MATHEMATICAL MODELING OF LASER-FIELD HARDENING

[a]DMITRIY ALEKSANDROVICH BASHMAKOV, [b]AZAT TALGATOVICH GALIAKBAROV, [c]DANIS IREKOVICH ISRAPHILOV

Kazan Federal University, 18 Kremlyovskaya street, Kazan 420008, Russia
Email: [a]bashmakovda@yuandex.ru. [b]russia@prescopus.com. [c]editor@ores.su

Abstract: Modern methods of laser processing of materials are actively being introduced into production. This work is devoted to laser-field technology for processing materials. A theoretical study of the process of laser interaction with metal was carried out, it was shown that the reflection coefficient of laser radiation and its penetration depth depend on the electrical conductivity of the skin layer. The main relationships between the quality indicators of the treated layer and the parameters of the laser-field technological complex are revealed. The results of studies on laser-field hardening in an electrostatic field of steel widely used in mechanical engineering are presented (Steel 10, Steel 45, Steel 65). It is shown that the application of an electrostatic field to the treatment zone leads to an increase in the depth and hardness of the hardened layer due to the directed motion of electrons deep into the metal. A mathematical model of the distribution of the temperature field in a metal under the influence of laser radiation is proposed, taking into account the application of an electrostatic field and allowing us to study the dynamics of the hardening process. It is mathematically justified to limit the increase in the cooling rate of a material by the directed movement of electrons in an electrostatic field.

Keywords: laser radiation, laser-field processing, hardening, electrostatic field, laser.

1 Introduction

In mechanical engineering, the possibilities of using laser radiation (LI) as a universal tool in processing various materials are determined by the laws of such processes and phenomena as absorption of LI, surface and volume heating of the material, melting of the material, its erosion, the formation of heat-affected zones (HAZ) (Bashmakov, 2010; Kuznetsov et al, 2014), a change in the stress-strain state, diffusion of elements under thermal effects, etc. (Bashmakov, 2010; Pesoshin et al, 2010). Hybrid laser technologies in the world practice are mainly represented by laser-arc processing (Turichin et al, 2013; Turichin et al, 2010), which is associated with the presence of a large amount of experimental data and developed technologies (Turichin et al, 2009; Grigoryants et al, 2016). Other hybrid processing methods have been developed and are being applied: double-beam laser, laser-induction, laser-plasma, laser-light-beam, which also find application in industry and are fairly well researched (Grigoryants et al, 2016). However, scientific papers in laser field processing are practically absent. There is no complete theory of the combined effect of LI and various fields on the material being processed.

In world science, the work on the combined effects of different fields and LI is mainly concentrated in Japan. Work on laser-electrostatic and laser-electromagnetic technology in the field of mechanical pressure is carried out at Tokai University in Japan (O'Briant et al, 2016; Akashi et al, 2014). It is worth noting studies on laser-electrostatic technology for the modification of graphene at Shahid Beheshti University, Iran (Yadi et al, 2017).

From the brief review, it is clear that there are practically no studies on laser field technology in the Russian Federation. In this regard, to solve the increase in the productivity of laser processing and expand the field of use of laser radiation, it is necessary to further develop the theory of the interaction of laser radiation with the material, taking into account the influence of external disturbing factors, such as electromagnetic, magnetic and electrostatic fields.

The purpose of the work is to study the combined effect of LI and the electrostatic field on the metal being processed used in mechanical engineering, identifying the characteristics of HAZ and creating a mathematical model of such a combined effect for the further development of laser-field exposure technology.

2 Methods

The relationship of the absorption coefficient with the conductivity of materials, in particular metals, shows that free electrons in the metal crystal lattice increase the fraction of reflected LI. The depth of the skin layer δ, for LI, is determined by the formula:

$$\delta = 2\,(2\mu\mu 0\sigma\omega)^{-0.5},$$

here: μ is the magnetic permeability of the material, at frequencies of the optical range for metals is 1; $\mu 0 = 4\pi 10^{-7}$ GN / m; σ is the electrical conductivity of the processed material; ω is the cyclic radiation frequency.

Materials reflect surface radiation depending on the dielectric constant of the medium, which can be seen in the following dependency:

$$R = \frac{Q_{ref}}{Q_{inc}} = \left|\frac{\sqrt{\varepsilon}-1}{\sqrt{\varepsilon}+1}\right|^2,$$

where Q_{ref}, Q_{inc} is the LI energy reflected from the metal surface and incident on it, respectively; ε is the dielectric constant of the medium.

In a metal, conduction electrons can be considered completely free, then the reflection coefficient will be calculated in accordance with the formula:

$$R = 1 - \sqrt{\frac{2\omega}{\pi\sigma}}.$$

Based on theoretical data, an experimental laser-field technological complex (LPTK) was developed, an analysis of the relationship between its parameters, quenching parameters and quality parameters of the heat-affected zone (HAZ) showed that the former has a greater influence on temperature, and all process quality indicators depend on it hardening (Kuznetsov et al, 2014). Hardening the working surface of a metal product with laser radiation (LI) at a critical energy density in the beam does not give stable surface quality indicators. Significant importance in this is played by the parameters of LPTC, which must be considered as a set of interacting links of a complex system, the influence of external electric fields on the physical process of interaction between the laser radiation and the metal, and the electrical conductivity of the metal, on which the absorption coefficient directly depends (Shlyakova et al, 2008).

LI power density, exposure time, laser beam positioning accuracy, electrostatic field strength, etc. are the main parameters of LPTK having a direct impact on the quality indicators of TP. Microstructural analysis of steels treated with concentrated energy fluxes in regimes close to critical, without the use of additional external influences, shows a significant increase in microhardness and depth of the hardened region of the material, but this increases the likelihood of not achieving the required surface quality in the form of its fusion, which leads to a change geometric parameters, as well as a possible increase in roughness by 3-5 classes (Khisamutdinov et al, 2016; Zamorsky, 2003).

By adjusting the LI power, the focal length and the electrostatic field strength, the parameters necessary for achieving the required TP quality indicators and LPTK are established. Experimental testing of TP was carried out on samples of steel 10, 45 and 65G. Such a choice of sample materials is due to an analysis of the use of steel grades in the production of KAMAZ automobiles (Bashmakov, 2010).

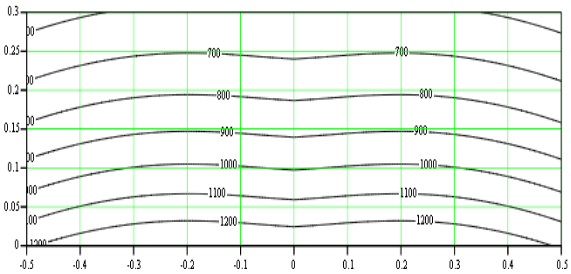
3 Results and Discussion

Calculation of the temperature field in the metal under the influence of LI without applying an electrostatic field was carried out according to the mathematical model (Bashmakov, 2010):

$$T = AP\int_{-\infty}^{t}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{I(x',y')}{4(\pi a(t-t'))^{3/2}}e^{\frac{-((x+vt'-x')+(y-y')^2+(z-z')^2)}{4a(t-t')}}dx'dy'dt'$$

here: A is the absorption coefficient of LI by the surface; P - power LI; I — intensity distribution in the spot of focus LI; a - thermal diffusivity $a=\frac{\lambda}{c\rho}$; s - specific heat; ρ - density of the material; λ - thermal conductivity.

In fig. 1 shows the calculations according to the above model. According to the temperature curves, it is noticeable that within 0±0.3 mm the temperature deviation does not exceed 30 ° C. The studies carried out unambiguously show that these deviations of the temperature field on the surface of the sample cannot have a significant effect on the quality indicators of TP (Zvezdin et al, 2007).



T

Figure 1. Temperature curves of the calculated LI effect (TEM_{10})

In the absence of an external electric field, an electron gas in a conductor, in particular in a metal, is at rest concerning the positive ions of the lattice, because all directions of electron motion are equally probable (Tamm, 2003). The average current density will be zero, as well as the average electron velocity relative to the lattice (Parkin, 2004). Under the influence of an electrostatic field, free electrons acquire an additional to the fundamental velocity u, directed along the electric field vector. An increase in the velocity of movement u can occur only during the free flight of an electron between two successive collisions of it with ions of the lattice (Parkin, 2004). Immediately before the collision, the electron velocity:

$$u=\frac{eE}{m}\tau ,$$

here: e - electron charge; E - electrostatic field strength; m - mass of the electron; τ - time between collisions of an electron, calculated by the formula: $\tau=\frac{l}{v}$; l - average path length of an electron; v - the average speed of random motion of electrons in the absence of an electrostatic field.

The average value of u can be calculated:

$$\bar{u}=\frac{1}{2}\frac{eE}{m}\tau .$$

These considerations make it possible to obtain the electric current density in a conductor under the influence of an electrostatic field:

$$j=\frac{e^2nl}{2mv}E ,$$

where: n is the number of electrons in a unit volume of metal (Bashmakov, 2010).

The limited number of free electrons, conduction electrons moving to the unprocessed edge of the part to compensate for the electric field is confirmed by experimental data (Bashmakov, 2010). Thus, in the interaction with electrostatic and other electric fields, a limited-small part of Δn electrons that are located in a narrow ($\Delta E << E_F$) energy layer ΔE limited by the Fermi surface since only for them there are possible free energy states with higher energy (Mironova, 2001).

Electrons located below the Fermi level at distances greater than ΔEcannot separately interact with an external electrostatic field, because all energy levels to which they could go after interaction are filled with other electrons. However, it is worth considering the probability of a simultaneous change in energy by electrons by the same amount. The distribution of conduction electrons in the elementary volume of a conductor (steel) under the influence of an electrostatic field can be calculated by the formula:

$$dn_s(E)=2\frac{4\pi p^2dp}{(2\pi\eta)^3}=\frac{\sqrt{2}m_0^{\frac{3}{2}}}{\pi^2\eta^3}\sqrt{E}dE .$$

It should be clarified that the number of electronic states dn_s *(E)* with given energies in the range from E to *(E + dE)* is equal to twice the number of elementary quantum cells in p-space in a spherical layer of radius $p=(2mE)^{\frac{1}{2}}$ and thickness $dp=d(2mE)^{\frac{1}{2}}$. This system under certain conditions, under the influence of an external field, can shift as a whole (Zvezdin & Bashmakov, 2008).

We transform the initial mathematical model of the distribution of the temperature field (1) in the following form:

$$T = P\sqrt{\frac{2\omega}{\pi\sigma}}\int_{-\infty}^{t}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{I(x',y')}{4(\pi a(t-t'))^{3/2}}e^{-\left(\frac{(x+vt'-x')+(y-y')^2}{4a(t-t')}+\frac{(z-z')^2}{4a(t-t')}\right)}dx'dy'dt'$$

Further, the HAZ depth, if the LI acts at the point x '= 0, y'= 0 and z '= 0, and considering the initial moment, the moment of the beginning of the interaction of the LI with the metal, it is possible to write:

$$h^2_{зак}(x,y,t)=4at\ln\sqrt{\frac{8\pi\sigma}{\omega}}\frac{T_{зак}(\pi at)^{3/2}}{PI}-(x^2+y^2) .$$

To take into account changes in the hardening depth using a hybrid laser field effect, we introduce the coefficient of influence of the electrostatic field (K_E):

$$h_{зак}(x,y,t)=K_E\sqrt{4at\ln\sqrt{\frac{8\pi\sigma}{\omega}}\frac{T_{зак}(\pi at)^{3/2}}{PI}-(x^2+y^2)} .$$

Inverse transformations allow to supplement and refine the initial model of the distribution of the temperature field in the metal for the requirements of laser-field technology:

$$T = P\sqrt{\frac{2\omega}{\pi\sigma}}\int_{-\infty}^{t}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{I(x',y')}{4(\pi a(t-t'))^{3/2}}e^{-\left(\frac{(x+vt'-x')+(y-y')^2}{4a(t-t')}+\frac{(z-z')^2}{4K_E^2 a(t-t')}\right)}dx'\,dy'\,dt'$$

Based on the obtained experimental data (Bashmakov, 2010) (Table 1), we compose the dependences K_E for the steel grades chosen by us.

Table 1. The relationship of the depth of the hardened layer from the intensity of the electrostatic field.

Electrostatic field strength, MV / m	Hardening zone depth mm., Steel 10, W = 3 KJ	Hardening zone depth mm., Steel 65G, W = 4,5 KJ	Hardening zone depth mm., Steel 10, W = 3 KJ
4.69	0.11	0.1	0,08
3.13	0.1	0.0915	0.073
1.55	0.08	0.078	0.061
0.56	0.057	0.06	0.05
0.32	0.05	0.052	0.046
0	0.04	0.037	0.04

Based on the results of experimental data, it is possible to calculate the value of the coefficient K_E at reference points (Tab. 2).

Table 2. Values K_E for separate steel grade.

Electrostatic field strength, MV / m	K_E, Steel 10, W = 3 KJ	K_E, Steel 65G, W = 4.5 KJ	K_E, Steel 65G, W = 3.8 KJ
4.69	2.75	2.7027	2
3.13	2.5	2.473	1.825
1.55	2	2.1081	1.525
0.56	1.425	1.6216	1.25
0.32	1.25	1.4054	1.15
0	1	1	1

Most often, when solving problems in production, it becomes necessary to calculate the maximum depth of the hardened layer, i.e. directly under the spot of exposure to LI:

$$h_{har}^2(t,\mathrm{E}) = \mathrm{K}_\mathrm{E}^2 4at\,ln\sqrt{\frac{8\pi\sigma}{\omega}\frac{T_{har}(\pi at)^{3/2}}{PI}},$$

$$\sqrt{\frac{8\pi\sigma}{\omega}\frac{T_{har}(\pi at)^{3/2}}{PI}} = e^{\frac{h_{\text{зак}}^2}{\mathrm{K}_\mathrm{E}^2 4at}}.$$

The calculation of the required power LI to achieve a given depth of HAZ in LPTK it is possible to use the following model:

$$P(t,E,h_{har}) = \sqrt{\frac{8\pi\sigma}{\omega}\frac{T_{har}(\pi at)^{3/2}}{I}}\,e^{-\frac{h_{har}^2}{\mathrm{K}_\mathrm{E}^2 4at}}.$$

In the case of a hard-set LI power, the electrostatic field strength is easily determined using the known coefficients K_E, and then by the dependences for various metals (Bashmakov, 2010).

$$\mathrm{K}_\mathrm{E} = h_{har}\left(4at\,ln\sqrt{\frac{8\pi\sigma}{\omega}\frac{T_{har}(\pi at)^{3/2}}{PI}}-(x^2+y^2)\right)^{-\frac{1}{2}}$$

4 Summary

Studying the dynamics of the temperature field in a metal over time based on the obtained mathematical model, the heating and cooling rates and the limiting emerging temperatures are determined. By systematizing the nodes of the LPTK control system according to related signs (reaching the required temperature, the time of the volume spent in the required temperature range, etc.), it is possible at the stage of preparation for production to determine not only the depth of the HAZ, but also the shape and size of the various structural zones that arise when laser-field processing of metals. The results of the solution of the presented models can be presented in the form of isothermal surfaces of temperature distributions in space and in time, outlines of various structural zones that arise during laser-field processing. The created mathematical model of metal surface hardening allows one to study the dynamics of the hardening process and increase its efficiency.

Literature:

1. Bashmakov, D.A.: Control of laser thermal hardening of metals in an electric field: a dissertation for the degree of candidate of technical sciences. Naberezhnye Chelny, 2010. 151 p.
2. Kuznetsov, I.N., Zvezdin, V.V., Israfilov, I.H., Portnov, S.M.: The automatic control system of high precision welding of workpieces in mechanical engineering. IOP Conference Series: Materials Science and Engineering Ser. "Innovative Mechanical Engineering Technologies, Equipment and Materials-2013". 2014. Vol. 69, No. 1, p. 012029.
3. Shlyakova, E.V., Brain, I.V., Soloviev, A.A.: Investigation of the effect of laser irradiation on the resistance to electrochemical corrosion of the cylinder liner material of an internal combustion engine. Omsk Scientific Bulletin. 2008. No. 2 (68). pp. 22-25.
4. Pesoshin, V.A., Zvezdin, V.V., Portnov, S.M., Kisaev, R.A., Kuznetsov, I.N.: Investigation of the process of the influence of power changes during gas laser cutting of metals, Bulletin of Kazan State Technical University named after A.N. Tupolev, 2010, No. 2, pp. 43–46.
5. Turichin, G.A., Tsibulsky, I.A., Kuznetsov, M.V., Akhmetov, A.D., Velichko, O.V.: Laser-arc welding in various spatial positions. Scientific and technical statements of SPbPU. Natural and engineering sciences. 2013, No. 183-1, pp. 218-225.
6. Turichin, G.A., Tsibulsky, I.A., Kuznetsov, M.V., Somonov, V.V.: Hybrid laser-arc welding of metals of large thickness. Scientific and technical statements of St. Petersburg Polytechnic University. Natural and engineering sciences, 2010, No. 110, pp. 181–187.
7. Turichin, G.A., Tsibulsky, I.A., Valdaitseva, E.A., Karasev, M.V.: Theory and technology of hybrid welding of metals of large thicknesses. 6th Intern. conf. “Beam technologies and the use of lasers” - St. Petersburg. 2009. pp. 11–18.
8. Grigoryants, A.G., Shiganov, I.N., Chirkov, A.M.: Hybrid Laser Welding Technology: A Training Manual. M.: Publishing of MGTU named after N.E. Bauman. 2004, 52 p.
9. O’Briant, S. A., Gupta, S. B., Vasu, S. S.: Laser ignition for aerospace propulsion. Propulsion and Power Research, 2016, Vol. 5, Is. 1, pp. 1-21.
10. Akashi, N., Oigawa, Y., Hosokawa, H., Horisawa, H.: Plasma acceleration characteristic of a rectangular laser-electromagnetic hybrid thruster. In 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference. 2014. pp. 1585-1594.
11. Yadi, M., Karimzadeh, R., Abbasi, A.: Effect of treatment by electrostatic field and 532-nm laser irradiation on optical and thermo-optical properties of graphene oxide colloids. Journal of materials science, 2017, Vol. 52, Is. 8, pp. 4532–4542.

12. Khisamutdinov, R.M., Zvezdin, V.V., Israfilov, I.H., Saubanov, R.R., Spirin, A.A., Rakhimov, R.R.: Study of processes of steels surfaces modification with highly concentrated energy flows. Journal of Physics: Conference Series, 2016, Vol. 669, No 1, pp. 012024.
13. Zamorsky, V.V.: Improving the quality of the control system of the laser technological complex for welding critical parts: a dissertation for the degree of candidate of technical sciences. - Naberezhnye Chelny. 2003. 126 p.
14. Bashmakov, D.A.: A model for calculating the parameters of laser thermal strengthening, taking into account the influence of the electrostatic field. Socio-economic and technical systems: research, design, optimization, 2010, No. 2, pp. 10-14.
15. Zvezdin, V.V., Karimov, R.B., Khamadeev, A.V.: A model of the formation of microstructures in metals during laser processing. Design and study of technical systems interuniversity scientific collection, 2007, No. 11, pp. 150-154.
16. Tamm, I.E.: Fundamentals of the theory of electricity: textbook. allowance for students of physical Universities specialties. M .: Fizmatlit. 2003: 615 p.
17. Parkin, A.A.: The technology of processing concentrated energy flows: Textbook. Samara State Technical University. Samara, 2004 - 494 pages.
18. Mironova, G.A.: The band structure of the electronic energy spectrum in solids. Models of free and strongly bound electrons. Preprint number 5. - Faculty of Physics, Moscow State University Moscow. 2001.
19. Zvezdin, V.V., Bashmakov, D.A.: Improving energy efficiency during laser hardening. Energy Resource Efficiency and Energy Saving in the Republic of Tatarstan Proceedings of the IX International Symposium "Energy Resource Efficiency and Energy Saving" GU "Center for Energy Saving Technologies of the Republic of Tatarstan under the Cabinet of Ministers of the Republic of Tatarstan". 2008. pp. 369-371.

Primary Paper Section: B

Secondary Paper Section: BA, BH