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STUDY OF THE PROCESS OF RAPID PROTOTYPING WITH LASER BEAM

Анотація

У роботі, за допомогою обчислювальних експериментів, досліджується технологічний процес створення виробу за допомогою технології Rapid Prorotyping (основна схема обробки — метод спікання порошкового матеріалу, який був ущільнений). У якості матеріалів, з яких буде виготовлено майбутній виріб, розглядаються порошкиа на основі Ni та Co.

Встановлено, що на параметри ванни розплаву роблять вплив параметри сфокусованого лазерного випромінювання (густина енергії, густина потужності) але і властивості порошкового матеріалу (склад, кількість атмосфери, його товщина матеріалу), та властивості матеріалу, який був отриманий на попередньому технологічному циклі. У роботі встановлено, що за допомогою додаткового сканування сфокусованого лазерного випромінювання, в межах плями фокусування, можливе підвищення ефективності і якості виготовлення виробів за допомогою технології Rapid Prorotyping.

Abstract

Some research results of the developed technology of rapid prototyping are presented. Two schemes of process realization are discussed. First scheme lies in laser sintering of the powder material layer after its compressing with rollers, second - in material sintering at powder injection into the zone of laser irradiation. As a basic material for products' manufacturing, different powders based on Ni, Co and others were studied. Numerical experiments and their planning were used to find the optimal working conditions. It was found that to increase the productivity and processing quality, without introduction of additional energy sources, the most efficient way was to apply the additional scanning of the focused laser radiation within the limits of the focused spot.

Introduction

The increase in productivity and quality of laser processing technology (and basically of any other technology) is usually achieved by minimization of machining and auxiliary times, optimization of modes of processing and an introduction of additional energy sources into a zone of laser (irradiation) influence. The above mentioned tools are interconnected among each other.

Having taken the advantage of terminology of laser marking [1] (plane marking — analogue of dot-matrix marking and vector marking), we may state that manufacturing of thin-walled details by vector method is the most rational (Fig. 1). Optimization of modes of processing (for the given type of the equipment) provides the maximal productivity for the estimated level of quality (or vice versa). Introduction of additional energy into a zone of laser influence (ultrasonic fluctuations, electric current, electric arc, water pressure) allows to increase considerably the productivity and quality of processing with minimum (in comparison with the cost of laser equipment) capital investments. The specified methods of the increase of laser processing' productivity are successfully applied at various technologies: from drilling, cutting and alloying. At manufacturing a product with Rapid Prototyping technology, the application of the given methods not expedient because of the time lag of power supply systems of additional energy sources. Moreover, when a product is manufactured by sintering of preliminary con-

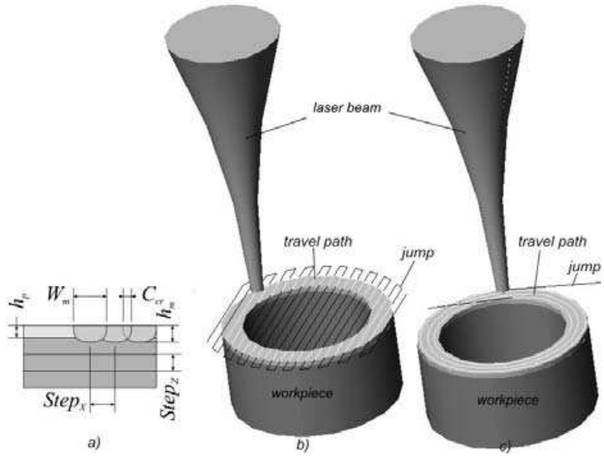

Fig. 1. The scheme of layer dispositions in treated zone, which forms a detail using Rapid Prototyping technology, where:
a — the scheme of layer dispositions in treated zone;
b — Sintering of powder material "layer by layer " with its compaction by rollers (plane scheme); *c* — Sintering of powder material with its injection into the focusing spot of laser radiation (vector scheme)

densed powder layer with scanning laser beam, it is practically impossible to supply additional energy into a zone of laser influence, due to the lack of rigid connection of an axis of a laser beam with system of delivery of additional energy into a zone of laser influence.

One of the most efficient methods that allows to increase the productivity and quality of performed operations is the management of distribution of energy density $W_E(x, y)$ of the focused beam on a surface of a sample. Optimization of $W_E(x, y)$ is achieved by means of alteration of power density of focused laser beam $W_P(x, y)$. In this case special focusing systems (mirror ones, diffractive optical element, for example, [2—4]) that change the law of distribution of intensity of a stream of laser radiation which has left the resonator. Another way is to provide additional scanning (with the help of moving of tilting or focusing optics) on a surface of a sample [5—9].

It is worth to mention, that at manufacturing products on technology Rapid Prototyping a vector method, use of the first way of management $W_E(x, y)$is inconvenient, because of moving to space of a spots of focusing under the any law and necessity of tracking of a trajectory of its moving делительным in unit. Additional scanning of laser radiation (within the limits of a spot of focusing) is easily realized in two circuits of laser prototyping: sintering of preliminary condensed powder layer by scanning laser radiation to the circuit of direct inflation of a powder in a zone of laser influence. Therefore, the given work is devoted to research of Rapid Prototyping technology with scanning laser beam.

Theoretical consideration

As well as for any kind of laser technology, the main technology factors of process of Rapid Prototyping are factors which render the direct influence on energy density $W_E(x, y)$ and power density $W_P(x, y)$ of the focused laser radiation — average power P_m, speed of movement V_x, focusing spot radius r_p and other). Among responses of the process that are possible to determine with the help of calculation experiments, are:

- Parameters of a melt bath (depth h_m, width W_m and time of existence t_m) which was formed under action of the focused laser radiation;
- The law of the focused beam movement on a surface of a detail;
- Coefficient of overlapping of paths CC_r and a step of escalating on vertical coordinate $Step_Z$ (Fig. 1 *a*).

Thus at process realization the following factors had to be considered:

- The minimum thickness of walls of the future detail. Thus thickness of a wall (without shrinkage) cannot be less, than width W_m of a melt bath;
- A step of escalating on vertical coordinate which less or is equal to depth of a melt bath;
- Time of melt existence should be sufficient for realization of diffusion processes and creation of a detail with the set of physico- mechanical properties.

As a model of process the nonlinear non-stationary system of equations of heat conductivity with respect to phase transformations was used (1). To get the numerical solution to the problem, system (1) was replaced with finite-difference analogue with the implicit scheme of approximation of derivatives and non-uniform steps on spatial and time coordinates. Furthermore, the finite-difference system was solved with method of racing with the iterative scheme that takes nonlinearities into account. In addition to that, dependences of thermo-physical properties of sample material from temperature were interpolated by cubic splines. With this type of Rapid Prototyping technology, the condensed powder material is merged with the surrounding atmosphere (air, argon and other) and its contents depends on the particles size, thickness of a layer which is rolled, rolling load, etc. Dependences of thermo-physical properties of powder materials from the temperature, thickness and the quantities of layers (assuming that thermal contact between layers is ideal) were determined with help of additivity equations (2). The content of an atmosphere in a powder material were also estimated with help of the additive equations. The laser beam with power distribution $W_P(x, y)$ (3) scanned on a surface of a workpiece is governed by the equation (4).

$$\left.\begin{aligned}
&c_\Sigma(T)\rho_\Sigma(T)\frac{\partial T}{\partial t} = \\
&= \frac{\partial}{\partial y}\left(\lambda_\Sigma(T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial x}\left(\lambda_\Sigma(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(\lambda_\Sigma(T)\frac{\partial T}{\partial z}\right) \\
&c_{\Sigma_v}(T) = c_{\Sigma_v}(T) + Q_{\Sigma f}\,\delta(T - T_f) \\
&T_{start} = 25^0 C \\
&\left.\frac{\partial T}{\partial x}\right|_{\substack{x=0\\x=HX}} = \left.\frac{\partial T}{\partial z}\right|_{\substack{z=0\\z=HZ}} = \left.\frac{\partial T}{\partial y}\right|_{Y=HY} = 0; \\
&-\lambda_\Sigma(T)\left.\frac{\partial T}{\partial y}\right|_{y=0} = A_\Sigma(T)\cdot W_P(x,y,t)
\end{aligned}\right\} \quad (1)$$

$$\begin{aligned}
c_\Sigma &= \sum_{j=1}^{k} c_{1j} k_{1j}(T,x,y,z)\Big|_{\substack{x=0,\dots,x_1\\y=0,\dots,y_1\\z=0,\dots,z_1}} + \dots + \\
&+ \sum_{j=1}^{k} c_{ij} k_{ij}(T,x,y,z)\Big|_{\substack{x=0_{i-1},\dots,x_i\\y=0_{i-1},\dots,y_i\\z=0_{i-1},\dots,z_i}}
\end{aligned} \quad (2)$$

$$W_P(x,y) = \frac{2P_m}{\pi r_P^2}\exp\left(-\frac{2\left((x-x_c)^2 + (y-y_c)^2\right)}{r_p^2}\right) \quad (3)$$

$$x_c(t) = x_o + V_x t + AsCos(2\omega t)$$
$$y_c(t) = y_o + BsSin(2\omega t) \quad (4)$$

where: $c_\Sigma(T)$, $\rho_\Sigma(T)$, $\lambda_\Sigma(T)$ — dependencies of heat capacity, density and heat conductivity of material from temperature T

$c_{\Sigma_v}(T)$ — volumetric heat capacity;

$Q_{\Sigma f}$ — latent heat of phase transformation;

δ — δ — Dirac function;

T_f — latent heat of phase transformation;

T_{start} — initial temperature of the sample;

HX, HZ, HY — dimensions of sample;

$A(T)$ — dependence of the absorption coefficient of the laser radiation from temperature T;

c_{ij}, ρ_{ij}, λ_{ij} — dependencies for heat capacity, heat conductivity and density for i component and j layer of composition material;

k_{ij} — amount of i component of j layer;

x_i, y_i, z_i — size of i-layer i-material;

P_m — average power of radiation;

r_P — radius of the focused spot

x_c, y_c — the current coordinates of an axis of the focused laser beam;

x_0, y_0 — initial position of an axis of a beam;

As, Bs, ω — amplitude and frequency of scanning.

Let's consider process of interaction of the focused laser radiation with powder materials on Ni-based (powder type PGSR-3) and Co (powder type PG-10K-01) with the contents of an atmosphere of 5—15%. Percentage of components in the specified powder materials is presented in Table 1.

Dependences of thermo-physical properties (density $\rho_\Sigma(T)$, heat conductivity $\lambda_\Sigma(T)$, and thermal capacities $c_\Sigma(T)$) of powder materials from temperature were determined by the additivity equations (3), using data presented in Tab.1 and in reference literature [10]. Phase transformations (solid body — melt - evaporation phase — solid body) that occur in a material of a sample during laser heating had been considered, taking into account the implicit allocation of their borders. Temperature dependences of absorbing ability of powder compositions have been established with the help of experiments which are shown in detail in the reports [11].

Table 1

Percentage of alloying elements in powder compositions

The elements	Type of a powder	
	PGSR-3 (100%)	PG-10K-01(100%)
Ni	95,9	28
B	1,2	1,2
C	0,4	1,3
Si	2,4	1
Fe	0,1	0,1
W	-	2,5
Cr	-	21
Co	-	44,9

While analyzing the experimental results, it was noted that the main factor that influences thermophysical properties of powder is the content of the basic element in it. For example in Fig. 2 the dependencies of heat conductivity of PGSR-3 powder particles and heat conductivity of PGSR-3-based alloy from temperature.

Presence of other elements despite of their low contents influences the thermal capacity and is observed only at high temperatures (in the field of phase transformations of components) (Fig. 3).

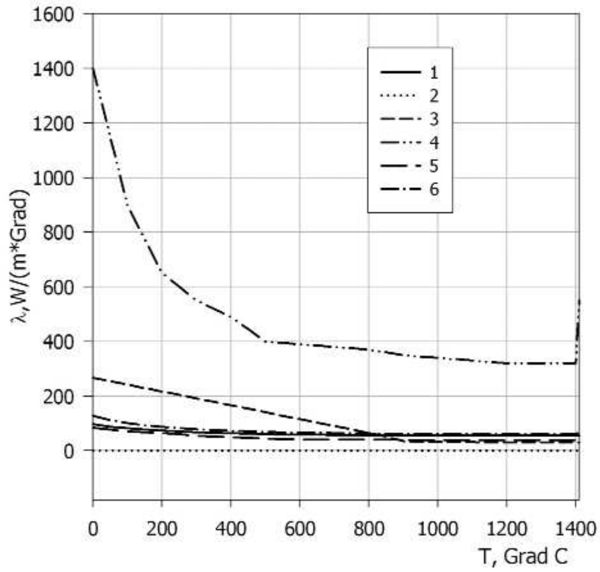

Fig. 2. Heat conductivity of components of powder PGSR-3 and an alloy on a basis of PGSR-3 powder to temperature, where:
1 — Ni; *2* — B; *3* — C; *4* — Si; *5* — Fe; *6* — alloy on base PGSR-3

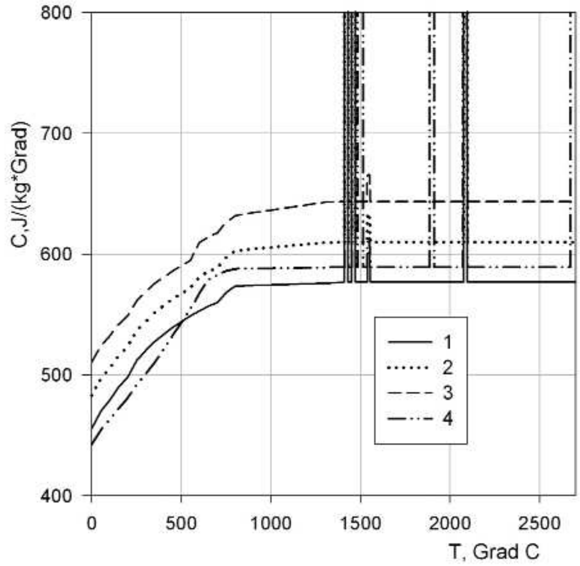

Fig. 3. Heat capacity of material to temperature, where:
1 — alloy on base PGSR-3; *2* — powder PGSR-3 with the contents of an atmosphere of 5%; *3* — powder PGSR-3 with the contents of an atmosphere of 10%;
4 — alloy on base PG-10K-01

Results and discussion

The increase in percentage of an atmosphere in gaps between powder particles (read — the density of rolled powder) leads to the reduction of its heat conductivity, density and to the increase of thermal capacity (Fig. 3). The specified changes occur at laser heating of a powder with different concentration of an atmosphere in it. So, while heating the powder PGSR-3 with laser radiation at power P_m = 150 W focused in a spot of the radius r_p = 0,6 mm, moving at speed V_x = 2 mm/s, reduction in powder density leads to the growth of sample surface's temperature, the dimensions of a melt bath and time of its existence (Fig. 4). It is necessary to note, that here and further parameters of a melt pool (depth h_m, width W_m and time of existence t_m) were defined on

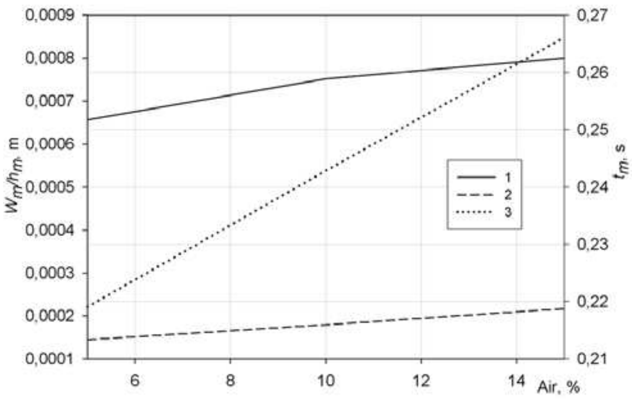

Fig. 4. Parameters of a melt pool (width W_m, depth h_m and time of existence t_m) of sample made of powder PGSR-3 to concentration of an atmosphere (Air, %) (P_m=150 W, r_p =0,6 мм, V_x = 2 mm/s), where:
1 — width W_m of a melt bath to Air, %; *2* — h_m to Air, %; *3* — t_m to Air, %.

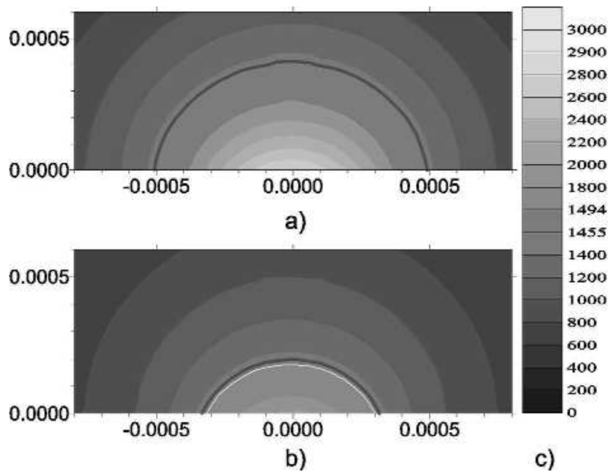

Fig. 5. Temperature distribution in samples, made of powders PGSR-3 and PG-10K-01 (P_m=150 W, r_p =0,4 мм, V_x = 2 mm/s, air contents — 5%) where:
a — sample from powder PGSR-3; *b* — sample from powder PG-10K-0; *c* — scale bar for temperature;
"___" melt bath for Ni, "___" melt bath for Co

limiting positions of a line of phase transformation temperatures of matrix material.

For different thermo-physical and optical properties of powder mixtures on the basis of PGSR-3 and PG-10K-01, under identical heating conditions, the parameters of melt bath that forms in samples under action of laser radiation appeared to be different (Fig. 5). And apart from more efficient absorption of laser radiation by powder PG-10K-01, under identical processing conditions, values of parameters of melt pool in Ni-based powder are essentially higher, than similar melt pool parameters for powder PG-10K-01.This could be explained either by greater heat conductivity at high temperatures of primary powder metal Co (in comparison with Ni) and, correspondingly, of mixtures, or by the influence of high specific heat of melting of Cr and W on the amount of laser energy spent for phase transformations.

Taking into account the significant content of Ni in powder PG-10K-01 (Table 1), its sintering (melting) is possible due to the diffusion in a liquid phase not only of the basis material (Co), but also of an alloying material — Ni.

It is obvious that the parameters of a melt pool also depend on the thickness of a layer of the powder covering material that was alloyed during previous heating cycle. Thus, the parameters of a liquid bath, that forms while processing the specified composition of materials, change, in comparison with the processing of mono systems.

Let's consider, as an example, a processing system that consists of a layer of powder PGSR-3 with the atmosphere contents of 10% and a layer of an alloy on the basis of the specified powder. With the increase of a thickness powder layer h_p, depth h_m (dependence 2, Fig. 6) and time of existence t_m (dependence 1 Fig. 6) of liquid bath decrease.

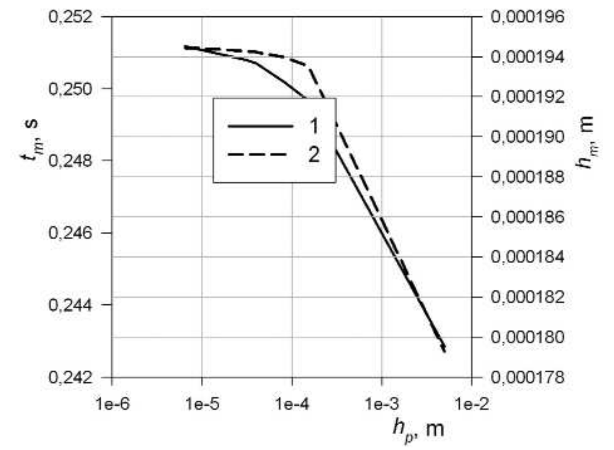

Fig. 6. Parameters of a melt pool (depth h_m, time of existence t_m) in a sample made of composition of powder PGSR-3 and an alloyed powder PGSR-3 to thickness of the powder layer h_p (P_m = 150 W, d_p = 0,6 mm, 10% Air), where:
1 — time of existence of a melt bath t_m to powder layer thickness hp; *2* — depth of a melt pool h_m to powder layer thickness h_p

The specified phenomenon is explained by the increase in volume of a material with low heat conductivity that locates heat in a superficial layer and adjoins to a mono-material. It does not give an opportunity for the phase transformation front to move effectively into depth and leads to the reduction of volume of a liquid bath and, correspondingly, minimizes time of its existence.

While creating products with prescribed physical and mechanical properties, layers of the future detail may be made of various materials. One example is the formation of consecutive layers of powders PGSR-3 and PG-10K-01. In comparison with manufacturing from monolithic material (identical conditions of laser processing), the depth of a melt bath for the aforementioned composition changes. In a mixture of powder PGSR-3 and an alloyed PG-10K-01 powder layer, the depth of a melt bath increases, on the contrary, the mixture of powder PG-10K-01 and alloyed PGSR-3 powder layer causes reduction of melting zone dimensions (Fig. 7). As well as in previous cases, melting depth was determined by the fusion temperature of matrix material. In the first case, the specified phenomenon is explained by either the increment of heat conductivity of the bottom layer of the molten material that promotes penetration of fusion front of Ni to more significant depth or by the decrease of percentage of Ni in the alloy PG-10K-01, that also leads to the increase of fusion front depth. It is necessary to note, that materials, the powder PG-10K-01 consists of, have significant specific fusion heat and accumulate a significant amount of energy which is gradually spent for the movement of molten Ni.

In the second case, the reduction of penetration depth hm is explained by the increase of total specific fusion heat of a powder material which covers alloy of PGSR-3. It should be noted that with the increase of laser processing speed above 0,006 m/s (P_m = 150 W, r_p = 0,4 mm), the energy density of the focused laser radiation is not enough for melting of a basis of the bottom layer of material. In this case, the joining of layers of a material is possible due to the diffusion of Ni in liquid phase (a component of powder PG-10K-01) into the alloyed PGSR-3 layer.

For the given laser system (power, mode of generation and other), the increase in speed of movement of the focused laser beam can be achieved due to the reduction of focusing spot (increase in power density of the focused laser radiation). However, change of the focusing spot size will cause ambiguous influence on the size and time of existence of a melt bath. Fig. 8 Shows the dependencies of laser radiation power density $W_P(t)$ and of surface temperature $T(0,\ t)$ in samples from the composition of powder PGSR-3 with 30 m thickness (the atmosphere contents 10%) and an alloyed PGSR-3 powder layer from time t are given which were observed at processing by laser radiation by power P_m = 150 W, moving on a surface with speed V_x = 20 mm/s for different focusing spots.

It is apparent from the presented curves that with laser beam focused to a spot of 0.1—0.2 mm, the surface temperature of a sample exceeds the evaporation temperature of a basis material of the powder mixture (curves 5, 6 on Fig. 8). It is obvious, that while irradiating with a focused spot size of r_p = 0,1 mm

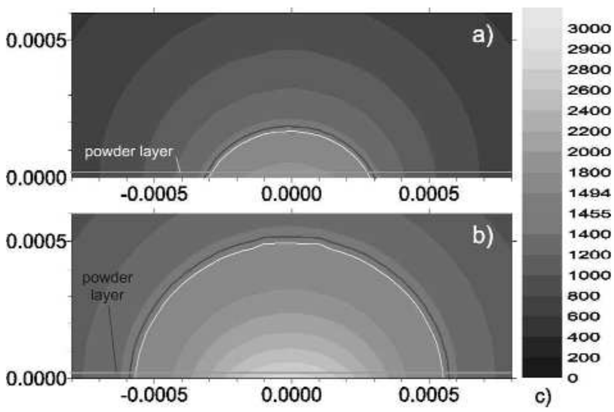

Fig. 7. Temperature distribution in a sample made of composition powder PG-10K-01 and an alloyed powder PGSR-3 (*a*) and in sample made of composition of powder PGSR-3 and an alloyed powder PG 10K-01 (*b*) (P_m = 150 W, r_p = 0,4 mm, V_x = 2 mm/s, thickness of the powder layer h_p = 30 m and air contents — 10%) where: *c* — scale bar for temperature; "___" melt pool for Ni, "___" melt pool for Co

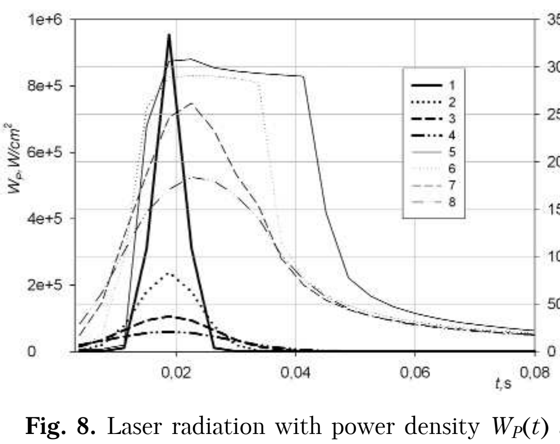

Fig. 8. Laser radiation with power density $W_P(t)$ and surface temperature $T(0,\ t)$ of a samples composed of composition powder PGSR-3 and alloyed PGSR-3 powder layer to the size of focusing spot r_p (thickness of powder layer h_p = 30μm, 10% Air, P_m = 150 W, V_x = 20 mm/s), where:
1 — dependence $W_P(t)$ from time *t* for r_p = 0,1 mm; *2* — $W_P(t)$ for r_p = 0,2 mm; *3* — $W_P(t)$ for r_p = 0,3 mm; *4* — $W_P(t)$ for r_p = 0,4 mm; *5* — dependence of a surface temperature $T(0,\ t)$ sample from time *t* for r_p = 0,1 mm; *6* — $T(0,\ t)$ for r_p = 0,2 mm; *7* — $T(0,\ t)$ for r_p=0,3 mm; *8* — $T(0,\ t)$ for r_p = 0,4 mm

(P_m = 150 W, V_x = 20 mm/s), the destruction of coating material occurs and does not allow to obtain high quality product [11—13]. Focusing of laser beam to a spot with r_p = 0,2 mm initiates material surface evaporation, thus the dimensions of the melt bath increase in comparison with the previous case. The gradual increase in size of focusing spot leads to the reduction of the melt pool dimensions, and more intensive shortage of depth hm and time of existence tm (Fig. 9).

Changes of speed of the focused laser beam movement (at constant power density) will also modify parameters of a melt pool. It is obvious, that for given values of WP, increment in moving speed of the focused laser beam will reduce the size of a melt bath. Fig. 10 shows the parameters of a melt bath, that occur while irradiating the composition of a layer of powder PGSR-3 with thickness 30 м (atmosphere contents 10%) and an alloy on the basis of PGSR-3 with the focused laser beam (P_m = 150 W, r_p = 0,3 mm), in relation to the speed of laser processing.

As it was mentioned above, for the given schemes of laser processing, the use of the specific devices leads to the increase of processing costs, because of significantly overpriced equipment. For this reason, changes of energy density $W_E(x, y)$ of the laser radiation focused on a surface of a sample (due to its additional scanning), would be the simplest way of control for the size and time existence of a melt bath. Besides, as it is shown in [5—9], the increase of productivity of operation is achieved for the account of an increase of absorption efficiency of the focused laser radiation. Thus it is known, that during laser heating of a sample, growth of a sample temperature leads to the increase of absorption abilities [11]. But at phase transformations which occur during laser heating: solid body — liquid — vapor, there is a "spasmodic" reduction of laser energy which has reached the sample surface. The given phenomenon is explained by a number of reasons: plasma shielding and refocusing of laser radiation in plasma, changes of focusing spot (plasma and heated air near a surface are the media that have square law factor of refraction of light which depends on medium temperature of environment).

Thus to increase the productivity and the quality of laser processing the use of additional scanning of the focused laser radiation in the spot of its action is recommended, and the easiest way of realization is focused laser beam scanning under the elliptic or the harmonic law [5—9, 14, 15].

In our case, at additional scanning the focused laser radiation, which moves parallel to the axis OX (for example, under the elliptic law), coordinates of the centre of focusing spot could be found with help of equation (4). We shall note now that with additional focused laser beam scanning, the influence of it on parameters of a liquid bath (which was formed at laser processing) is possible not only due to change of P_m, V_x, r_p, but also at change of amplitude *As*, *Bs*, and frequencies of scanning ω as well.

While the continuous scanning focused laser beam in researched modes of change of sample speed, the temperature in considered section responds to the periodicity of heating (the moments of beam's peak occurrence). And, as well as at laser welding and cladding, the periodicity of heating affects with

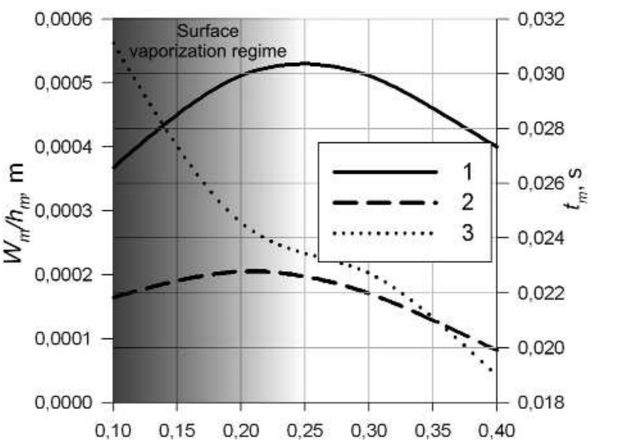

Fig. 9. Parameters of a melt pool (depth h_m, width W_m and time of existence t_m) of a sample composed of the powder PGSR-3 and an alloyed powder layer PGSR-3 to the size of focusing spot r_p (P_m = 150 W, V_x = 20 mm/s, powder layer thickness h_p = 30 mm, 10% Air) where: *1* — width W_m of a melt bath to speed V_x; *2* — depth h_m of a melt bath to speed V_x; *3* — time of existence t_m of a melt bath to speed V_x

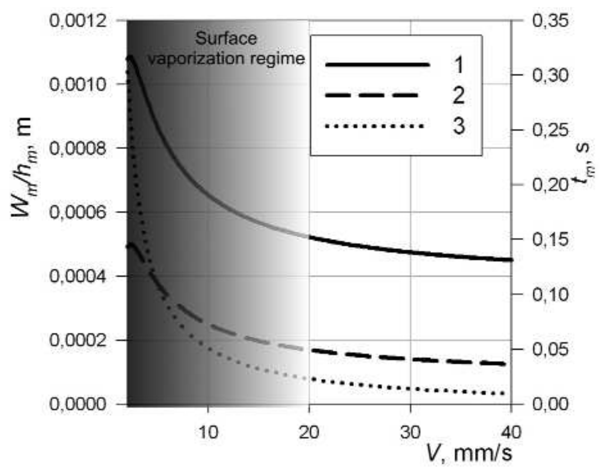

Fig. 10. Parameters of a melt pool (depth h_m, width W_m and time of existence t_m) of a sample composed of powder PGSR-3 and an alloyed PGSR-3 layer powder to processing speed V_x (P_m = 150 W, r_p = 0,3 mm, thickness of the powder layer h_p = 30 mm, 10% Air): *1* — width $W_m(V_x)$ of a melt bath to speed V_x; *2* — depth $h_m(V_x)$; *3* — time of existence $t_m(V_x)$

growth of depth lessens. A decrease in surface temperature is observed as well, which could be explained by high speed movement of focusing spot on a surface of a sample. Nevertheless, at the moment when focused beam strikes the sample and their resulting speed equals the difference of speed vectors of the sample and scanned laser beam and, which in some cases is close to or is equal to zero, the short-term rises in temperature of a surface of the sample are observed. This, correspondingly, leads (along with laser beam multy-pass scanning of zone of processing) to growth of melt pool size. With the increase in frequency of scanning (in an analyzed range of ω) and, correspondingly, resulting speed of the focused beam and the sample, the efficiency of formation of interconnections of the melted powder mixture and a of a substrate material grows.

Productivity and quality of formation of separate melted "pathes" and their groups rise because of the reasons listed below. First reason is the sluggishness of heating systems which is shown in the certain time lag (Fig. 8) between the maximum sample surface temperature and an axis of the focused laser radiation (according to the maximal power density of the focused laser beam). Second reason is high-speed scanning of focused laser beam (affects the reduction of energy density of the focused laser beam) and melt pool existence time in limits of 0.01—0.3s. Finally, it is possible due to multiple passes of the focused laser beam along the irradiated zone (depends on speed V_x of beam movement, amplitude and frequency of its scanning, that allows "to warm up" a liquid phase longer, than with ordinary laser processing).

It could be noted from the presented dependences that with focusing of laser beam (power 150 W) into a spot with radius 0.1 and 0.2 mm, the power density reaches values of $9.5 \cdot 10^5$ W/cm^2 and $2.4 \cdot 10^5$ W/cm^2, respectively. If focused laser beam moves along the surface of a sample with a speed of 20 mm/s, the peak laser energy density in a processing zone reaches values $5.98 \cdot 10^4$ J/cm^2 and $2.99 \cdot 10^4$ J/cm^2, respectively. As it was mentioned earlier, at laser processing of the mixture of composition powder PGSR-3 and PGSR-3 alloyed powder layer, on the specified modes, there is an evaporation of surface layer that leads to destruction (Fig. 8—10) of coating material.

At additional focused laser radiation scanning, due to the change in speed of movement of focused beam axis and the processing zone, there is a change in the maximum energy density $W_E(x, y)$ of the focused laser beam in a processing zone and, respectively, in a surface temperature.

Thus, in Fig. 11 the distribution of energy density along a focused laser beam' speed vector (V_x = 20 mm/s) on a surface of a sample (focusing spot with radius 0.1 mm and 0.2 mm) with different parameters of scanning is presented.

In the considered range of focusing spot sizes and parameters of scanning of the focused laser beam, in comparison with usual laser processing that is when ω =0, (Fig. 3—9) there are significant changes in energy densities of the focused laser radiation in the processing zone. So, while preserving the power density of the focused laser radiation and speed V_x of sample movement at their respective values, it is possible both increase (Fig. 10) and to reduce the maximum of energy density of the focused laser beam. The increase in energy density occurs when the resulting speed of focused beam movement is close (or equals) to zero. Changes in focused laser beam' energy density (due to its additional scanning) affects parameters of a melt pool.

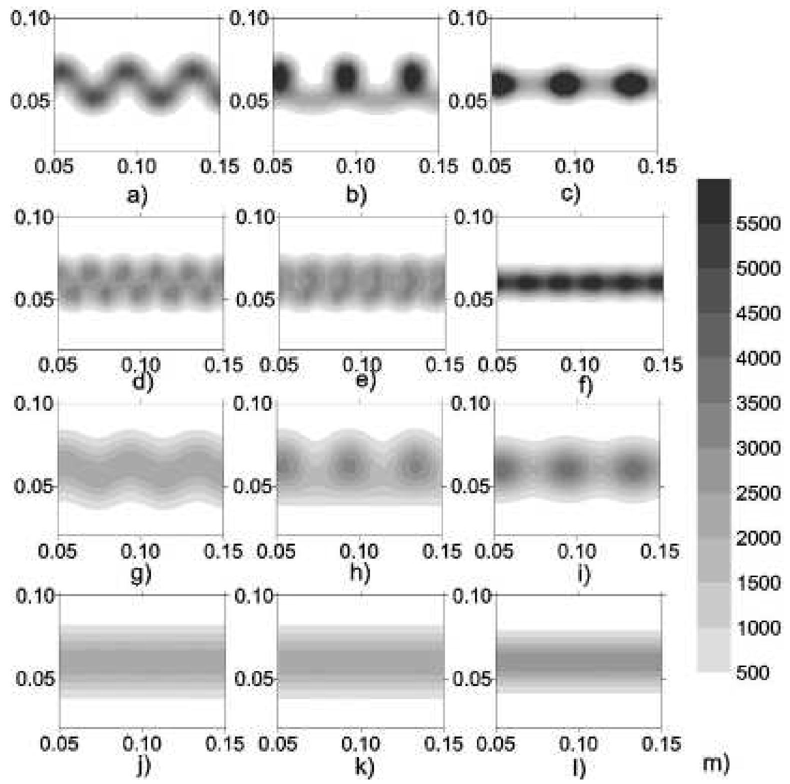

Fig. 11. Distribution of energy density $W_E(x, y)$ in a processing zone (P_m = 150 W, V_x = 20 mm/s), with different focused beam sizes and laws of scanning, where:
a — r_p = 0.1 mm, As = 0.0 mm, Bs = 0.1 mm, ω = 50 Hz; *b* — r_p = 0.1 mm, As = 0.1 mm, Bs = 0.1 mm, ω = 50 Hz; *c* — r_p = 0.1 mm, As = 0.1 mm, Bs = 0.0 mm, ω = 50 Hz; *d* to *f* dependencies are similar *a*—*c* under condition of ω = 100 Hz; *g*—*l* dependencies are similar *a* to *f* under condition of r_p = 0.2 mm; *m* — scale bar for energy density (J/cm^2)

So, in Fig. 12—14 the distribution of temperatures is given (at different time moments) in samples made of composition of powder PGSR-3 with 10% of air (thickness 30μm) and alloyed powder layer PGSR-3 which takes place at processing focused laser beam (focusing spot size r_p = 0,1 mm (Fig. 12) and r_p = 0,2 mm (Fig. 14)) with power P_m = 150 W that moves at speed V_x = 20 mm/s according to different laws of scanning. Analyzing the dependences presented in Fig. 12 and Fig. 13, we shall specify, that in all considered cases of scanning of the focused laser beam with power $W_P = 9.5*10^5$ W/cm^2 the evaporation of a surface layer of a powder occurs. The specified phenomenon occurs even in case (Fig. 13) when the amplitude of fluctuations is equal to A = 0.1 mm; B = 0.3 mm with frequency ω =100 Hz, and the maximum energy density reaches only $2.016*10^4$ J/cm^2. It is possible to reduce energy density of the focused beam by excluding generation of laser radiation in extreme points of fluctuations amplitude, thus causing changes in time and the contour of the melt pool. It is necessary to note, that in case of laser beam scanning under the circular or elliptic law when the amplitude of fluctuations exceeds the size of focusing spot, the distribution of density of energy along a line of processing has significant non-uniformity which affects parameters of a melt bath.

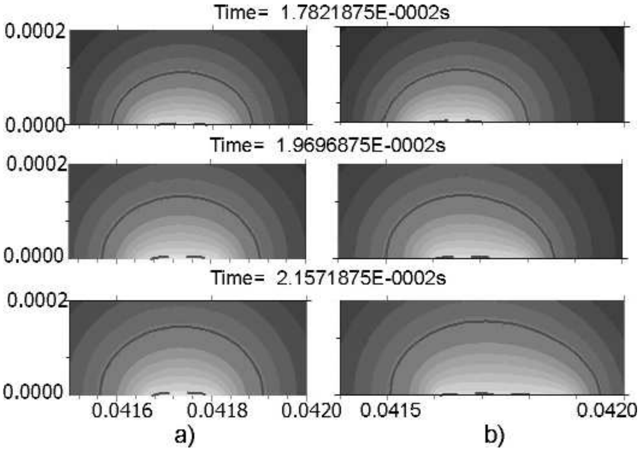

Fig. 12. The distribution of temperature in sample for the composition of powder PGSR-3 and alloyed PGSR-3 powder layer (P_m = 150 W, r_p = 0.1 mm, V_x = 20 mm/s, thickness powder layer h_p = 30 μm and air — 10%) where a — ω = 0 Hz; b — As = 0 mm; Bs = 0.1 mm, ω = 100 Hz; "___" melt pool for Ni; "- - -" vapor pool for Ni

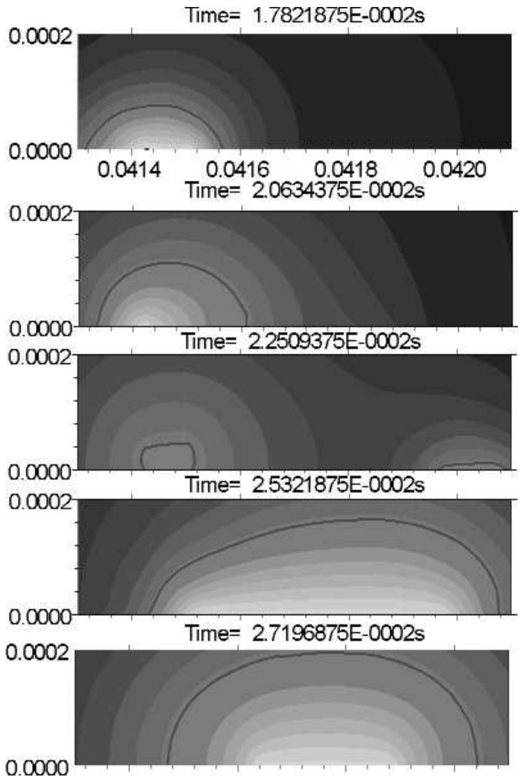

Fig. 13. The distribution of temperature in sample for the composition of powder PGSR-3 and alloyed PGSR-3 powder layer (P_m = 150 W, r_p = 0.1 mm, V_x = 20 mm/s, powder layer thickness — h_p = 30 μm and air — 10%, As = 0.1 mm; Bs = 0.3 mm, ω = 100 Hz)

As it was shown earlier, at focused laser beam processing with P_m = 150 W, focused in a spot of r_p = 0,2 mm ($W_P = 2.4*10^5$ W/cm^2), moving at a speed 20 mm/s (W_E = $2.99*10^4$ J/cm^2), the surface layer of a composition powder PGSR-3 with 10% of air (thickness 30 μm) — alloy PGSR-3 evaporates on non-significant depth (Fig. 13). Due to the change in size and distribution of energy density of the focused laser beam, it is possible to avoid destruction of the

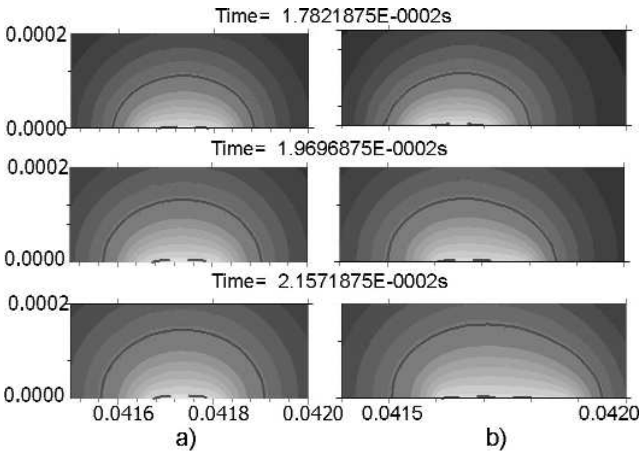

Fig. 14. The distribution of temperature in sample for the composition of powder PGSR-3 and alloyed PGSR-3 powder layer (P_m = 150 W, thickness powder layer h_p = 30 μm and air — 10%) where: the size of focusing spot r_p = 0.2 mm a — ω = = 0Hz; b — As = 0.mm; Bs = 0.1 mm, ω = 100 Hz

top layer of a coating. At scanning of the focused laser radiation with considered modes of processing, distribution of energy density (in comparison with processing with a beam focused to a spot of r_p = 0,1 mm) has more uniform character (Fig. 11), and, in cases when scanning of laser radiation occurs in a plane of a movement vector of the sample V_x, the excess of base value W_E = 2.99*10[4] J/cm[2] is observed. For example, in case of laser beam scanning (P_m = 150 W, r_p = 0,2 mm, V_x = 20 mm/s with parameters B = 0, A = 0.1 ω = 50 H and ω = 100 H maximum value W_E reaches 3.99*10[4] J/cm[2] and 3.0*10[4] J/cm[2], respectively (Fig. 11). But, due to the fact that the increase of W_E occurs at certain time, keeping balance of energy that is introduced into sample and is removed from its body (due to heat conductivity), temperature of a surface does not exceed temperatures of evaporation of a material of a basis of a powder (in comparison with usual processing), and parameters of a melt bath increase.

Thus, in Fig. 15 dependences of power density of focused laser radiation $W_P(0,0,t)$ (P_m = 150 W, r_p = 0,2 mm, V_x = 20 mm/s) and temperatures of surface T $(0,0,t)$ compositions powder PGSR-3 with 10% of air (thickness 30 μm) — alloy PGSR-3 from time t for different laws of scanning of the focused beam are presented. A conclusion could be drawn that at processing on a usual mode, the temperature of a surface of a sample exceeds temperature of evaporation of a basic material of powder mixture. At scanning of the focused beam along the speed vector of sample V_x, due to the fact that action of laser radiation "is stretched" in time, the temperature of a surface only reaches the temperature of evaporation of a basic material. But, due to periodic introduction of laser radiation (due to scanning) to processing zone its amount of energy is not enough for excess of heat of phase transformation. Constant supply of energy in this case (on evaporation border) leads to the increase in the size and time of existence of a melt pool that affects the quality of melted (or sintered) layers of a material of a created detail.

In Fig. 16 and Fig. 17 dependences of parameters of a melt bath are presented, which are observed at laser processing at different working conditions of a composition of powder PGSR-3 with 10% of air (thickness 30 μm) — alloyed PGSR-3 powder layer. Apparently from the resulted dependences, maximum time of existence of a melt bath is possible under conditions when the plane of scanning (Bs = 0) coincides with a vector of speed of laser beam movement (dependence 3, Fig. 16) and

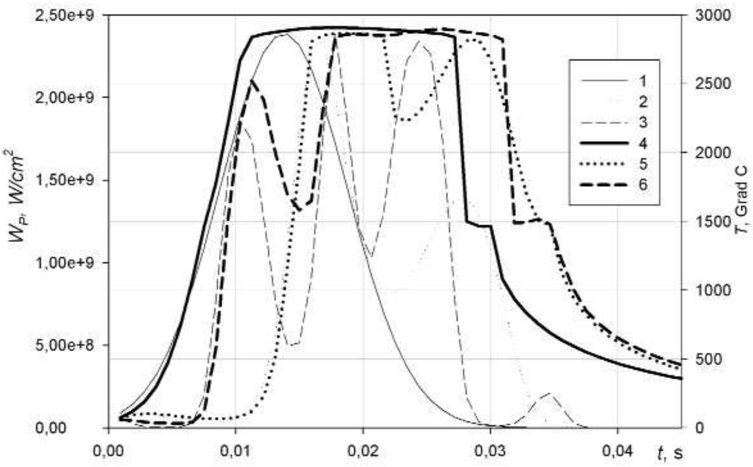

Fig. 15. Laser beam power density $W_p(t)$ and surface temperature $T(0, t)$ of a samples made of composition of powder PGSR-3 and alloyed PGSR-3 powder layer to time t of the frequency of then scanning laser beam (thickness powder layer h_p = 30 μm, 10% Air, P_m = 150 W, V_x = 20 mm/s, r_p = 0.2 mm, As = 0, Bs = 0.1 mm), were: *1* — dependence W_p from time t for ω = 0 Hz; *2* — dependence $W_p(t)$ for ω = 50 Hz; *3* — dependence $W_p(t)$ for ω = 100 Hz; *4* — dependence of a surface temperature T sample from time t for ω = 0 Hz; *5* — dependence $T(t)$ for ω = 50 Hz; *6* — dependence $T(t)$ for ω = 100 Hz)

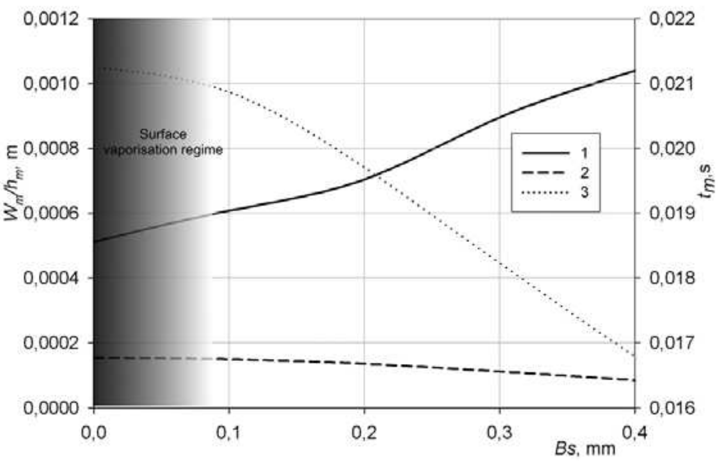

Fig. 16. Parameters of a melt pool (depth h_m, width W_m and time of existence t_m) a samples in a composition of powder PGSR-3 and alloyed PGSR-3 powder layer from amplitude Bs of additional scanning of the focused laser radiation (P_m = 150 W, r_p = 0,2 mm, V_x = 20 mm/s, As = 0 mm, ω = 100 Hz thickness powder layer h_p = 30 μm, 10% Air) where: *1* — dependencies of a width W_m of a melt bath from amplitude Bs of additional scanning; *2* — dependencies of a $h_m(Bs)$; *3* — dependencies of $t_m(Bs)$

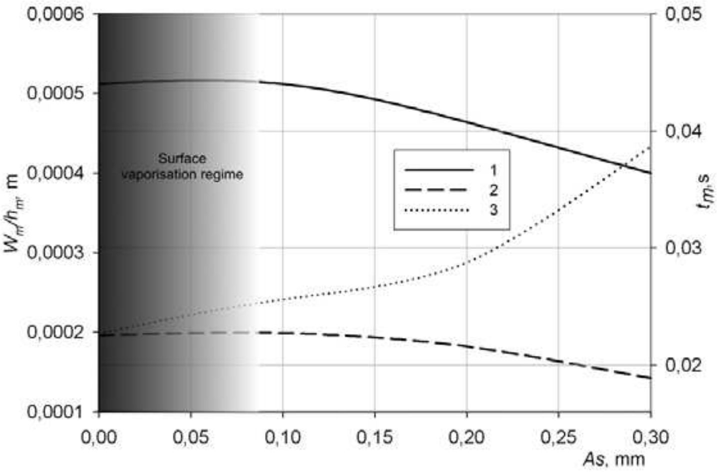

Fig. 17. Dependencies of parameters of a melt bath (depth h_m, width W_m and time of existence t_m) of the sample from the composition of powder PGSR-3 and alloyed PGSR-3 powder layer from amplitude *As* of additional scanning of the focused laser radiation (P_m = 150 W, r_p = 0,2 mm, V_x = 20 mm/s, *Bs* = 0 mm, ω = 100 Hz thickness powder layer h_p = 30 μm, 10% Air) where: *1* — dependencies of a width W_m of a melt bath from amplitude *As* of additional scanning; *2* — dependencies of a $h_m(As)$; *3* — dependencies of $t_m(As)$

grows with the increase of amplitude of scanning. On the contrary, under conditions when the plane of scanning is perpendicular to a vector of speed of laser beam movement, the time of melt existence decreases (dependences 3, Fig 17). In both cases depth of a melt bath gradually decreases with increase of amplitude of scanning of the focused laser beam.

Conclusions

Thus, analyzing calculations, we can draw the following conclusions:

Modifying the amplitude, frequency and pattern of additional scanning of the focused laser beam we have an opportunity to control and operate the parameters of a melt bath.

The increase of a melt pool dimensions (with the help of additional scanning) is the most expedient for carrying out on a limiting mode (for usual processing, that is ω =0) when there comes the beginning of evaporation of a surface of the top layer of a composition;

Prevention of destruction (due to evaporation) of compositions in "dead" points of amplitude is possible due to synchronous blocking of the access of laser radiation in a zone of processing.

References

1. *Beker P.M.* (1981) Laser Marking and Serializing in Proceeding of the First International Laser Processing Conference, November 16—17, Anaheim, California.

2. *Jimbou R., Inagaki M., Tamamura T.* (1981) A method for laser alloing and transformation hardening using a uniform intensity rectangular beam in Proceeding of the first International Laser Processing Conference. November 16—17, Anaheim, CA, USA.

3. *Iwase T., Shibata K., Sakamoto H., Dausinger F., Hohenberger B., Muller M., Matsunawa A., Seta N.* (2000) Realtime X-Ray Observation of Dual Focus Welding of Aluminum Alloys in "Proceedings of International Congress "ICALEO'2000", Dearborn, USA, Oct. 2000.

4. *J. Lawrence, D. W. Evans, J. Kell and J.R. Tyrer* (2006) An analysis of crack and porosity formation in laser surface treated magnesia partially stabilized zirconia (MGO-PSZ) and methods for alleviation "Proceedings of International Congress "ICALEO'2006", Scottsdale, USA, Oct. 2006 (Paper P506).

5. *Arai T., Riches S.* (1997) Thick Plate Cutting with Spinnng Laser Beam in "Proceedings of International Congress "ICALEO'97", San Diego, USA, Nov. 1997, vol. B19—B26.

6. *Yamamoto H., Minamaida K., Oikawa M., Kido M.* (1997) Development of a Continuous Laser Hardening Method without Temepering Zone in "Proceedings of International Congress "ICALEO'97", San Diego, USA, Nov. 1997, vol. F83—F89.

7. *Kovalenko V., Anyakin M., Uno Y., Khaled Al Shaboul* (2001) Laser technology application in transformers and electro motors manufacturing in "Proceedings of 13th International Symposium for Electromachining (ISEM-XIII)", May 9—11th, 2001, Bilbao, Spain, Vol.II., p.p. 839—850.

8. *Kovalenko V., Anyakin M., Uno Y.* and others (2000) Modeling and Optimization of Laser Semiconductors Cutting in "Proceedings of International Congress "ICALEO'2000", Dearborn, USA, Oct. 2000, Vol.90, p. D82—D92.

9. *Kovalenko V., Anyakin M., Uno Y.* (2002) Planning and Optimization of Laser Material Welding and Cutting in Proceeding of the 35th CIRP International Seminar on Manufacturing Systems "Manufacturing Technology in the Information Age", May 13—15, 2002, Hotel President, Seoul, Korea, p.p. 588—595.

10. *N.V. Vargaftik* (1956) Thermal properties of substances. Handbook / Ed. Chief N.V.Vargaftik in- M.: Gosenergoizdat, 1956. — 367 p.

11. *Kovalenko V., Anyakin M., Meijer J., Degtyarev A., Kozyrev A.* (2002) Studying of Laser Processed Material Optical Parameter Dependencies from Temperature in "Proceedings of International Congress "ICALEO'2002", Scottsdale, USA, Oct. 2002.

12. *Nadine Coulon, Yorris Lafaye, Pascal Aubry* "Analysis of the laser sintering process for direct

manufacturing of mould" "Proceedings of International Congress "ICALEO'2006", Scottsdale, USA, Oct. 2006 (Paper #1803).

13. *Yadroitsev, Ph. Bertrand, I. Smurov* (2006) Parametric analysis of selective laser melting technology "Proceedings of International Congress "ICALEO'2006", Scottsdale, USA, Oct. 2006 (Paper 1805).

14. *V. Kovalenko, M. Anyakin, P.Kondrashov, A. Mukhoid, A. Stepura, R. Zhuk* (2006) Study of the process of rapid prototyping with laser beam "Proceedings of International Congress "ICALEO'2006", Scottsdale, USA, Oct. 2006 (Paper 1802).

15. *V. Kovalenko, M. Anyakin, R. Zhuk, J. Meijer, Y. Uno* (2007) The Increase in Productivity and Quality of Laser Machining "Proceedings Of The 15th International Symposium On Electromachining (ISEM-XV)" April 23—27, 2007 Pittsburgh, Pennsylvania — USA. — P. 439—444.