DOI: 10.17580/cisisr.2020.01.09

USING THE SIMILARITY THEORY FOR DESCRIPTION OF LASER HARDENING PROCESSES

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Key words:

laser hardening, theory of dimensions, dimensionless parameters, maximum hardening depth, surface temperature, laser run overlap factor, relative power of laser processing, relative velocity of the laser beam movement.

ABSTRACT

Based on the theory of similarity for describing laser hardening processes, we suggested dimensionless parameters that simultaneously take into account both process parameters of the laser heat processing and the thermophysical characteristics of the metal being processed, and have a clear physical meaning. To build a statistical model of the laser exposure area depth from the laser radiation parameters, we used in our studies the methods of mathematical experiment design, and in order to summarize the results obtained on the basis of applying similarity theory relations, we suggested to use the following dimensionless (generalized) parameters: 1) the laser run overlap factor S^*; 2) the relative power of the laser processing P^*; 3) the relative velocity of the laser beam movement V^*; 4) the relative depth of the hardened layer Z^*. The overlap factor S^* describes the effect of subsequent adjacent laser runs on the previous ones: with $S^* < 1$, the runs overlap, and the material structure in the previous laser area changes; usually, with $S^* > 2$, the mutual effect of adjacent runs can be neglected; therefore, this condition is often used in the laser hardening of a metal working process (MWP) tool. The value P^* corresponds to the ratio of the effective laser radiation power $P_{ef} = K_{abs}\cdot P$ to the power that can be diverted from the surface due to thermal conductivity deep into the metal without melting. The value V^* is equal to the ratio of the laser beam velocity to the temperature front propagation velocity in this material. As the relative value Z^*, we adopted the ratio of the hardened layer depth to the maximum possible theoretical value , which is achieved when the temperature on the metal surface reaches its melting point. The use of dimensionless parameters allows us to build mathematical models for laser hardening and, based on the same, to develop and to optimize the laser heat processing method.

Introduction

One of the promising methods for increasing the MWP tool performance is laser surface hardening [1—8], the practical use of which was made possible due to the availability of high-power industrial lasers. In laser processing, metal is heated from the surface, without the need for using any cooling medium, which greatly simplifies the heat hardening method. In addition, laser processing is characterized by a short exposure time and provides virtually complete absence of deformations in the processed products. By changing the laser radiation parameters and processing modes, we can adjust the metal heating and cooling rate within a wide range, as well as the radiation time, which allows us to get the required metal structures and properties in the laser exposure area [9—11].

For laser heat processing, both pulsed and continuous-wave lasers can be used. The main factors for the choice of a laser type are the hardened layer depth and the process performance. For hardening an MWP tool in industrial production, the most widely used are continuous-wave CO_2 lasers, because, as compared to pulsed lasers, they feature a higher power and provide a deeper laser exposure area and a higher performance.

The main process parameters of continuous-wave laser heat processing are: P — the radiation power of a continuous-wave laser; d_s — the laser spot diameter on the workpiece surface; V — the linear velocity of the laser beam movement relative to the workpiece; s — the distance (pitch) between the midpoints of adjacent laser runs; K_{abs} — the ratio of laser radiation absorption by the coating applied to the workpiece surface to reduce its reflectivity.

For laser processing of various materials, an important factor is the density q of the laser radiation power, that is equal to the laser radiation power ratio P to the surface area $A = \pi \cdot d_s^2 / 4$, upon which it falls

$$q = \frac{4P}{\pi d_s^2}.$$

In this equation, it is assumed that the radiation energy is uniformly distributed over the cross-section of a cylindrical laser beam with a diameter d_s. During heat hardening, the density value for most metals and alloys is within the range of $q = 10$—100 kW/m².

The main parameters of the metal thermophysical properties, which shall be taken into account during laser heat processing, are: λ — the thermal conductivity factor; c — the specific heat capacity; $\alpha = \lambda/(c\cdot\rho)$ — the thermal diffusivity factor, where ρ is the density; T_{melt} is the melding temperature; T_{hard} is the hardening temperature.

Purpose of the Paper is finding dimensionless parameters to describe laser hardening processes based on criteria equations of the theory of dimensions and similarity.

Research and discussion

Currently, the heat conduction theory has no general methods to accurately solve the problem of laser processing of metals, taking into account its inherent nonlinearities. Therefore, in practice, we often have to use various simplifications and resort to approximate solutions based on digital methods, simulation principles, etc. In particular, to build experimental and theoretical models, we can use methods of the theory of dimensions and similarity.

In the theory of dimensions, the main theorem is the so-called π-theorem (the theorem of E. Buckingham), which suggests that any physical and mathematical equation can be presented in the form of a dimensionless criteria equation that comprises the basic dimensions of all values included in such equation [12, 13]. The SI system uses the following dimensions of the basic values: unit of length — meter (m); unit of time — second (s); unit of weight — kilogram (kg); unit of temperature — Kelvin (K).

It is known that the maximum hardening depth h_{max} and the surface temperature T_{surf} in laser heat processing of metals are functions of several process parameters and thermophysical characteristics of metal.

$$h_{max} = F_1(\lambda,\ a,\ q,\ t,\ T_{melt},\ T_{hard}). \tag{1}$$

$$T_{surf} = F_2(\lambda,\ a,\ q,\ t). \tag{2}$$

Using the π-theorem, the dimensionless criteria equation can be presented, for example, in the following form:

$$h_{max} = C_1\sqrt{at}\left(\frac{q_{melt}\sqrt{at}}{\lambda T_{melt}}\right)^g\left(\frac{T_{hard}}{T_{melt}}\right)^n. \tag{3}$$

$$T_{surf} = T_{melt} = C_2\frac{T_{melt}}{\lambda}\sqrt{at}. \tag{4}$$

where C_1, C_2, g and n are experimentally found constants.

When deriving these equations, we can use the Rayleigh method; for this purpose, we will find the function of maximum hardening depth (1) as follows:

$$h_{max} = C_1\lambda^e a^f q^g t^h T_{melt}^m T_{hard}^n. \tag{5}$$

The dimensions of parameters included in this equation are expressed through dimensions of the basic units in the following form:

thermal conductivity factor λ . . . . [$kg{\cdot}m{\cdot}s^{-3}{\cdot}K^{-1}$]
thermal diffusivity factor a. . . . . [$m^2{\cdot}s^{-1}$]
laser radiation power density q . . . . [$kg{\cdot}s^{-3}$]
maximum depth of the hardened layer. . . . . [m]
time t . . . . [s]
temperature of hardening T_{melt} and melting T_{hard} . . [K]

Substituting these dimensions in (4.5), we will get

$$[m] = C_1\left[kg\cdot m\cdot s^{-3}\cdot K^{-1}\right]^e\cdot\left[m^2\cdot s^{-1}\right]^f\cdot\left[kg\cdot s^{-3}\right]^g\times$$
$$\times[s]^h\cdot[K]^m\cdot[K]^n$$

or

$$[m] = C_1\cdot[kg]^{e+g}\cdot[m]^{e+2f}\cdot[s]^{-3e-f-3g+h}\cdot[K]^{-e+m+n} \tag{6}$$

Since the powers in both sides of the equation shall be the same, we obtain a system of algebraic equations:

$$\begin{cases} e+g=0 \\ e+2f=16 \\ -3e-f-3g+h=0 \\ -e+m+n=0 \end{cases}$$

By solving this system, we will find the values of factors and, having substituted them into (4.5), we get the formula for the maximum hardening depth:

$$h_{max} = C_3\frac{\lambda T_{melt}}{q_{melt}}\left(\frac{T_{hard}}{T_{melt}}\right)^n = C_3\sqrt{at}\left(\frac{T_{hard}}{T_{melt}}\right)^n. \tag{7}$$

From this formula, which is completely similar to equation (3), it follows that the exposure time t and the laser radiation power density q are determining factors for the maximum hardening depth. Since, for a particular metal, the ratio of T_{hard}/T_{melt} is constant value, then, by adopting $n = 1$ in equation (7), we get the simplest formula for determining the maximum hardening depth:

$$h_{max} = C_4\frac{\lambda}{q_{melt}}T_{hard} = C_4\sqrt{at}\frac{T_{hard}}{T_{melt}}. \tag{8}$$

This formula shows that the maximum hardening depth is influenced by the metal melting temperature T_{melt} either explicitly or indirectly, via the power density q_{melt} that, according to (4), is related to the metal surface temperature $T_{surf} = T_{melt}$ and time t of exposure to laser radiation.

The established patterns well agree with the experimental results (**Fig. 1**), as presented in [14]. An analysis of the above dependencies allows us to conclude that the maximum hardening depth during laser heat processing is inversely proportional to the density q of the heat source power (**Fig. 2**).

If the surface temperature of the material being processed by laser heating is within the range of $T_{hard} \le T_{surf} \le T_{melt}$, we can draw the following conclusions from the above formulas:

1) at the same time of exposure to the heat source, i.e. with t = const, with increasing density q of the heat source power, hardening depth h_{max} increases;

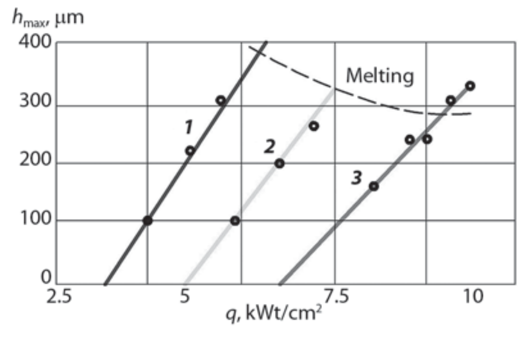

Fig. 1. Dependence of the hardening depth for AiSi4304 steel [14] on the density *q* of the laser radiation power with d_s = 3 mm and processing rates *V*: *1* — 0.65 m/min; *2* — 1.5 m/min; *3* — 2.0 m/min

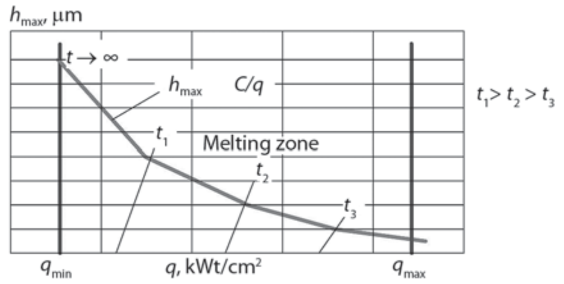

Fig. 2. Dependence of the maximum hardening depth on the density *q* of the laser radiation power with different exposure time fusion (melting) zone

2) when the surface temperature is equal to the metal melting temperature, i.e. $T_{surf} = T_{melt}$, the lower the density q of the laser radiation power, the greater hardening area depth h_{max};

3) different values of density q of the heat source power usually correspond to different maximum values of the hardened area depth h_{max}.

Currently, in the analysis of laser heat processing of metals, the choice of dimensionless parameters for laser processing of metals by various authors is quite arbitrary. At the same time, in the theory of dimensions and similarity, general principles have been developed, according to which, e.g., it is recommended to choose parameters that have a certain physical meaning and that are usually applied in classical theories (that of continuum mechanics, heat conductivity, etc.).

To build a statistical model of the laser exposure depth dependence on the laser radiation parameters, we used in our study the methods of mathematical experiment design, and in order to summarize the results obtained on the basis of applying similarity theory relations, we suggested to use the following dimensionless (generalized) parameters:

1) the laser run overlap factor:

$$S^* = S/d;$$

2) the relative power of the laser processing:

$$P^* = \frac{2K_{abs}P_0}{d\lambda T_{melt}};$$

3) the relative velocity of the laser beam movement:

$$V^* = \frac{Vd}{4a};$$

4) the relative depth of the hardened layer:

$$Z^* = \frac{4h_{hard}P_0}{\pi d^2 (T_{melt} - T_{hard})\lambda}.$$

Here, S is the distance between laser runs, m; d is the beam diameter, m; K_{abs} is the absorption factor; P is the laser radiation power, W; λ is the thermal conductivity factor, W/(m·K); T_{hard} and T_{melt} are hardening and melting temperatures, respectively, °C; V is the laser beam movement velocity, m/s; a is the thermal diffusivity factor, sq.m/s; h_{hard} is the hardened layer depth, m.

Let us explain the physical meaning of these parameters.

The overlap factor S^* describes the effect of subsequent adjacent laser runs on the previous ones: with $S^* < 1$, the runs overlap, and the material structure in the previous laser area changes; usually, with $S^* > 2$, the mutual effect of adjacent runs can be neglected; therefore, this condition is often used in the laser hardening of an MWP tool.

The value P^* corresponds to the ratio of the effective laser radiation power $P_{ef} = K_{abs} \cdot P$ to the power that can be diverted from the surface due to thermal conductivity deep into the metal without melting.

The value V^* is equal to the ratio of the laser beam velocity to the temperature front propagation velocity in this material.

As the relative value Z^*, we adopted the ratio of the hardened layer depth to the maximum possible theoretical value , which is achieved when the temperature on the metal surface reaches its melting point.

Conclusion

Based on criteria equations of the theory of dimensions and similarity, we obtained dimensionless (generalized) parameters to describe laser hardening processes. As compared with the parameters known from the scientific and engineering publications, the suggested dimensionless systems favorably differ in that they simultaneously take into account both the process parameters of laser heat processing and the thermophysical characteristics of the metal being processed; in addition, they have a clear physical meaning.

Recommendations. The use of dimensionless parameters allows us to create mathematical models of laser hardening and, based on the same, to develop and to optimize the laser heat processing method and other processes [15–23].

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