width of the heat affected zone for the entered value of distribution of laser power density $q(\varphi, z)_1$.

5. Determine the relative mean deviation RMD% of the required temperature:

$$RMD\% = \frac{\sum_i \left| T\max_\varphi|_h - \max T_\varphi|_h \right|}{n \cdot \max T_\varphi|_h} \cdot 100\,, \qquad (2)$$

where n – is the number of object points in which the discrete values of the temperature $\max T_\varphi|_h$ are set.

6. Compare the relative mean deviation RMD% with a predetermined allowable value ε.

7. Correction of distribution of laser power density, processed on the surface of technological object $q(\varphi, z) = q(\varphi, z)_k$, where k – is a number of iteration. Choose the $q(\varphi, z)$ values which corresponds to condition $RMD\% \le \varepsilon$. Further correction of spatial-temporal characteristics of laser action (distribution of laser power density $q(\varphi, z)$, as well as the angular velocity ω of heat source υ), with taking into account the conditions to achieve favorable thermal cycles to obtain the desired properties of material of the technological object. In moving coordinate system, heating and cooling rates are determined by the equation:

$$\upsilon_{heat}; \upsilon_{cold} = \omega[T(\rho, \varphi + \Delta\varphi, z) - T(\rho, \varphi, z)] / \Delta\varphi\,, \qquad (3)$$

where – $\Delta\rho, \Delta\phi, \Delta z$ – is spatial discretization interval.

A flowchart for calculating the power density distribution of the laser beam $q(\varphi, z)$ to formation a desired thermal effect on technological object is shown in Fig. 2.

As a result of calculation, the distribution of laser power density $q(\varphi, z)$ for the formation of the desired thermal effects on technological object of chrome-nickel-molybdenum steel was defined. The calculation of maximum temperatures values across the width of the heat affected zone of the cylindrical technological object with a diameter $D = 80$ mm was performed. The rectangular-shaped heat source with power $Q = 900$ W moved with a constant angular velocity $\omega = 0.25$ rad/s on the object surface. The calculation results obtained by finite element method have adequate compliance with the results received at using the control volume method [23].

During applying of heat source $k = 10$ the equality of maximum temperature values could be almost accomplished at the center of the heat affected zone and in case of $z = \pm 2$ mm; ± 4 mm:

$$T\max_\varphi (z = 0;\ \pm 2 \text{ mm};\ \pm 4 \text{ mm})|_h = 1050 \pm 12K$$

Moreover, in comparison with the applied of heat source $k = 1$, there is 1.17 times decrease of $T\max_\phi(z = 0)|_h$, and 1.31 times increase of $T\max_\varphi(z = \pm 4 \text{ mm})|_h$.

The isotherm width $T = 1100$ K is increased by 1.31 times and has the value $b_{T=1100K} = 9.83 \cdot 10^{-3}$ m. The maximum rate of heating of technological object points at the depth of $h = 0.75 \cdot 10^{-3}$ is $\upsilon_{heat} \approx 7 \cdot 10^3$ K/s. The cooling rate in the range of temperature values from $T = 1100$ K to $T = 940$ K is $\upsilon_{cold} \approx 10^3$–$2 \cdot 10^3$ K/s.

The results of experimental studies

The experimental research of processes was conducted during action on the metallic material of the laser beam what transformed by using a DOE. Chromium-nickel-molybdenum 40HNMA steel was chosen as sample material. It is widely used in engine manufacturing for crank shafts, propeller shafts, connecting rods and other massive parts with working temperatures of up to 770 K. The chemical composition of this material is shown in Table 1.

Table 1. Chemical composition of steel 40HNMA, wt %

C	Si	Mn	P
0.36… 0.44	0.14… 0.17	0.5… 0.8	≤0.035
S	Cr	Ni	Mo
≤0.003	0.6… 0.9	1.25…1.75	0.15…0.25

Laser irradiation of the samples was performed by a continuous wave mode Hebar-1A CO_2 laser that emits a Gaussian beam with a maximum output power of 1000 W. An absorbing methylcellulose and sodium silicate-based coating, MCS-510, was used. The laser optical system was modified for this research. In this system, the beam focusing mirror was a DOE [24–27]. This DOE have the form of a reflecting plate with micro-relief surface. Micro-relief surface is defined by the desired shape of the treatment zone, required distribution of laser beam intensity and wavelength of the laser radiation. It ensured the turn of the laser beam and distribution of its intensity within the treatment zone. The laser beam was focused to an approximately rectangular laser spot, the power density distribution of the laser beam was corresponded to $k = 10$. A modified KELVIN 1300 infrared pyrometer was used to take the measurements of heat affected zone surface temperature.

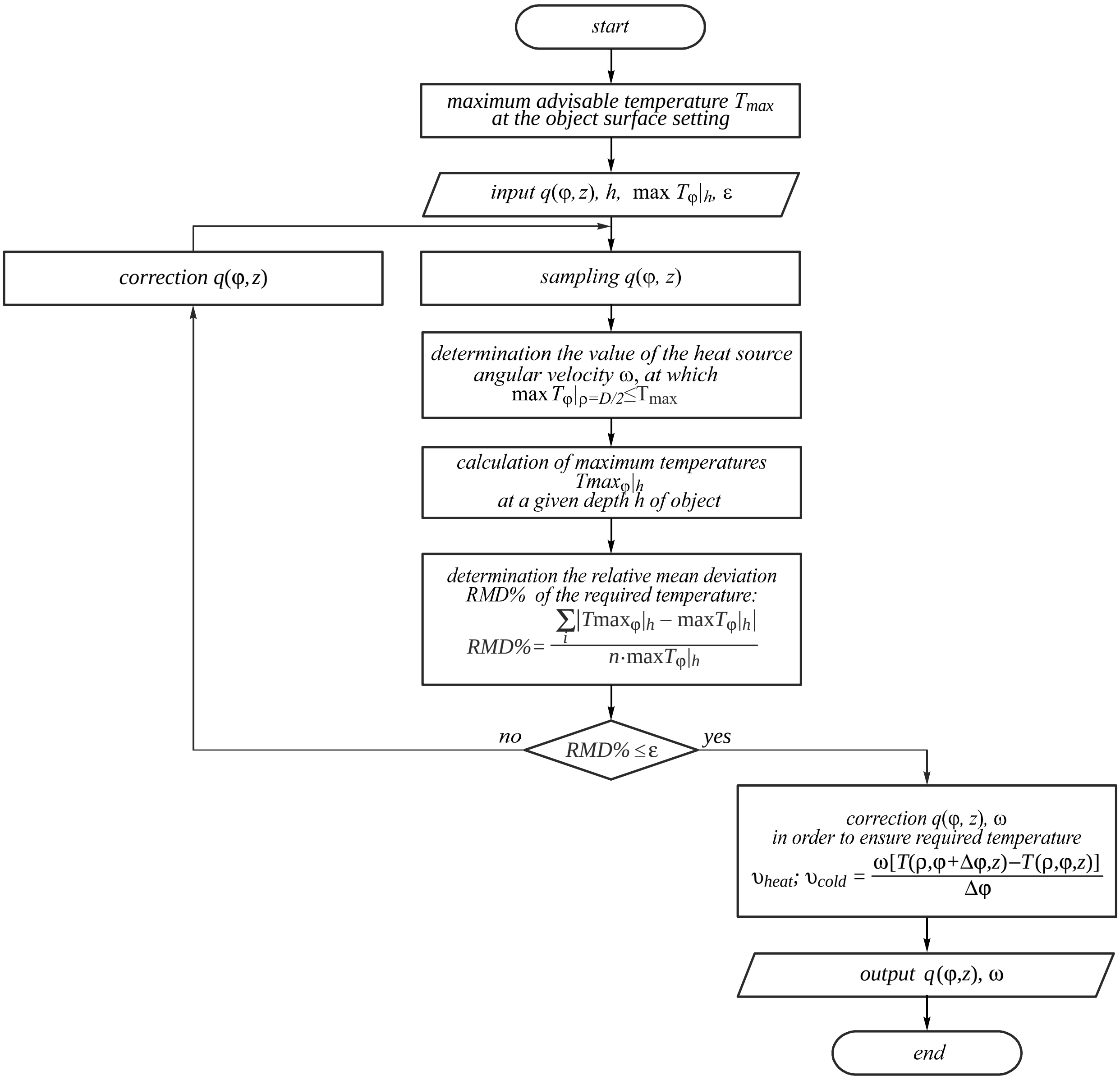

Fig. 2. A flowchart for calculating the power density distribution of the laser beam q(ϕ, z) to formation a desired thermal effect on technological objects

Temperature rate conditions for the laser treatment of steel 40HNMA were achieved when the power of the laser source was varied over the range of 800 to 1000 W; processing angular speed was $\omega = 0.175 - 0.375$ rad/s. The structure of chrome-nickel-molybdenum steel 40HNMA in the cross-section of the heat affected zone after laser heat treatment using the moving rectangular-shaped heat source was also studied. For the metallographic study the fracture of chromium-nickel-molybdenum steel object was performed (Fig. 3). The metallographic analysis confirmed the surface treatment without undesirable surface melting. Heat affected zone consists of several layers, in each of which microhardness is different from the initial microhardness in varying degrees.

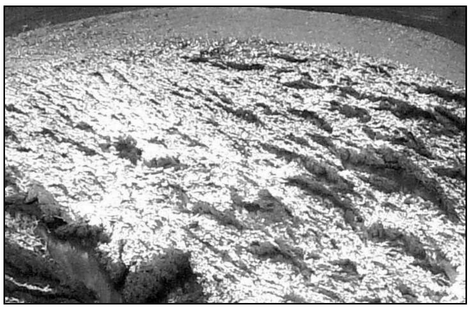

Fig. 3. Fracture area of the sample of chromium-nickel-molybdenum steel; increase × 7

The hardest surface layer, having a reduced etchability, is a martensite, which has microhardness $H_\mu = 7500 -$

8000 MPa. Below this martensitic layer is the region of incomplete hardening with martensitic and ferritic structure. The third layer is the transition zone. In the case of laser treatment of preliminarily thermally modified steel, this layer has a microhardness reduction, connected to the formation of tempering structures – troostite or sorbite. The initial structure of the material is sorbite with hardness $H_{\mu} = 2850 - 3410$ MPa.

Formation of such structures in the heat affected zone is caused by the character of the distribution of temperature fields and the difference in the cooling rate along the depth. Fig. 3 shows two clearly distinguish areas, the relief of which is different. The near-surface layer after laser treatment has less rough relief. The structure is represents martensite, that typical for the hardened structure. The core is characterized by a structure with rough relief and consists essentially of sorbite and troostite. When the laser heat treatment use the moving rectangular-shaped heat source shaped by DOE a uniform hardening depth across the width of the heat affected zone is achieved.

Conclusions

Algorithm for calculation the power density distribution of the laser beam, based on methods for solving inverse problem of heat conduction was developed. This algorithm allow us to create a desired thermal effect on technological objects. The power density distribution of the moving distributed surface heat source is determined by the temperature in the points of object, defined in accordance with the required change in its values. The redistribution of power density of the moving distributed surface heat sources should be used to control the temperature distribution in the treated zone. Usage of moving rectangular-shaped heat sources provides an opportunity to ensure equalization of maximum temperature values in the cross sections of the heat affected zone on objects during the thermal cycles of heating and cooling. The increase of power density at the edges of the laser spot compensates the increased heat loses caused by peripheral regions. The results of thermal processes calculation shows that the application of the developed algorithm allows to create a more uniform temperature field across the width of the heat affected zone. Equalization of maximum temperature values is achieved in the center and in the periphery of the heat affected zone with an increase in the width of the regions, where required temperature is reached.

Research on application of a DOE in technologies for laser materials processing can reveal one of progressive directions of development of these technologies. The use of DOEs gives the opportunity to obtain the required properties of constructional materials in a heat affected zone. In this case, the shape of the laser beam spot and spatial distribution of laser power density advisable to consider as the main parameters of the processing mode.

A regulation of parameters of temperature field in chrome-nickel-molybdenum 40HNMA steel for laser heat treatment was implemented and uniform hardening depth across the width of the heat affected zone was achieved. Changing the shape and the spatial intensity distribution of a laser beam spot leads to differences of the temperature field in a treated material. It was possible to ensure uniform properties and a constant depth of the heat treatment zone across its entire width. In addition to achieve uniform temperature conditions across the width of the heat affected zone, proposed approach allows the increase of the width of the isotherms of temperature fields. Wider isotherms provides an opportunity to process the larger area per unit time at the same laser beam power.

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