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THEORETICAL CALCULATIONS OF POWER DENSITY VARIATION RANGES AS A FUNCTION OF RATE IN LASER-ASSISTED WELDING

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Abstract

The first phase of studying the process of laser-assisted welding necessarily goes through a preliminary theoretical physical-engineering analysis of the roles of the major manufacturing parameters. This is especially important for the practice when new technologies are being developed. This paper deals with the process of laser-assisted welding with a diode laser (λ=808 nm; 940 nm) by heat conduction of lamella packs of electrical steel. On the basis of dependencies and correlations between physical quantities and manufacturing parameters of treatment, concrete numerical calculations of critical power density of melting and evaporation for specific values of welding rate have been presented.

Keywords: laser-assisted welding, factors, power density, numerical calculations

INTRODUCTION

Laser welding technology is successfully replacing traditional welding methods due to the advantages [1,2,3] it possesses, namely: reaching higher power density of output radiation, small volume of welding pool; welding from a distance; welding materials of different chemical composition; small zone of thermal effect; high production rate of the process, etc.

The introduction of laser-assisted welding into production as an innovative method sets a number of concrete engineering-physical problems to be solved in advance by implementers in order to achieve positive results in the end.

The study of the manufacturing process is accompanied by preliminary model numerical calculations, with a view to optimize the process. It is necessary to know the factors affecting the process and the relations between physical quantities and manufacturing parameters because this plays an essential part in conducting these numerical experiments.

The objective of this study is to determine by numerical calculations the performance ranges of power density q_S for various welding rates. The calculations have been specified for welding by heat conduction of electrical silicon steel M 330-50A with a diode laser.

MODELING OF THE WELDING PROCESS

The knowledge of the basic correlations between physical quantities and parameters related to the process leads to clarifying the role of the two most important manufacturing parameters: power density and action time in the process of welding with laser radiation.

In general, the factors which have an effect on the process of welding with a laser source can be divided into three groups (Fig.1):

- ➢ parameters related to the laser source
  - wave length;
  - power density;
  - power rate;
  - beam quality;
- ➢ parameters related to the manufacturing process
  - welding rate;
  - defocusing;
- ➢ parameters related to the material
  - optical and thermo-physical properties (absorption, thermal conductivity coefficient, thermal diffusivity coefficient, etc.);
  - material thickness;
  - chemical composition;

Knowing the relations between physical quantities and manufacturing parameters of treatment, for the purpose of orientation, can be obtained theoretical performance ranges resulting in running the process of laser-assisted welding. The process of welding by heat conduction with a laser source is characterized by applying a large quantity of laser energy into the zone of treatment and as a result of this the metal melts and crystallizes. The highly concentrated laser beam creates power densities q_S within the range of $10^8 \div 10^9$ W/m^2 [5,6,7] in the zone of welding.

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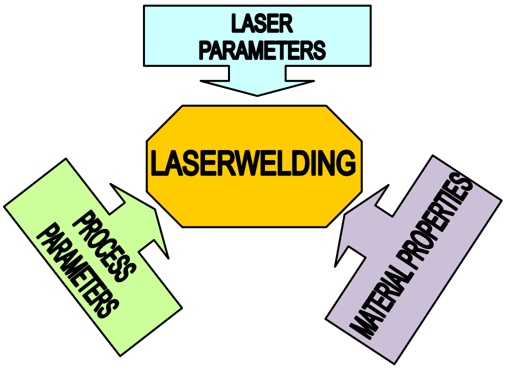

Fig. 1. Factors affecting the process of laser welding [4]

Power density q_S and action time of laser radiation t_{vd} are the two main factors that account for which of the physical processes: heating, melting and evaporation in the material will prevail (Fig.2). By adjusting their values, proper energy conditions can be set for which the desired process can proceed optimally.

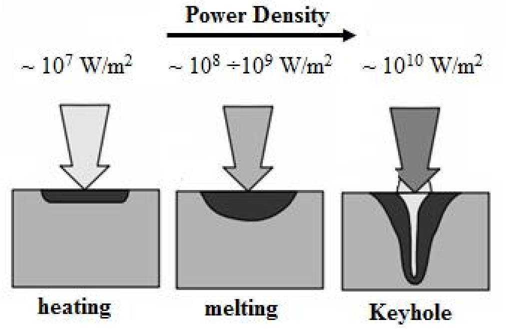

Fig. 2. Impact of power density q_S when laser radiation interacts with the substance [8]

For the studied material – electrical silicon steel M 330-50A, (packs of lamellas of these materials, respectively), a suitable method of welding with a laser source is the method of welding by heat conduction [3,9,10]. To run this process, for different kinds of materials, values of power density between $10^8 \div 10^9$ W/m^2, and action time $t_{vd} = 10^{-3} - 10^{-2}$ *[11]*s were given in literature.

Power density q_S is one of the most important manufacturing parameters affecting the welding process which is in close relation with the power of the laser source P,

$$q_S = \frac{P}{S} \tag{1}$$

where S is the weld spot area on the material surface.

Weld spot diameter d depends on a number of parameters of laser radiation and the focusing optical system, as laser radiation wave length λ, focal distance f, etc. :

$$d = M^2 \frac{4\lambda}{\pi} \frac{f}{D} \tag{2}$$

where D is the diameter of the radiation falling on the focusing lens, M^2 is a parameter characterizing the laser beam quality.

For this specific case of welding a lamella pack performed in our study, $d = 1{,}65.10^{-3}$ m is obtained for the weld spot diameter at values of $\lambda = 808$ nm, $f = 62.10^{-3}$ m, $M^2 = 777{,}2$ and $D = 0{,}03$ m. A change in diameter can be effected by replacing the focusing optics or by operating in defocusing mode.

The process of welding lamellas of silicon steel M330-50A is run at power densities in the range between the critical melting value q_{Skrm} and the critical value of evaporation q_{Skrv} for the specific material. Therefore the numerical calculation of these values is a major task before carrying out the experiments.

The formula by which the values of critical power density are calculated at certain welding rate v is [5]:

$$q_{Skr} = \frac{k(T - T_0)}{2A} \sqrt{\frac{\pi v}{ad}} . \tag{3}$$

Applying the heat balance equation and after transforming formula (3), employing the latter two analytical expressions can be reached for determining the critical values of melting q_{Skrm} and of evaporation q_{Skrv} for the specific material and at a specific value of the welding rate [12]:

$$q_{Skrm} = \frac{(1+s)k(T_m - T_0)}{2A} \sqrt{\frac{\pi v}{ad}} , \tag{4}$$

where $s = \dfrac{L_m}{c(T_m - T_0)}$

T_m is the melting temperature of the material; L_m is the latent heat of fusion.

$$q_{Skrv} = \frac{(1+s')k(T_v - T_0)}{2A} \sqrt{\frac{\pi v}{ad}} \tag{5}$$

$$s' = \frac{L_m + L_v}{c(T_v - T_0)} ,$$

where T_v is the temperature of material evaporation; L_v is the latent heat of evaporation

Calculation results:

The numerical calculations presented in this paper have been done for electrical steel M330-50A and laser source – diode laser with power of 2200W. The values of thermo-physical properties of the material used are presented in Table 1

Table1

Thermo-physical characteristics of electrical steel M330-50A	Value
Density ρ, kg / m^3	7730
Specific thermal capacity c, J/(kg K)	465
Thermal conductivity coefficient k, W/(m K)	38
Thermal diffusivity coefficient a, m^2 /s	$1{,}057.10^{-5}$

When calculating q_{Skrm} and q_{Skrv} for diode laser, three different values of diameter d of the focal spot have been used: 1.10^{-3} m, $1,65.10^{-3}$ m and 2.10^{-3} m. Welding rate varies within the range of v Є [0,01;0,1] m/s by a step of 0,01 m/s.

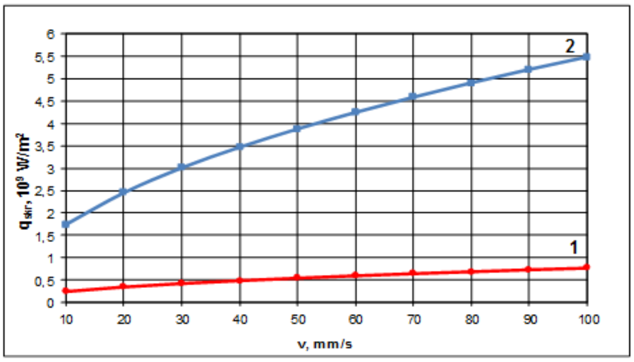

Fig.3.Impact of welding rate v on the critical power density q_{Skr} when d = 1 mm for:
1-melting; 2-evaporation

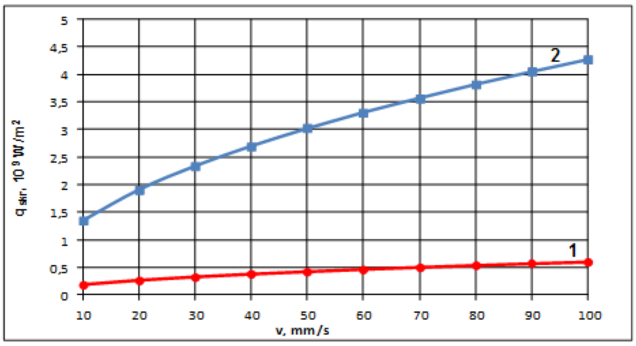

Fig.4 Impact of welding rate v on the critical power density q_{Skr} when d = 1,65 mm for:
1-melting; 2-evaporation

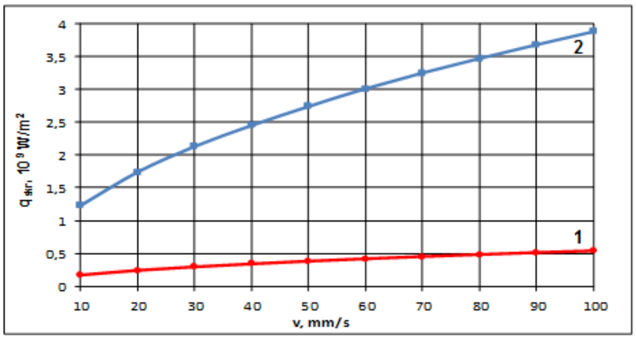

Fig.5Impact of welding rate v on the critical power density q_{Skr} when d = 2 mm for:
1-melting; 2-evaporation

From the numerical calculations and graphically presented results, the variation ranges of power density of melting q_{Skrm} and evaporation q_{Skrv} can be determined. Table 2 shows the variation ranges of q_S at different welding rate for weld spot diameter d = $1,65.10^{-3}$ m. Respectively, for performance range limits of welding at a certain rate, lower limit q_{Skrm} and upper limit q_{Skrv} have been accepted. The results of these preliminary engineering calculations can be employed in planning real experiments.

Table 2

d, m	$d = 1,65.10^{-3}$ m
v, m/s	q_S, W/m^2
0,01	$1,89.10^8 \div 1,35.10^9$
0,02	$2,67.10^8 \div 1,91.10^9$
0,03	$3,27.10^8 \div 2,34.10^9$
0,04	$3,78.10^8 \div 2,70.10^9$
0,05	$4,22.10^8 \div 3,02.10^9$
0,06	$4,63.10^8 \div 3,31.10^9$
0,07	$5,00.10^8 \div 3,57.10^9$
0,08	$5,34.10^8 \div 3,82.10^9$
0,09	$5,67.10^8 \div 4,05.10^9$
0,1	$5,97.10^8 \div 4,27.10^9$

Knowing the critical values of power density at a certain rate and applying formula (1) the values of threshold (critical) power rate P_{krm} for melting and the one for evaporation P_{krv} respectively, can easily be obtained. In the case considered in this study of welding rotor and stator lamella packs by heat conduction, it is desirable the operator of the technological system to set values of power in the range between $P_{krm} \div P_{krv}$ at certain welding rate. It is not desirable temperatures close to evaporating temperature to be reached in the welding pool owing to the formation of blow-holes in the weld seam.

For instance, on the basis of numerical calculations as optimum operating power rates P with focal spot diameter d = $1,65.10^{-3}$ m and welding rate v = 0,01 m/s, P = 404W is obtained, and at welding rate v = 0,06 m/s, P = 990W is obtained.

From the graphical results presented in this paper of the critical values of power density at different welding rates, the following conclusions can be drawn:

- With a rise in welding rate v , the critical power densities in melting q_{Skrm} and evaporation q_{Skrv} grow as well.
- Critical power density during evaporation is about seven times higher than the one during melting at one and the same welding rate.
- The slope of the curves for q_{Skrv} during evaporation is steeper compared to the slope of the curves for q_{Skrm} during melting. This shows that the change in welding rate v has a stronger effect on the critical power density during evaporation.

CONCLUSION

The theoretical calculations of variation ranges of power density as a function of welding rate (respectively action time), considered in this paper, are directly dependent on the chosen physical model of interaction between the laser radiation and the substance. They throw light upon the role of some major physical quantities and their relation to manufacturing parameters defining the process. The analysis of the numerical calculations obtained contributes to the successful carrying out of preliminary experimental studies affecting the quality of laser-assisted welding. Last but not least, the presented results provide information about the applicability limits of the physical model.

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