

Laser Welding of Slices of Magnetic Circuit

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(Received December 11, 2000)

In electric power industry, there is a problem of achieving stable joint in different components using high productive and efficient technologies. One type of these components is packages of slices for magnetic circuit of electric motors, transformers etc., which need reliable means for their fixing. Laser welding is proposed to solve this problem as an alternative for existing technologies. The development of the laser welding process is presented based on process simulation, study of heat history and comparison with experimental results. Laser beam additional scanning technique is proposed to improve the quality and efficiency of the joining operation.

1. INTRODUCTION

On firms, bound with manufacturing of magnetic circuits, one of the most mass and labor-consuming operations is the fixation of slices of transformers, electric motors, etc. with the strength necessary for normal operation of off the shelf items. With the purpose of obtaining permanent joints of slices of a magnetic circuit, in conditions of mass production the broad application has found compression of slices of an anchor of the electric motor concerning its shaft, that, however, causes its buckling (especially for micro electric motors), and also deterioration of magnetic properties of an anchor. The manual operations of slices fixing with the help of fasteners or sintering of a magnetic circuit, require additional operations. Besides, the last method of obtaining of connections is not ecologically clean because of application as binding different lacquers partially evaporating at polymerization during heating in the furnace. The replacement of mentioned operations on welding allows to automate process of assembly and, accordingly, to increase its output. From all kinds of welding the most preferable for that operation is laser because of high concentration of energy in a focusing spot, ensuring the minimum size of a thermal effect zone^{(1), (2)} and, accordingly, deformation. The simplicity of radiation transportation in a working zone, processing in air or environment of noble gases (if necessary) enables execution of operations of welding of slices of magnetic circuits with high efficiency and quality. And, as the trial experiments and prior information have shown, for implementation of the given process (obtaining of a solid seam by depth of 0.2-0.6 mm and width 0.1-0.4 mm, ensuring the reliability of the product and minimum of electromagnetic losses) the application of laser head with a mean power of a beam about 180 W is quite sufficient. While development of a manufacturing process, it was decided to use the classical scheme to determine the conditions of irradiation:

- analysis of operation by computer simulation (study the effect of different processing conditions on parameters of a welding bath) and selection of preliminary conditions of processing;
- realization of experiments, with the subsequent matching of the obtained results with results of calculations and assignment of welding conditions ensuring required quality and output.

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2. PROCESS COMPUTER SIMULATION

2.1. Used relations

Fig.1 shows the model of laser irradiation in this study. Laser beam was irradiated in the y-axis on the x-z plane. x-axis shows the distance from the specimen surface. As a model of process was used a non-steady non-linear heat conduction equation (1) with a terminal conditions of a second type (2) and registration of phase transformations (implicit scheme of allocation of their boundaries⁽³⁾), melting and evaporation of a processed material (3):

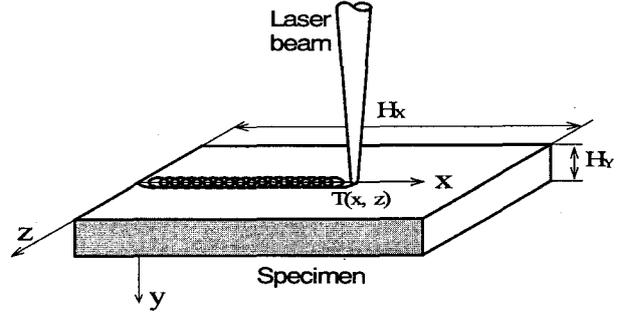


Fig.1 Model of laser irradiation

$$c(T)\rho(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T}{\partial y}\right) \quad (1)$$

$$\left. \begin{aligned} \frac{\partial T}{\partial x}\Big|_{x=0} = 0; \frac{\partial T}{\partial y}\Big|_{y=Hy} = 0 \\ -\lambda(T)\frac{\partial T}{\partial y}\Big|_{y=0} = (1-R(T))W_p(x, t) \\ T_{Start} = 25^\circ\text{C} \end{aligned} \right\} \quad (2)$$

$$C_V(T) = C_V(T) + \delta Q_f(T_f - T) \quad (3)$$

where: x, y, t - space and time co-ordinates;

$\rho(T)$, $C(T)$, $\lambda(T)$, $R(T)$ - relations of density, thermal capacity, heat conduction and optical properties of a processed item's material from temperature T;

Q_f - enthalpy of phase transformation;

T_f - temperature of phase transformation;

δ - Dirac delta function;

H_x , H_y - length and width of an item;

$W_p(x, z, t)$ - relation of a brought power density to an irradiated surface from space and time co-ordinates

2.1.1 Heat source

At determination of a diameter of a focusing spot d and distribution law of intensity in a focusing spot $W_p(x, z)$ a method of "scanning diaphragm" was used, with an after treatment of observed data by a least squares technique. In Cartesian co-ordinate system, in which Y-axis coincides a normal to a processed surface, the function $W_p(x, z)$ at a distance from the focal plane ($\Delta F = 1$ mm) looks like:

$$W_p(x, z, t) = \frac{4P(t)}{\pi d^2} \exp\left(-8\left(\frac{(x_c - x)^2}{d^2} + \frac{(z_c - z)^2}{d^2}\right)\right) \quad (4)$$

where: $P(t)$ - relation of beam power P from time t ;
 d - diameter of a focusing spot, equal 0.3 mm ($\Delta F = 1$ mm);
 x_c, z_c - co-ordinates of center of a beam;
 x, z - present co-ordinates on appropriate axes.

And, x_c, z_c in view of additional circle scanning look like:

$$\left. \begin{aligned} x_c &= x_0 + V_x t + A \cos(2\omega t) \\ z_c &= z_0 + A \sin(2\omega t) \end{aligned} \right\} \quad (5)$$

where: x_0, z_0 - initial position of an axis of a beam;
 V_x - speed of moving of an item coinciding with a x axis;
 A, ω - amplitude and scanning frequency;
 To define the ultimate output of a pulse P_{\max} at process simulation in a pulse mode of activity of the laser a ratio (6) have been used, taking into account equality of a mean power irradiation P_m in different modes of generation and equality of the integral characteristic radiation energies:

$$\int_0^{\tau} P(t) dt = P_m / f \quad (6)$$

where: τ, f - duration and frequency of following of laser pulses

2.2 Methods of the solution

The set of equations (1) - (6) was substituted by finite difference analogue with the implicit scheme of derivatives approximation and irregular steps on space and time co-ordinates on mobile, bound with an axis of a focused beam grid, and was solved by a sweep method⁽⁵⁾. The relations of thermal properties $C(T), \rho(T), \lambda(T)$ of electrical sheet steel corresponded to those was given by B. E. Neimark⁽⁴⁾. In view of absence of the data for this steel about relation of a reflection coefficient to temperature, $R(T)$ for steel U8 (classic carbon steel with 0.8%C, 0.3%Mn, 0.25%Si) with a clean surface was used⁽⁵⁾. All relations ($C(T), \rho(T), \lambda(T), R(T), P(t)$) were interpolated by cubic splines. In given instants on the display of PC the pictures of distribution of temperatures $T(x, y)$ or speeds of thermal cycles $\partial T(x, y)/\partial t$ were injected. On finishing stages of calculations the conclusion of a thermal history $T(x, y, t)$ in considered cross section for all time of integration, relation of infiltration of front of a melting $C_m(x, y, t)$ and evaporation $C_f(x, y, t)$, speed of their motion $\partial C_m(x, y, t)/\partial t, \partial C_f(x, y, t)/\partial t$ etc. was stipulated. The quality of welding was valued on depth and life time of a bath of a melt, determining the entirety of passing diffusion processes.

2.3 Discussions of results of calculations

In Fig.2 the thermal histories of heat affected zones (relation of temperature $T(y, t)$ on different depth y from an irradiated surface from time t) and relation of a power density of the focussed radiation W_p , from time t are presented at processing by a CW laser beam (Fig.2 (a), (b)) and pulsed periodic beam at frequency $f = 150$ Hz, $\tau = 4.5$ ms (Fig.2(c), (d)) for a case, when speed of movement of an item $V_x = 0.3$ m/min (Fig.2 (a), (c)) and for a case, when $V_x = 1.2$ m/min (Fig.2 (b), (d)), and scan frequency $\omega = 0$. Taking into account the large difference between the speeds of component movement (for given working conditions) and differences between the duration of thermal cycles the dependencies $T(y, t)$ and W_p are given in different time scales. The results of calculation of depth of front of a melting $h_m(t)$ for given modes of processing are shown in Fig.3. While processing in a continuous mode of generation, the analysis of relations $T(y, t), W_p(t)$ allows to make the following conclusions:

- lowering temperature in considered cross section is seen in process of increasing of speed of movement V_x ;

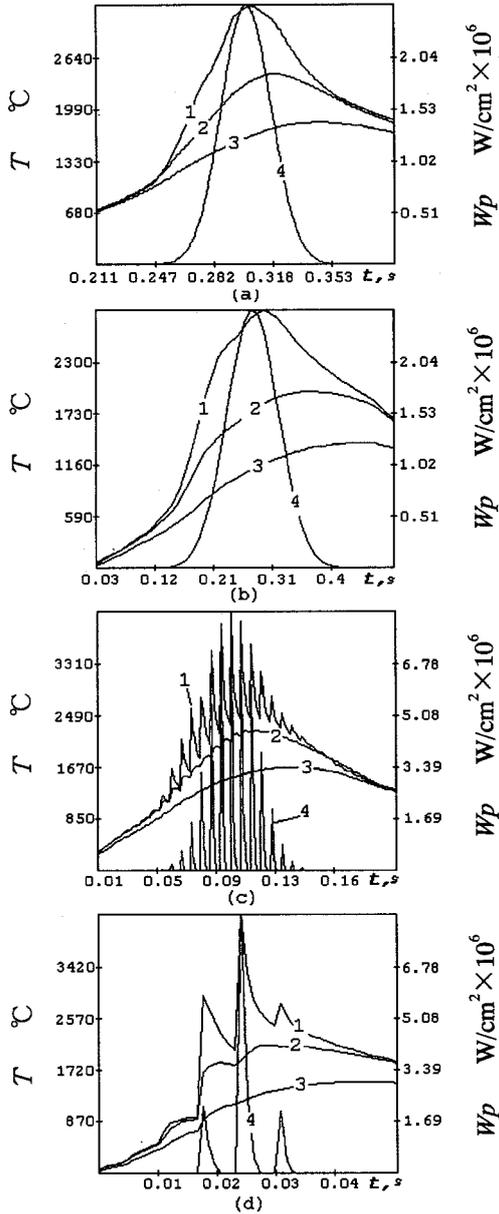


Fig.2 Relation of temperature $T(y)$ on different depth from an irradiated surface and power density of the focused laser beam W_p from time t at processing of an electrical sheet steel with a laser beam with $P_m = 180W$, (a, b- CW mode, c, d -pulse mode) focused in a spot with $d = 0.3$ mm and moving with speed $V_x = 0.3m/min$ (a) and $V_x = 1.2m/min$ (b), where:

- 1 - dependence of temperature $T(y)$ on a surface ($y = 0$) from time t ;
- 2 - dependence $T(y)$ on depth ($y = 0.09mm$) from time t ;
- 3 – dependence $T(y)$ in a case $y = 0.25mm$ from t ;
- 4 - relation W_p from time t .

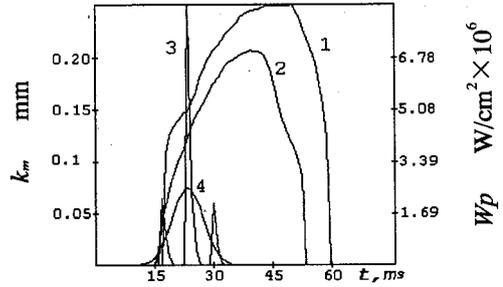


Fig.3 Relation of position of boundaries of a melting front $h_m(t)$ and power density of focused beam W_p from time t at processing of an electrical sheet steel by a laser beam with $P_m = 180 W$, focused in a spot with $d = 0.3$ mm and moving with speed of $V_x = 1.2$ m/min for pulse (1,3) and CW (2,4) laser operations, where:

- 1,2 - relation of position of boundaries of a melting front h_m ;
- 3,4 - relation of a power density of focused beam W_p .

- the relations of temperature to time $T(y,t)$ in considered cross section have smoothly varying character, repeating smoothly varying increasing of a power density of a laser beam W_p ;

- a lag time t_{wait} occurrence of maximum temperature, both on a surface T_{sMAX} , and in depth of a detail, in relation to the moment of a maximum application of energy of a laser radiation is fixed. And, t_{wait} is magnified in process of increase of speed of processing. The latter should essentially change character of interaction of focused laser radiation with a processed material. In the whole studied factor space (speed of movement of a detail $V_x = 0.3... 1.2$ m/min, scan frequencies $\omega = 40... 80Hz$ and etc. temperature of a surface T_s exceeds a boiling temperature of steel T_v . The metal vapor and erosion plasma reduce (because of absorption, reflection etc.) quantity of laser energy reaching processed surface (especially in the case of low speeds of processing). At the expense of growth t_{wait} bound with increase V_x , the pike of a beam intensity "escapes" from plasma, thus magnifying efficiency of interaction of the focussed laser beam with processed surface. While processing in a pulse mode of a laser oscillation and preservation of remaining conditions of processing (Fig.3), the relations of temperature to time $T(y, t)$ repeat (with some delay) periodicity of a source

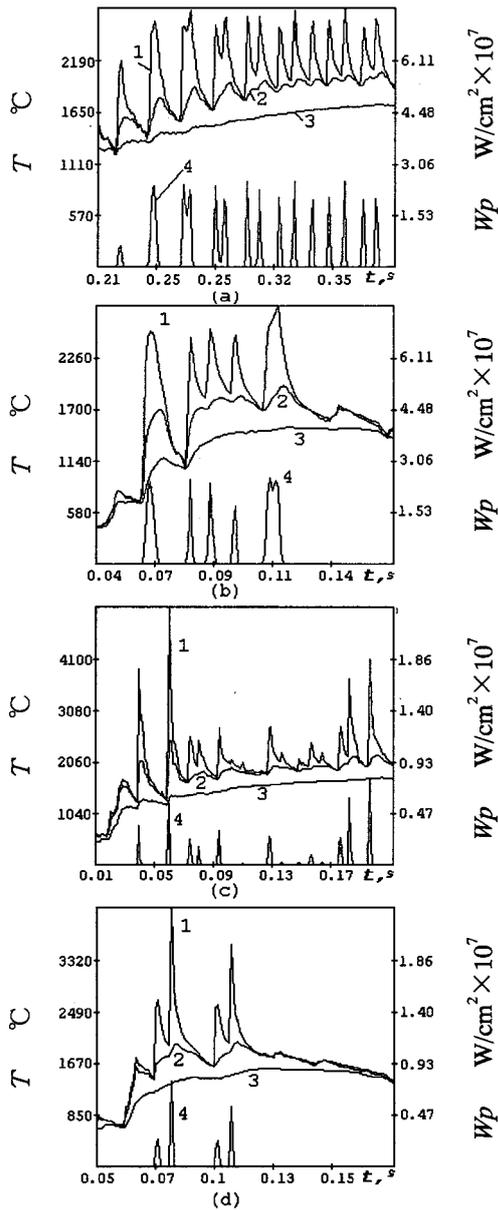


Fig.4 Relation of temperature $T(y)$ on different depth from an irradiated surface and power density of the focused laser beam W_p from time t at processing of an electric-sheet steel by a scanning laser beam with $P_m = 180$ W, (a, b - CW mode, c, d - pulsed mode) focused in a spot with $d = 0.3$ mm and moving with speed $V =$ of 0.3 m/min (a) and $V = 1.2$ m/min (b), ($\omega = 55$ Hz), where:

- 1 - dependence of temperature $T(y)$ on a surface ($y = 0$) from time t ;
- 2 - dependence $T(y)$ on depth ($y = 0.09$ mm) from time t ;
- 3 - $T(y)$ in a case $y = 0.25$ mm; 4 - relation W_p from time t .

of heating. And, in process of increase of depth h , because of a sluggishness of a heating system (damping effect of structural and phase transformations) the relations $T(y, t)$ have more smoothly varying character. Let's mark, that at equal speeds of processing (in melting in the latter case exceeds similar parameters of a zones obtained for a continuous mode of continuous and pulse laser mode), temperature in a zone of irradiation and the depth of front of a processing. It is connected with the fact that in a pulse mode the power of a separate pulse reaches 600 W (6), that density of the focussed beam. We shall underline, conducts to more than 3 growth of power that motion of a phase surface the liquid solid body has different character:

- at a stage of a melting the stepwise growth $h_m(t)$ is seen;
- at cooling - more smoothly varying motion of front of a crystallization (Fig.4).

The latter is explained by increase of damping effect of heats of phase transformations (pairs liquid – solid body) with simultaneous (at the expense of moving beam) lowering of a power density of a laser irradiation in considered cross section. Besides the sluggishness of a heating system and damping effect of phase changes has an effect that the liquid bath magnifies the sizes as well after passing a peak of intensity of the focused beam and, accordingly, maximum of brought laser energy to considered cross section. We shall underline, that in studied factor space, $T_s > T_m$, and as it was indicated this, probably, conducts to lowering efficiency of processing. It was earlier marked, that the increase of speed of welding conducts to increase of quantity of laser energy reaching processed surface. However, despite of high density of power in a focused spot, especially in a pulse mode of processing, the lowering of density of energy, by increase of speed of movement of a detail from 0.3 m/min up to 1.2 m/min, conducts to decreasing (Fig.2, Fig.3) of parameters of a welding bath (life time and depth of penetration of front of a melting):

- depth of a bath of a melt from 370 μm down to 250 μm ;
- time of its existence from 0.14 s down to 0.04 s, that is obviously not enough for obtaining high quality weld joint.

To increase the absorption of energy of the focused laser beam by processed surface the following methods may be used:

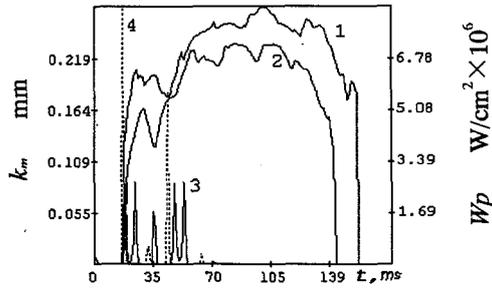


Fig.5 Relation of a position of boundaries of a melting front $h_m(t)$ and power density of focused beam W_p from time t at processing of an electrical sheet steel by a scanning laser ($\dot{u} = 55\text{Hz}$) with $P_m = 180\text{ W}$, focused in a spot with $d = 0.3\text{ mm}$ and moving with speed of $V_x = 1.2\text{ m/min}$ for pulse (1, 3) and CW (2, 4) laser operation, where:
 1, 2 -relation of a position of boundaries of a melting front h_m ;
 3, 4 - relation of a power density of focused beam W_p

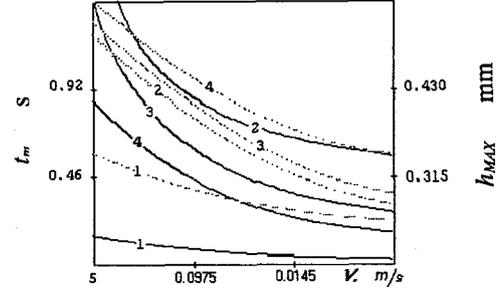


Fig.6 Relation of a position of boundaries of a melting front $h_{mMAX}(t)$ (-) and life time of a liquid bath (...) from speed of a detail movement V_x at processing of an electrical sheet steel by a laser beam with $P_m = 180\text{ W}$, focused in a spot with $d = 0.3\text{ mm}$ ($\tau = 4.5\text{ ms}$, $f = 150\text{ Hz}$) for different scan frequencies, where:
 1-scan frequency $\omega = 0$; 2- $\omega = 55\text{Hz}$; 3- $\omega = 65\text{Hz}$; 4- $\omega = 75\text{Hz}$.

- deposition of light absorbing coatings;
- blowing a steam-gaseous cloud by noble gas;
- additional scanning of the focused beam.

In the present work the last case is studied. At processing with a CW scanning beam, in studied conditions of component speed of movement changes (Fig.4 (a), (b)), temperature in considered cross section repeats periodicity of heating (moments of appearance of a beam). And, as well as in a described earlier case of a pulsed welding, periodicity of heating all less has an effect with growth of depth. Besides some lowering of a surface temperature is watched, that is connected with a high speed of movement of a focusing spot on a surface of a sample. However, at the moment of counter motion of a detail and focused beam, when the general speed of a beam is equal to a difference of speeds of a detail and beam scanning and in some cases is close or is equal to null, the short term temperature splashes on a surface of a detail, exceeding temperature of evaporation T_v , are observed. Thus, because of a high speed of movement of a heating source permanently escaping plasma, the efficiency of laser radiation absorption by a processed surface is increasing, that, accordingly, conducts together with repeated pass by the beam of an exposure zone, to growth of the sizes of a bath of a melt. In process of increase of a scan frequency (in considered range of change ω) and, accordingly, of general speed of a beam, the efficiency of formation of weld joint increases.

The similar picture is watched and in case of irradiation by a scanning pulse beam (Fig.4c, d): the thermal history in considered cross section repeats periodicity of a heating source, and temperature reaches maximum in those instants, when minimum general speed of a beam coincides with moment of beam generation and so on. Thus as in case of absence of scanning, because of high density power of the focused beam, the life time of a liquid bath and depth of its spreading into a body of a detail, exceed the parameters of a welding bath obtained at similar working conditions in case of use a continuous mode of generation (Fig.5).

The scanning of a laser beam within the limits of a focusing spot at maximum speeds of processing conducts to increase of a life time of a melt and depth of a welding bath:

- depth of a bath of a melt up to $350\text{ }\mu\text{m}$;
- time of its existence up to 0.25 s ,

that allows to obtain high quality joint of slices of a magnetic circuit.

Analyzing the results of calculations, we shall mark, that in all cases the scanning of a laser beam conducts to

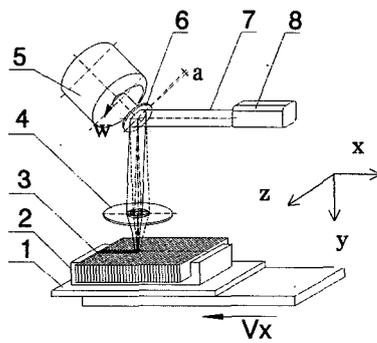


Fig.7. Schematic view of experimental setup for laser welding of slices of a magnetic circuit, where:
 1 - working table; 2 - gear; 3 - slices;
 4 - focusing lens; 5 - scanning engine;
 6 - scanning mirror; 7 - laser beam; 8 - laser.

increase of a life time of a melt (that promotes diffusion processes) and depth of molten metal increased with a scan frequency. The processing on low speeds of irradiation, allows receiving welds with maximum parameters of a welding bath. However, because of an overheating of a zone of processing (in a Fig.6 relations of a maximum depth of a liquid bath and time of its existence t from speed of processing for different scan frequencies are presented computed with the help of a system (1) - (6), the processing at maximum speeds with beam scanning is appeared to be expedient. Besides at increase of a scan frequency up to $\omega = 75$ Hz, the balance between laser energy input and heat drained from a HAZ at the expense of natural heat conduction is watched. In this case, the depth of a bath of a melt decreases in comparison with irradiation with frequency $\omega = 65$ Hz. However, due to a high speed of movement of a scanning beam permanently heating a melt, the time of its life is magnified, that doubtlessly will have an effect on quality of welded joint.

3. RESULTS OF EXPERIMENTAL RESEARCH

The experimental check of the obtained results was implemented on a setup equipped (Fig.7) with 180W YAG laser, working in continuous and pulse modes, and working table moving with speeds 0.3 - 1.2 m/min. The packets of slices of an anchor of the micro electric motor were held in special appliance and were processed at different working conditions. In each experimental point three samples were handled. In further, the single seams were tested on a break, the micro sections were made, on which depth and width of a bath of a melt were determined.

The graphic interpretation of experimental results is given at Fig.8. As expected, maximum sizes of a welding bath: depth (Fig.8 (a)), its width (Fig.8 (b)), and breaking load (Fig.8 (c)) are observed at use as the tool of the scanning focused laser beam. The minimum gradients on considered relations are watched at standard laser welding, that is

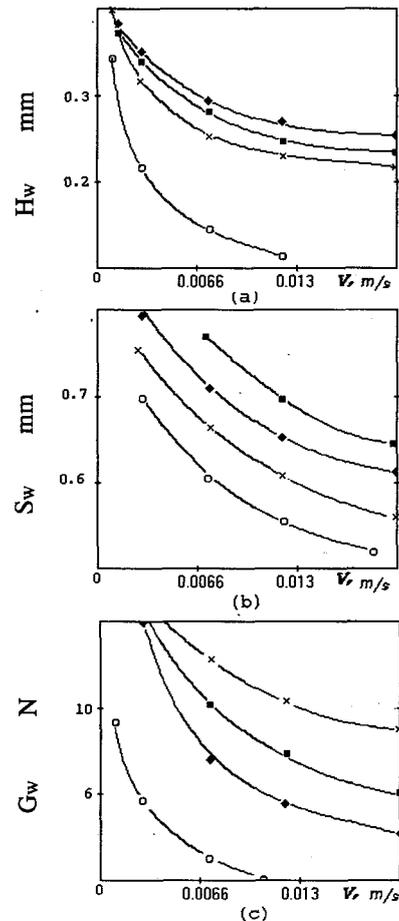


Fig.8 Relation of depth H_w (a) and width S_w (b) and braking loads G_w (c) of a welding seam from speed of a detail movement V at processing of an electrical-sheet steel by a laser beam with $P_m = 180$ W, focused in a spot with $d = 0.3$ mm ($\tau = 4.5$ ms, $f = 150$ Hz) for different scan frequencies, where:
 O - scan frequency $\omega = 0$;
 ◆ - $\omega = 55$ Hz;
 ■ - $\omega = 65$ Hz;
 × - $\omega = 75$ Hz;

connected with smooth (in process of increase of speed of processing) decreasing of energy density and, in case of pulse heating, decreasing of an overlapping coefficient of laser heated spots. Besides the maximum breaking loads are watched at processing by the focused laser beam scanning with frequency $\omega = 75 \text{ Hz}$ (Fig.7), that is connected, as it was marked, not with maximum depth of a bath of a melt, but with time of its existence. It is necessary to mark, that in case of a CW mode of generation, at speeds of processing exceeding 0.8 m/min, in all researched frequency band of beam scanning it was not possible to receive a high quality reliable joint of slices of a magnetic circuit, that is connected, perhaps, with a small life time of a liquid bath (less than 0.12 s) and, accordingly, with not by full diffusion. Thus, in the studied range of speeds of component movement, scan frequencies and laser operations, the welding of slices of a rotor of the micro electric motor is expedient to perform at a highest speed, with the purpose of obtaining maximum output of operation, with a scan frequency within the limits of a focused spot, equal 75 Hz. At conditions it is expedient to perform welding of slices of the transformer as well. In spite of the fact that even the single welding seam usually prevents slices from a separation, because of a poor quality sheet metal stamping, which appears especially in process of stamp wear, the welding seams may have some defects (influenced by gap between slices). Therefore, it is recommended to superimpose welding seams parallel to places of their mechanical joint. On determined conditions of irradiation the experimental batch of micro electric motors and transformers was processed, which bench tests have established their conformity to hardware products received on the standard technology.

4. CONCLUSIONS

The quality conformity of relations of parameters of a welding bath obtained as a result of the solution non-linear non-steady equation of heat conductivity in view of phase transformations, to seam depth and breaking loads obtained experimentally, is established.

- (1) The beam scanning within the limits of a focused spot conducts to lowering temperature of a processed surface and growth of life time of melting bath, that is connected, probably, with more effective absorption of a laser beam by a processed surface and its repeated passes on an irradiated zone.
- (2) The maximum quality of weld joint is determined not only by depth of penetration of front of a melting bath, but also by the time of its existence.
- (3) The greatest output of operation in studied factor space is possible in case of application of lasers working in a pulse mode with additional scanning of a beam.
- (4) The laser welding of slices of a magnetic circuit does not aggravate parameters of off the shelf items (in comparison with the standard technology).
- (5) The application for preliminary research of process multidimensional non-linear non-steady equation of heat conductivity in view of phase transformations, considerably reduces time expended for designing of the technology.

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