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DEVELOPMENT OF THE LASER-FOUNDRY PROCESS FOR MANUFACTURE OF BIMETALLS

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Запропоновано новий високоефективний спосіб виготовлення біметалевих листів, відповідно з яким тонкий поверхневий шар функціональної складової біметалу, що рухається з визначеною швидкістю, на певній площі розплавляється концентрованим лазерним випроміненням. Одночасно в зону його дії із спеціального дозуючого пристрою з певною витратою подається завчасно підготовлений розплав основи біметалу, внаслідок чого при охолодженні між ними утворюється надійне з'єднання.

Спосіб відрізняється високою продуктивністю і універсальністю процесу виготовлення широкої гамми біметалів різноманітного призначення, великою міцністю зчеплення їх складових, можливістю повної автоматизації. Проаналізовані теплові процеси, що відбуваються в поверхневому шарі функционального складового біметалу зі сталі 40Х13 при різних умовах лазерного опромінення. Визначені параметри лазерного опромінення, які забезпечують підплавлення поверхневого шару шириною 50 мм на глибину 50-100 мкм (потужність випромінення 8,5 кВт, швидкість переміщення 1 м/хв). Обгрунтовано умови подачи на підплавлений функциональній шар розплавленного металу основи зі сталі Ст.3 (висота стовпа росплаву 7,6 мм, розміри вихідного отвору 50×3 мм), які забезпечують формування біметалу з заданими розмірними характеристиками. Продуктивність розглянутого лазерно-ливарного процесу визначаається параметрами сканування і потужністю лазерного променю, витратними характеристиками розплаву одного зі складових, швидкістю відносного переміщення. Зона сплавлення, що утворюється при охолодженні і відносному переміщенні складових біметалу, обумовлює між ними металургійний зв'язок. Це дозволяє виготовляти біметалеву продукцію необхідної якості

Ключові слова: біметали, теплові процеси, лазерне опромінення, індукційний нагрів, зона сплавлення, металургійний зв'язок

1. Introduction

Trends in the development of modern technology, economic and technological aspects of its production necessitate the expansion of the use of materials with special properties. Parts of the metallurgical, mining, oil and gas extraction and overworking inventory, machines of the chemical, light and food industry in use are exposed to different types of wear. It is necessary to distinguish the parts of friction pairs among them, which in the process of operation are subject to wear in the absence or limited lubrication when particles of abrasive materials are present in the contact zone. Some parts of the equipment work under conditions of shock abrasive wear, when the destruction of their surface layer occurs under the influence of pulsed mechanical contact loads under conditions of simultaneous action of abrasive particles. A significant part of machine parts and mechanisms undergo gas-abrasive and hydro abrasive wear during work, when high-speed (more than 40 m/s) flows of various gases, including reactive gases or liquids, are present on their surfaces at temperatures up to 500 °C in the presence of disperse abrasive particles.

The service life of most parts working under conditions of various types of friction at elevated temperatures, cyclic alternating loads, and the action of abrasive or corrosive media is mainly determined by the physical and mechanical properties of their surface layers. In this case, often the thickness of the working layer does not exceed 4–5 mm.

In this regard, the development of a universal, economically expedient way of imparting properties to the surface layers of machine parts that ensure a substantial increase in the service life under various operating conditions is an urgent task. Its solution represents a certain interest, both for the scientific community of various countries of the world, and for representatives of the industrial production sphere.

2. Literature review and problem statement

In order to increase the service life and reliability of machine parts, various types of thermal or chemical-thermal treatment are used to increase the hardness of their surface layers. Such types include quenching with heating by high-frequency currents (HF), laser radiation or plasma, nitriding, nitrocarburization, etc. [1, 2]. The main disadvantages of these methods of hardening include, firstly, a limited number of materials (carbon steel and cast iron), and secondly, their use leads to an increase in the cost of manufacturing parts.

The technology of applying various types of adhesion coatings (gas flame, plasma, detonation and vacuum deposition, electrolytic deposition, etc.) to the working surfaces has been extended [1]. Along with high productivity and wide range of applied materials, the main disadvantage is low adhesion strength to the substrate, not exceeding 15–20 kg/mm^2, as well as a limited thickness of high-quality applied coatings. At the same time, it should be noted that it is impossible to use technologies for parts working under cyclic alternating loads.

In this regard, the processes in which various kinds of functional materials are applied to the surface of products by a number of other methods are more efficient. One of the main industrial methods for obtaining a wide class of bimetals (clad metals) is pressure treatment, in particular, cold pack rolling [3]. Similar methods include casting when the initial workpiece is produced by casting steel of one composition into a mold, in which one or two plates of steel of a different composition are installed [4]. The number and an arrangement of plates determine the further technology and number of layers in the finished steel.

Electronic-beam, laser, electric arc [5] and plasma surfacing (production of SWIP sheets) have become more widely used in mass and serial production [6]. Of particular interest is the method of electroslag remelting, where surfacing proceeds using an electrode of large cross-section, fixedly installed with small gaps in the space between the base and the deposited metals [7]. At the same time, due to small gaps, uniform penetration is achieved automatically due to self-regulation of the process.

The main advantage of these methods is the high strength of the joint of the coating with the substrate, which is determined by the strength of one of the materials to be joined. In addition, they allow you to control the formation of bimetallic compositions, giving them the necessary properties.

Along with the advantages, there are a number of shortcomings: a limited amount of materials making up bimetals, the presence of increased residual stresses, unpredictable local defects, the complexity of process automation, the use of energy-intensive equipment. When these sheets are heated, the bond strength drops sharply, and the interruption of the process leads to irreparable defects. There is also a need for expensive and cumbersome technological equipment.

Today, the method of manufacturing bimetals by explosion, which is characterized by high productivity, low production costs, a wide range of bimetals, and a simple process organization is the most widespread in the industry [8]. However, this method has a number of significant drawbacks, such as low controllability and low quality of the process, especially with a large area of materials being connected, a high level of noise and vibration, requiring protection measures.

From this point of view, plasma technologies, which allow producing double-layered bimetallic products with sufficiently high productivity are the most effective [6]. They were widely used in the manufacture of linings in the metallurgical industry, parts operating under hydro-, gas- and shock-abrasive wear. Noting the progress achieved in the use of technologies for the production of bimetallic compositions, it should be highlighted that in the practice of developing such technologies, intuitive experimental approaches still play an important role, in the presence of very limited quantitative estimates. In addition, modern methods for producing bimetallic materials have certain drawbacks related to the productivity of processes, surface quality, often requiring the use of subsequent machining, their structural-phase and stress state. There are difficulties in choosing a functional constituent of the bimetal, which is defined by the materials of the electrodes produced.

The analysis given above showed that the main areas of increasing the efficiency of manufacturing bimetals are the intensification and optimization of mass transfer processes in the compound joining zone by controlling the quality characteristics of surfaces, the aggregate state of the components.

An analysis of the existing methods for getting bimetals suggests that it is possible to improve the efficiency of their production and quality by dividing the entire process into two stages. In the first stage, using a highly concentrated energy source, laser radiation focused into a segment of a line with the distribution of intensity of the Top-Hat type or deployed in a line segment by means of a special scanning device. In this case, the surface layer of the moving constituent of the bimetal melts to a depth of 30–50 μm. In the second stage, simultaneously with the beginning of its movement to the molten surface, a melt of the functional constituent of the bimetal, previously prepared by induction heating, is fed from special tuyeres with a specified flow rate [9].

3. The aim and objectives of the study

The aim of the research is to develop a method for producing bimetallic materials using laser processing and casting processes.

To achieve this aim, it is necessary to accomplish the following objectives:

– to determine the factors and parameters affecting the laser-foundry process for manufacturing bimetals;

– to simulate the formation of a stationary zone of the molten surface of a bimetal component during laser heating by a scanning beam;

– to investigate the process of melt flow out of the tuyere, to calculate and determine its technological parameters.

4. Modeling of the process of laser submelting of the surface layer

The subject of the study are conditions for the formation of a local constant zone of molten metal, which is formed on the surface of one of the bimetal constituents under the action of laser radiation, and parameters of the fusion zone. The presence of such a zone, its geometric dimensions, the laws of formation in conjunction with the relative motion speed determine the possibility of the formation of a metallurgical bond between the components of the bimetal, and fusion zone parameters.

Analysis of various schemes for the bimetals formation has shown that two of them are of the greatest interest.

The first scheme involves scanning of the surface of one of the constituents of the bimetals moving at a speed V by a focused laser beam. A laser source of power P with a certain frequency f_{sk}, given trajectory and amplitude A_{sc} fuses the given surface to a depth Z. The molten metal of the constituent of the bimetal base, whose flow width B corresponds to the beam scanning amplitude is fed to the generated melt from a special tuyere with the specified flow rate *Q*. In this case, the first component moves rectilinearly relative to the beam axis at a constant speed (Fig. 1, *a*).

The second scheme differs from the above in that the surface of one of the bimetal constituents is melted by a laser beam focused in a line segment. The beam width corresponds to the beam size measured in the direction of displacement of the component, and the length – in the direction perpendicular to it (Fig. 1, *b*).

The crosswise dimensions of the molten metal flow also correspond to the dimensions of the beam focusing zone.

The first scheme was chosen as the base one since it requires a simpler optical system that forms a quasi-continuous heat source on the surface of the material in the form of a line segment with a relatively small laser radiation power.

In accordance with this scheme, the process of forming a bimetal is influenced by three main groups of factors. The first group is formed by the parameters of the laser beam and the characteristics of the material of the functional layer. The second group is the factors that characterize the molten metal of the second component. The third group combines factors reflecting the geometric parameters of the relative location and kinematics of the relative displacement of the bimetal constituents (Fig. 2).

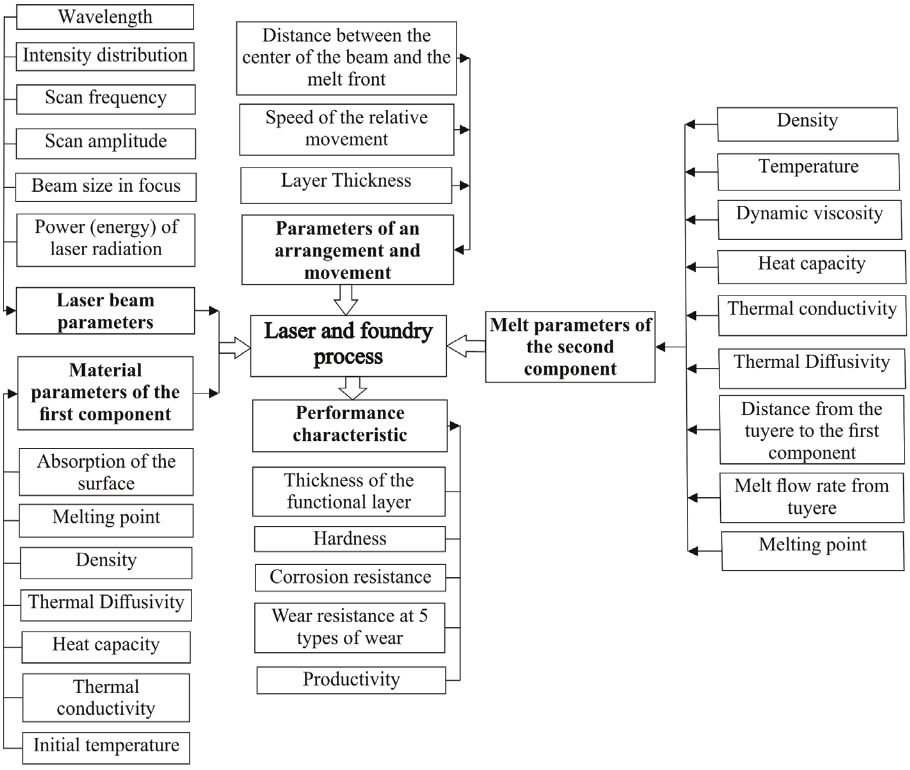
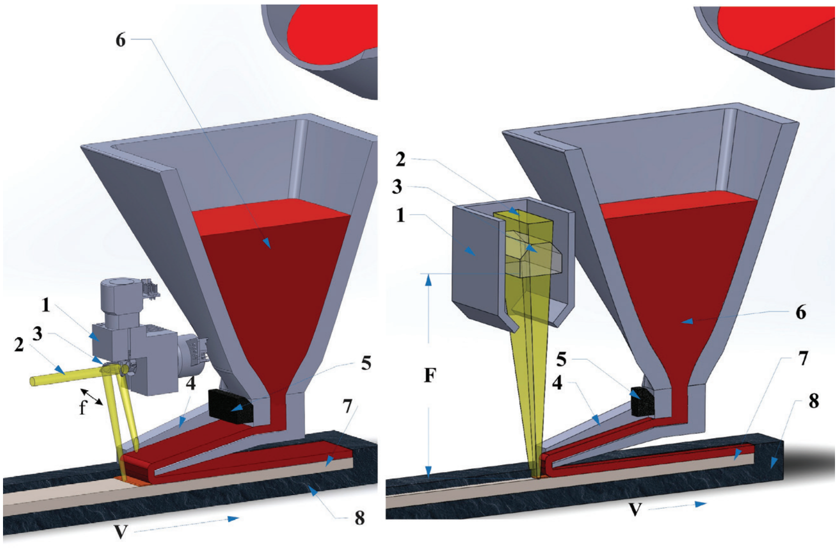


Fig. 2. The main factors and parameters of the laser-foundry process for manufacturing bimetals



a *b*

Fig. 1. Schematic diagrams of new ways of producing bimetallic materials: *a* – the first scheme; *b* – the second scheme; 1 – device for beam formation, 2 – laser radiation, 3 – scanning mirror (*a*), focusing lens (*b*), 4 – casting system, 5 – damper, 6 – melt, 7 – material of functional layer, 8 – limiter, *f* – direction of scanning, *F* – lens focal length, *V* – direction of travel

After analyzing the processing parameters, the factors that have a significant influence on the deposition process and which can serve to control the process have been identified:

– power of laser radiation;

– the velocity of the substrate for a bimetal relative to the laser beam;

– scanning amplitude;

– scanning frequency;

– the initial temperature of the base material for the bimetal;

– the configuration of the hole through which the melt is delivered (length, width, depth);

– the thickness of the layer to be fused;

– the height of the pressure melt column.

5. Simulation of the process of formation of a stationary zone of a molten surface by a laser scanning beam

The numerical analysis of the three-dimensional distribution of temperature in the certain solid body irradiated by a moving Gaussian laser beam is carried out by means of the COMSOL Multiphysics code 5.2 [10].

Initial data for the calculations were the following parameters of laser processing and configuration of the bimetal component:

– material of the component: 40H13 stainless steel (AISI 420);

– scanning amplitude is 20 mm, 30 mm, 50 mm;

– laser beam scanning frequency: 100 Hz, 200 Hz;

– moving speed of the base: 1 m/min, 10 m/min;

– power of laser radiation: 2–14 kW.

As a result of the simulation, it was found that the submelting of the surface layer of the metal does not occur when processing a 2-mm thick component with a laser beam of 2 kW with the scanning amplitude of 20 mm, scanning frequency of 200 Hz, and moving speed of the substrate of 1 m/min. This can be seen from the graph of the point temperature distribution over time (Fig. 3). The temperature of the surface layer does not exceed 1,000 °C. On the graph, each of the lines describes the temperature changes at the points on the central axis of the workpiece during the entire processing period, which coincides with the direction of motion of the component. The selected points for determining the temperatures are shown in Fig. 4.

By reducing the speed of movement of the functional layer, a regime was established that provided a fusion of its surface layer and thus made it possible to implement an effective surfacing process. The mode provides a reduction in the speed of the base movement to 0.25 m/min. In this case, the temperature distribution graph (Fig. 5) of points on the central axis of the workpiece during the entire processing time has the following form (Fig. 6).

In the course of further modeling, it was found that an increase in the scanning amplitude leads to the need for a substantial reduction in the processing speed, which is not practical. In addition, the simulation found that it is also irrational to reduce the scanning frequency since in this case the average temperature of heating of the surface layer is significantly reduced, which leads to the need to reduce the processing speed.

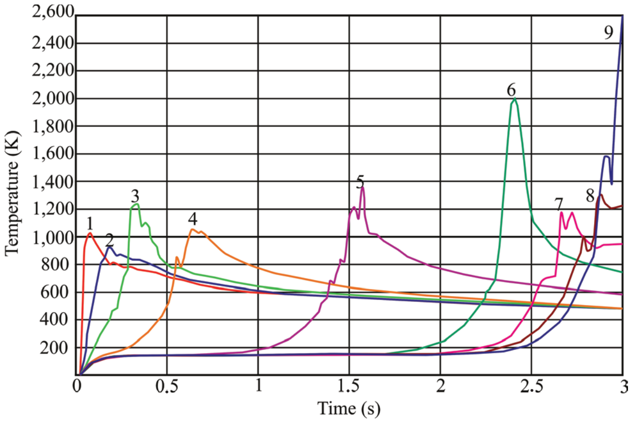


Fig. 3. Temperature of points on the central axis of the workpiece during the entire processing period at $P=2$ kW, $A=20$ mm, $f=200$ Hz, $Vx=1$ m/min

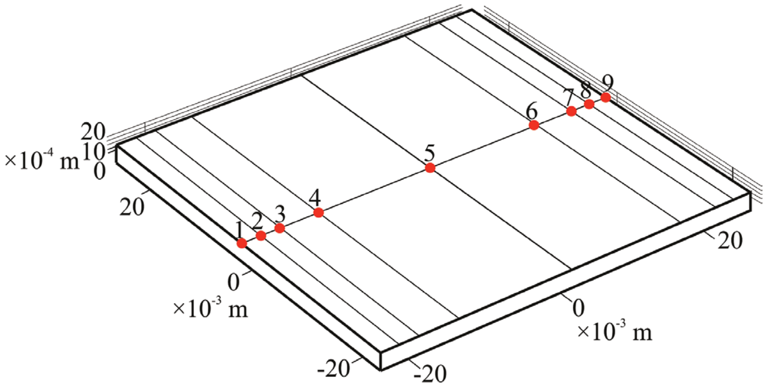


Fig. 4. Points for which values of the temperature were determined at various time points

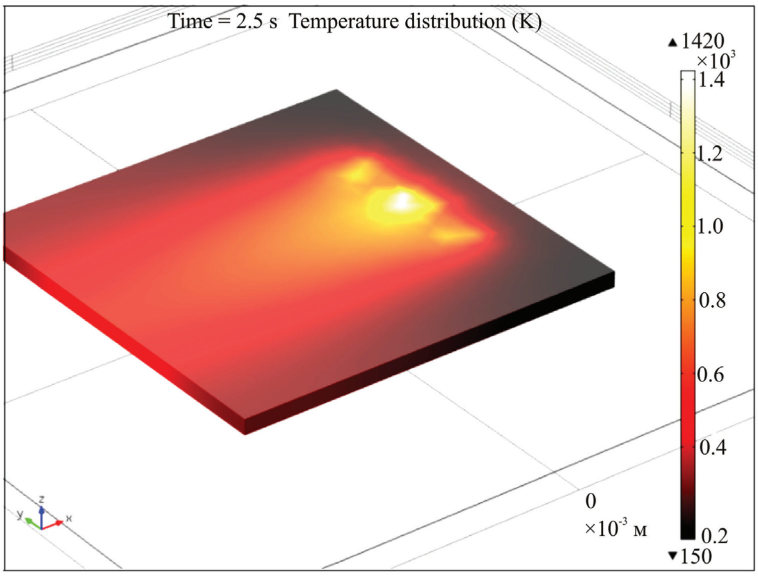


Fig. 5. Distribution of temperatures 2.5 seconds after the start of treatment

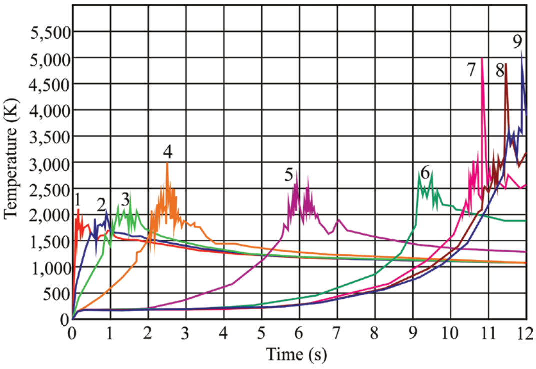


Fig. 6. Temperature of the points on the central axis of the workpiece during the entire treatment period at $P=2$ kW, $A=20$ mm, $f=200$ Hz, $Vx=0{,}25$ m/min

The following problem of the simulation is to determine the required laser power at which guaranteed submelting of the surface layer is provided in the processing zone under given irradiation conditions.

Thus, for processing conditions at which the values $A=30$ mm, $f=200$ Hz, $Vx=1$ m/min, the rational value of the laser radiation power is $P=5.25$ kW (Fig. 7).

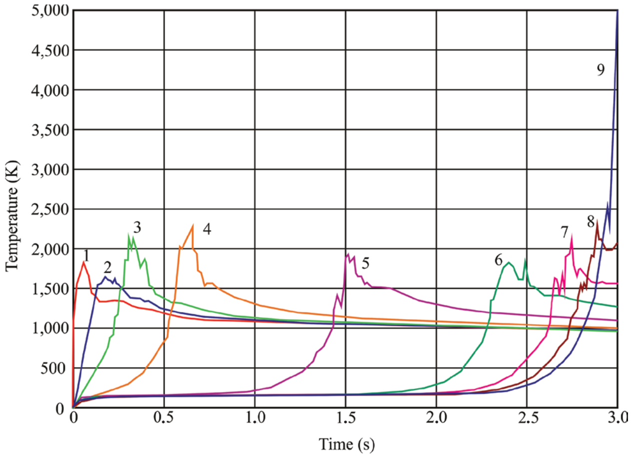


Fig. 7. Temperature of the points on the central axis of the workpiece during the entire processing period at $P=5.25$ kW, $A=30$ mm, $f=200$ Hz, $Vx=1$ m/min

For $A=20$ mm, $f=200$ Hz, $Vx=1$ m/min, the rational power of the laser radiation is $P=4$ kW (Fig. 8).

With an increase in the rate of movement of the base by a factor of 10 to maintain the penetration regime, the laser radiation power must be increased to 14 kW (Fig. 9).

For $A=50$ mm, $f=200$ gts, $Vx=1$ m/min, the rational power of laser radiation is $P=8.5$ kW (Fig. 10).

When studying the temperature distribution in depth of one of the bimetal components at a distance of 2 mm from the laser beam, it should be noted that at $P=2$ kW, $A=20$ mm, $f=200$ Hz, $Vx=0.25$ m/min, the heating of the surface layer is uneven on the entire length of the scanning amplitude (Fig. 11). Thus, foundering of the metal surface under such conditions occurs in a section with a length less than the scanning amplitude, namely, 15–16 mm. For ensuring submelting of the metal surface at a distance equal to the amplitude, it is necessary to increase the scanning frequency and reduce the speed of the workpiece movement. In order to increase the length of the melted-surface area, a surface scanning scheme by two laser beams can be applied.

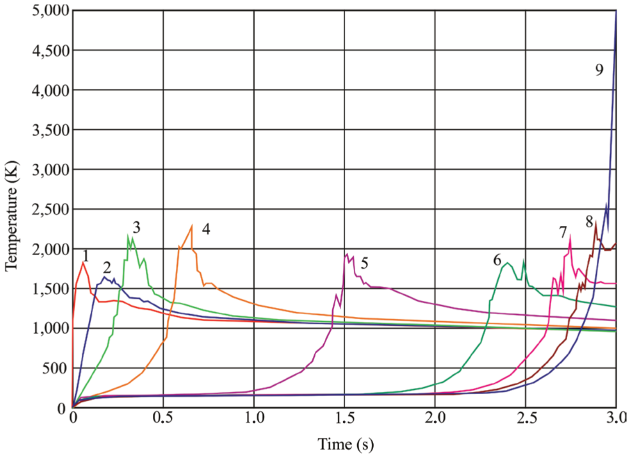


Fig. 8. Temperature of points on the central axis of the workpiece during the entire treatment period at $P=4$ kW, $A=20$ mm, $f=200$ Hz, $Vx=1$ m/min

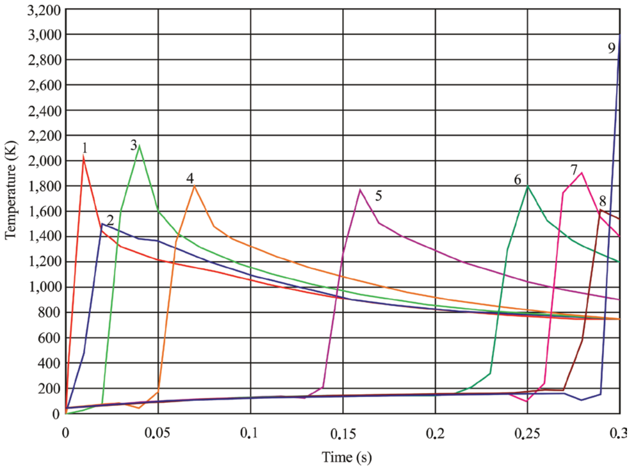


Fig. 9. Points temperature on the central axis of the workpiece during the processing period at $P=14$ kW, $A=20$ mm, $f=200$ Hz, $Vx=10$ m/min

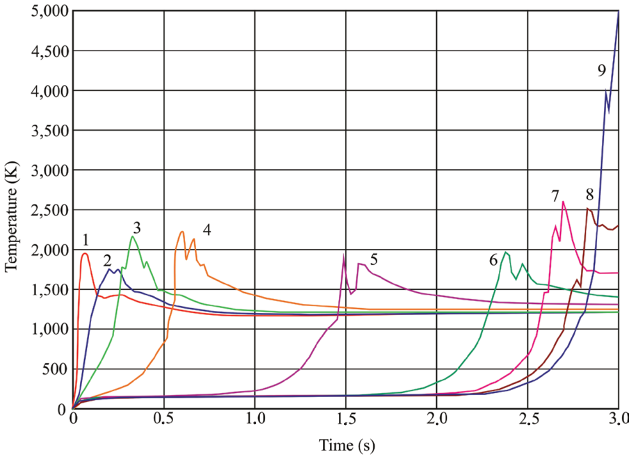


Fig. 10. Points temperature on the central axis of the workpiece during the entire treatment period at $P=8.5$ kW, $A=50$ mm, $f=200$ Hz, $Vx=1$ m/h

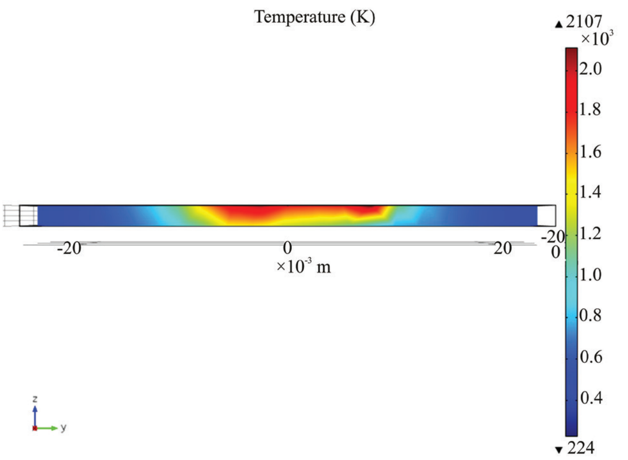


Fig. 11. Temperature distribution along the depth of the base at a distance of 2 mm from the laser beam 6 s after the beginning of treatment at $A = 20$ mm, $P = 2$ kW, $Vx = 0.25$ m/min

Under processing conditions $P = 8.5$ kW, $A = 50$ mm, $f = 200$ Hz, $Vx = 1$ m/min, heating occurs throughout the scanning amplitude, due to the lack of intense heat removal from the extreme scanning points in the unheated zones of the base by width (Fig. 12).

The study of parameters of the melt zone on the base depth in the direction of its movement in the bimetal manufacture showed that the stable melt zone on the surface makes $X = 1...1.5$ mm (Fig. 13).

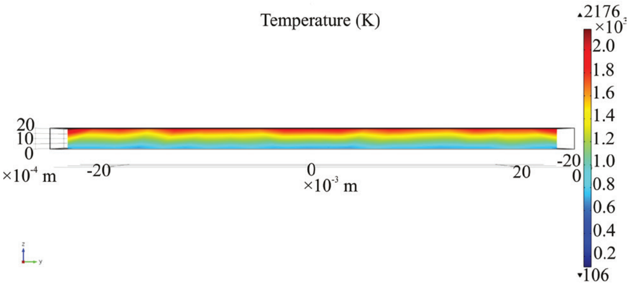


Fig. 12. Temperature distribution along the depth of the base at a distance of 2 mm from the laser beam 6 seconds after the start of treatment at $A = 50$ mm, $P = 8.5$ kW, $Vx = 1$ m/min

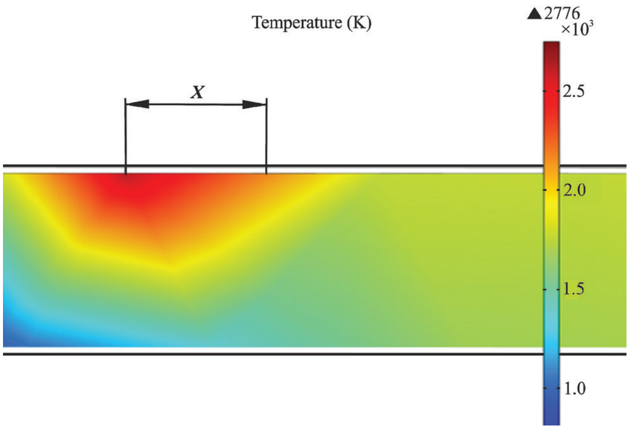


Fig. 13. Distribution of temperatures on the base depth in the direction of its movement in the bimetal manufacture ($A = 50$ mm, $P = 8.5$ kW, $Vx = 1$ m/min)

To increase the effectiveness of processing, the possibility of using the heating of the bimetal substrate to temperatures of 800–1,000 °C was tested. In processing regimes $A = 50$ mm, $P = 8.5$ kW, $Vx = 1$ m/min, the depth of the melt zone increases to $X = 2...2.5$ mm (Fig. 14).

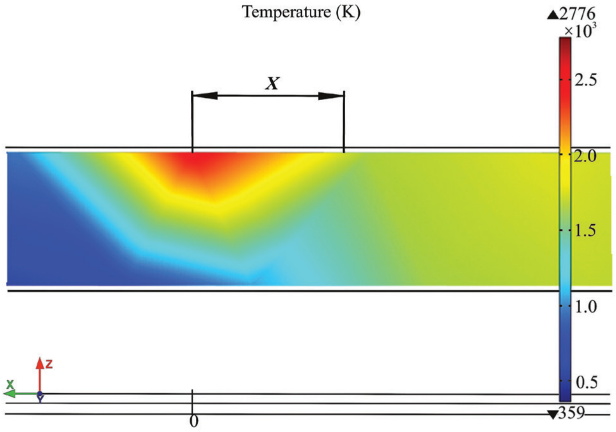


Fig. 14. Temperature distribution along the depth of the component of the bimetal in the direction of displacement during laser processing with the following regimes: $A = 50$ mm, $P = 8.5$ kW, $Vx = 1$ m/min and its heating up to 1,000 °C

Studies have shown that due to heating of the bimetal component, it is possible to reduce the necessary power of laser radiation or to speed up processing by the increase in the speed of its movement. However, such a method of increasing the efficiency of the process for manufacturing the bimetal is expedient only if the material of its constituent does not lose the necessary functional properties when heated to high temperatures.

6. Research of the melt flow from the tuyere

In the manufacture of bimetal, it is necessary to provide the constant discharge of the melt from the tuyere to the laser radiation area on the surface of one of its components. In this work, one of the easiest methods of melt delivery to the surface of the second bimetal component is considered. Pressure head supply of the melt through the opening in the tuyere having the rectangular section (Fig. 15) is the cornerstone of the method.

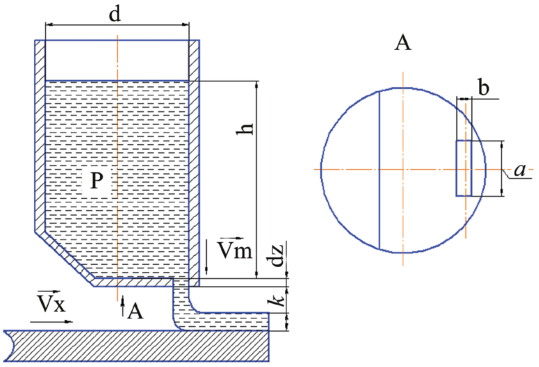


Fig. 15. Scheme of supply of molten metal to the surface of the bimetal component

The tuyere is equipped with the heating device, allowing maintaining a stable temperature of molten metal and also the mechanism providing support of the constancy of the molten metal level in it. Speed control of molten metal flow through the forming opening in the tuyere is carried out by changing the height of its pressure head column. At the same time, it is necessary to consider the pressure level causing the required outlet velocity of molten metal and also its loss when the melt passes the opening.

Proceeding from the chosen speed of one of the bimetal components movement and thickness of the molten metal layer, we will define the outlet velocity of molten metal from the tuyere. It can be found from the balance of mass flows.

The volume flow rate of molten metal is defined as:

$$Q = \rho b k V x, \tag{1}$$

where *Q* is the volume flow rate, ρ is the melt density, *b* is the workpiece width, *k* is the thickness of the deposited layer, *Vx* is the workpiece speed.

On the other hand:

$$Q = \rho b a V m, \tag{2}$$

where *Q* is the volume flow rate, ρ is the melt density, *b* is the groove length equal to the workpiece width, a is the groove width, *Vm* is the metal outflow rate.

From here, we will define the outflow rate of the metal:

$$Vm = \frac{Vx \cdot k}{a}. \tag{3}$$

The rate of outflow from the hole at a depth is equal to:

$$Vm = \sqrt{2gh}. \tag{4}$$

From here, we will receive the melt column height, which is necessary for its flow out with the chosen speed:

$$h_V = \frac{Vx^2 k^2}{2ga^2}. \tag{5}$$

The loss pressure can be determined from the dependence of the average outlet velocity of the melt from the rectangular section opening:

$$Vm = \frac{Q}{4ab} = \frac{-10a^2b^2}{36\left(a^2+b^2\right)\mu}\frac{dP}{dz}. \tag{6}$$

Let us define *dP* from this dependence:

$$dP = \frac{36\left(a^2+b^2\right)\mu Vm dz}{-10a^2b^2}. \tag{7}$$

Let us determine the padding height of the melt column to compensate for losses of hydraulic sliding friction in the opening using the formula for the fluid column pressure at a particular height *h*:

$$P = \rho g h. \tag{8}$$

And so the height of the melt column to compensate for losses of hydraulic friction should be equal to:

$$h_L = \frac{36\left(a^2+b^2\right)\mu \upsilon_{\text{cp}} dz}{-10a^2b^2\rho g}. \tag{9}$$

In the chosen configuration, the width of the aperture *a* is 0.2 mm, and its length *b*, 50 mm. In turn, *dz* is the depth of the opening through which molten metal flows. Dynamic viscosity of steel at a temperature of 1,450–1,500 °C is equal to 6 MPa, and its density is 7.070 kg/m^3. The gravity acceleration *g* is equal to 9.81 m/s^2. We accept the average outlet velocity of the melt – 0.16 m/s.

The total height of the melt column is equal to:

$$H = h_V + h_L. \tag{10}$$

For the selected processing conditions, the height of the column is equal to 7.5 mm. In the case of the 10 times increase in the speed of the workpiece, up to 10 m/min = 0.16 m/s, the total height of the column will be equal to 193 mm.

As a result of calculations, the dependences of the thickness of the built-up layer on the melt column height in the tuyere and also speeds of its flow from the tuyere depending on the melt height in it were obtained (Fig. 16, 17).

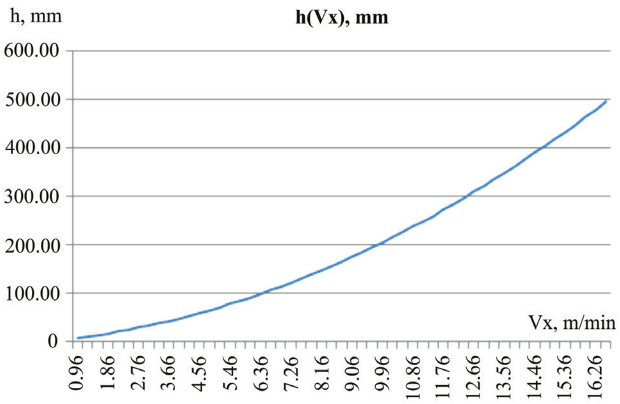


Fig. 16. Dependence of the height of the melt column on the speed of movement of the substrate

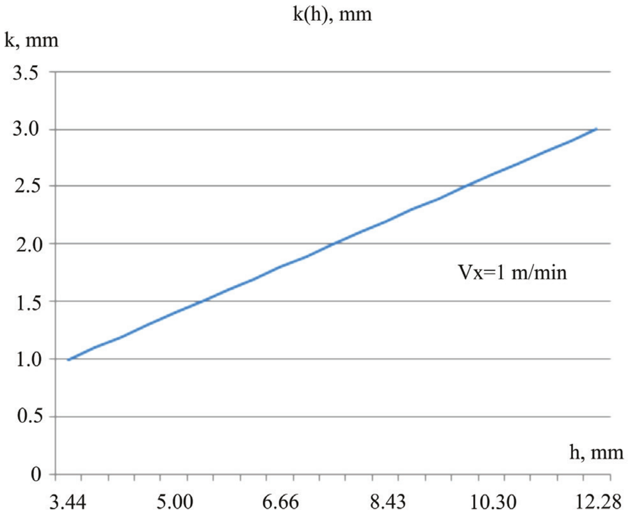


Fig. 17. Dependence of the built-up layer thickness on the melt column height in the tuyere

7. Discussion of the results of the investigation of the laser-foundry process for manufacturing bimetals

Using the numerical modeling of the process, the conditions for laser submelting of the surface layer of the bimetal substrate to a given depth are determined (Fig. 3–14), mathematical dependences are developed and the parameters of melt flow out of the tuyere of the functional component are determined. It is found that the presence of a local constant zone of molten metal, its geometric dimensions, the regularities of formation, combined with the relative motion speed, determine the possibility of the formation of a metallurgical bond between the bimetal components. This feature predetermines the high performance characteristics of bimetallic products and the reduction of destructive fatigue loads during temperature changes.

In order to increase the efficiency of the process, by reducing the fraction of the expensive energy of laser radiation in it, the possibility of using the heating of the bimetal substrate (Fig. 14) to 800–1,000 °C using induction heating was tested. During laser processing with $A=50$ mm, $P=8.5$ kW, $Vx=1$ m/min, the depth of the melt zone increases to $X=2...2.5$ mm. In this case, it is possible to reduce the necessary power of laser radiation or to increase the processing capacity by increasing the speed of its movement. However, such a method of increasing the production efficiency of bimetal is expedient only if the material of its constituent does not lose the necessary functional properties at high temperatures.

For the selected melt feeding scheme (Fig. 15), the bimetal functional component determines the outflow velocities of the liquid metal, the flow rate, and the height of the melt column in the tuyere taking into account the compensation for losses due to hydraulic friction. As a result of the calculations, dependencies were obtained that allow us to control the thickness of the functional layer of the bimetal.

In contrast to the closest analogs in the quality of joining the sheets, the developed process is characterized by high productivity and versatility in manufacturing a wide range of bimetals for various purposes, with a high adhesion strength of their components. It also allows you to obtain bimetallic sheets or products in automatic mode. The feature of this method is that there is no fundamental difference in what metal is applied to the expansion of the functional layer onto the base metal, or vice versa.

The results of mathematical modeling and the corresponding design data allow us to implement a new process for manufacturing bimetallic compositions, to develop appropriate technological processes and equipment.

The productivity of the developed process using a scanning laser beam is limited by the thermophysical properties of the functional material. It can be significantly enhanced by the simultaneous parallel use of several laser energy sources in one process. Another quite effective way can be the development of special optical systems that allow the formation of high-power laser beams with a rectangular-Gaussian radiation intensity distribution in the «Top-Hat» type cross-section.

8. Conclusions

1. The productivity of the laser-casting process for manufacturing bimetals is determined by the parameters of scanning and the power of the laser beam, the flow characteristics of the melt of one of the components, and the speed of their relative displacement.

2. It is advisable to carry out the process control by a complex change in the scanning parameters, laser radiation power, and the height of the pressure head column of the melt. To obtain a 50 mm wide bimetallic strip, the 2 mm thick functional layer which is made of martensitic grade 40H13 stainless steel (AISI 420), and the main one of St.3 structural carbon steel (AISI A284Gr.D), 4 mm thick, the radiation power is $P=8.5$ kW, the scanning amplitude is $A=50$ mm, the frequency $f=200$ Hz, the velocity of the base $Vx=1$ m/min, the height of the melt column $h=7.6$ mm.

3. To increase the productivity of manufacturing bimetallic sheets, it is advisable to apply to process with two or more simultaneously scanning beams or beams focused in a segment of the line with the distribution of radiation intensity of the «Top Hat» type.

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