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Improving the Quality of Products Created by Additive Technologies Based on Argon-Arc Welding

***Abstract**. The article considers the features of additive prototyping with the use of additive material by means of high-energy heating. Mathematical modeling of the process of surfacing of filler metal is performed. A significant influence of the feed and electrical characteristics of the arc on the parameters of the surfacing roller was revealed. Regression equations of influence of parameters of mechanized argon-arc welding on the shape of the seam and parameters of accuracy of the obtained product are determined.*

Streszczenie.** W artykule omówiono cechy prototypowania przyrostowego z wykorzystaniem przyrostu materiału za pomocą nagrzewania wysokoenergetycznego. Przeprowadzane jest matematyczne modelowanie procesu napawania spoiwa. Wykazano istotny wpływ parametrów posuwowych i elektrycznych łuku na parametry walca napawającego. Wyznaczono równania regresji wpływu parametrów zmechanizowanego spawania argonem na kształt spoiny oraz parametry dokładności otrzymanego produktu. **(Poprawa jakości produktów tworzonych przez technologie przyrostowe oparte na spawaniu łukiem argonowym

Keywords: additive technologies, welding, electric arc.
Słowa kluczowe:technologie przyrostowe, spawanie, łuk elektryczny

Introduction

The development of additive technologies based on the use of electric arc and wire (WAAM), known as the method of direct energy deposition (DED-arc), due to the need to increase the efficiency of production of engineering structures. This method allows to make blanks similar in shape to the finished product without the need to involve complex additional tools [1], molds and stamping and forging equipment and provides high potential for significant reduction of costs and time for technological preparation of production, turning it into chips during the next machining) and reducing the cost of inventory in the production of small batches to order.

Relevance

First patented in 1920 [2], WAAM is the oldest and simplest process for the production of additive materials (AM) (known as 3D printing). Using wire as a raw material, the main process is used for local repair of damaged or worn parts as well as for the restoration and repair of large parts and pressure vessels in recent decades [3-4]. The advent of appropriate software for automated design and manufacture (CAD/CAM) has made AM more common and applicable, outlined new horizons and directions for the development of such processes. Among them, WAAM is one of the most promising. With a resolution of approximately 1.0 mm and a deposition rate of 1 to 10 kg/h (depending on the source of the arc, [5-7]), the WAAM process has taken a niche as an additional, procurement. However, under certain circumstances, it can be high-precision, when using a laser that reproduces the workpiece in a protective gas or vacuum. Another variety is electron beam systems [8]. The latter processes are slower, especially compared to less accurate systems of multi-arc plasma heads.

WAAM manipulation systems are mostly of two types: robotic manipulators or working bodies of machines. Currently, some commercial machines and robotic WAAM systems are available, which are the market leaders in integrated systems and include some very powerful manipulation systems and CAD/CAM software: this, in particular, [9], [10]. Almost any three-coordinate manipulator or robot arm and arc welding source can be combined to create an entry-level WAAM system, as shown in [11].

The market also offers different types of power supplies, and to some extent the material used will determine the chosen process of arc deposition. For example, titanium alloys are typically applied with a more stable arc transmitted by a fusible electrode process (TIG process) or plasma, while most other materials are precipitated by the MIG/MAG process (melting in a shielding gas medium).

WAAM is not currently a fully automated process. Until fully operational commercial AMCAD/CAM software becomes available, the part model is virtually refined manually, and requires certain operator skills. The resulting surface (ripple) WAAM requires cutting to achieve geometric requirements and the appropriate quality of the surface layer. However, the volume of material to be removed can only be 1 mm. It does not increase with the size of the part, so the efficiency actually increases with the size of the parts. Another problem of the method is a certain hollowness of the structure, inherent in all AM processes, the reduction of which requires additional efforts to algorithmize the process of moving the working head. That is why the most appropriate use of WAAM in the aerospace industry, where the ability to manufacture large metal parts from light materials (in particular, titanium alloys) is the main advantage of the WAAM method.

Therefore, the problem of identifying ways and methods to improve the quality of reproduction of blanks WAAM process, in particular, reducing the ripple, reducing the void of the finished product, is relevant and relevant today.

Detection of conditions and reduction of surface layer undulation during reproduction of workpieces by the WAAM method is an urgent task.

Theoretical research

Additive processes using the phenomena of metal melting by an external heat source (electric arc, electron beam, laser) are based on the principles of forming a surface globule caused by the melting of a drop of metal flowing from the electrode or formed by introducing additive metal into the thermal zone. When reproducing a given three-dimensional object, it is generated in layers, by creating bands that lie in the same plane. Therefore, ensuring the quality of the product, its density, as well as the parameters of the surface layer (including surface waviness) is seen in the arrangement of the metal layer, in which the roller formed by globules will have the correct geometric shape, and the roller of the next layer should fill the gap between the rollers.

Melting of the filler material occurs simultaneously with the heating of the working area by an electric arc Fig. 4. In this case, according to [12], it is advisable to provide arc support with direct current, with direct polarity (with a cathode spot at the end of the electrode and the expected temperature up to 3200 °C), which allows to form a more compact thermal effect on the surface and get smaller melt drops.

Due to the action of an electric arc, the balance of forces in the melt zone can be represented in accordance with [13] (Fig.1).

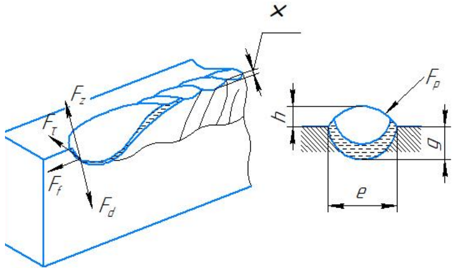


Fig. 1. The power balance of the melt bath: F_f – the force acting on the front of the melt; F_z − the displacement force of the liquid metal; F_τ – tangential forces in the melt bath, due to the movement of the electrode; F_d – force of electric arc; F_p – surface tension forces during solidification of liquid metal

The welding bath is formed due to the influence of the arc, the action of drops of molten metal vapors and reaction forces. In the melting zone for some time there is a movement of liquid metal, to which drops of molten electrode are introduced. When melting metals with an electron beam, the movement is observed from the front wall of the bath along the seam, with partial evaporation of the metal and with the maintenance of thermocapillary forces. According to [13], these forces are a consequence of the difference in surface tension forces caused by the temperature gradient between the melt and solidification zone.

The movement of liquid metal in the field of action of the arc occurs near the zone of influence (perpendicular to the axis of the electrode area) in the direction from the melting zone and in the direction of the arc counterclockwise. Thermocapillary convection due to the temperature gradient is known as the Maragoni effect. Wave phenomena occur in the melt zone due to the action of the system of forces of the melt zone and temperature effects at the time of arc combustion.

The formation of the surfacing roller as a fragment of the 3D model will occur in accordance with Fig. 2, and, as when using means of linear movement, and rotating. The variant of teaching also has essential value on geometrical parameters of the platen (Fig. 2, b.a).

If the intensity of a point heat source (electric arc) according to Gauss's law with its own intensity $I(w) = I_0 \exp\left(-w^2 / w_G^2\right)$, where I_0 − the intensity of heat release on the axis of the electric arc, w − the flow radius; w_G − the radius at which the radiation intensity decreases e times, the considerations will be as follows.

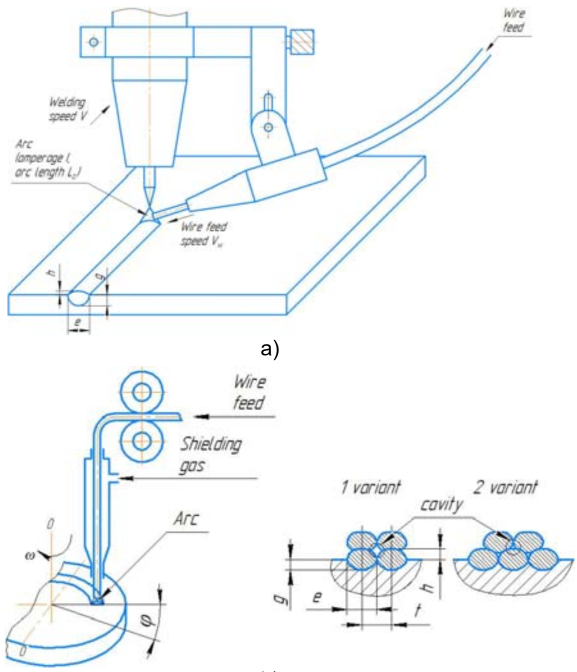


Fig. 2. The scheme of formation of the surfacing roller (a) and the process of reproduction of the model in the study and options for teaching the roller (b)

The known equation of non–uniform heating has the form [13]:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right), \tag{1}$$

boundary conditions on the surface from the action of the source, $-K\frac{\partial T}{\partial z} = q(x,y,t),$ where $q = q_0 1$, q_0 reflects the density of heat from the supplied energy, k − the coefficient of thermal conductivity of the material; the z axis is perpendicular to the surface and directed to the depth of the material. For a stationary system, the heat distribution will be:

$$T(x,z,t) = \frac{q(x) r^2}{\lambda}\left(\frac{a}{\pi}\right)^{1/2} \times \int_0^t \frac{P(t-\tau)\exp\left[\frac{z^2}{4at} - \frac{x^2}{4a\tau}\right]}{\sqrt{\tau}\left(4a\tau + r^2\right)} d\tau, \tag{2}$$

where λ – thermal conductivity; a – thermal diffusion of the material of the workpiece; t – current time; P – electric arc power.

The temperature on the surface of a semi-infinite body at a point with coordinates (x, y, z), provided the heat source, moves with velocity v, as well as ignoring heat loss from the surface will be:

$$\overline{T} = \frac{16}{\sqrt{\pi}} \int_0^\infty \frac{1}{\sqrt{\left(c'^2 + \tau^2\right)\left(b'^2 + \overline{\tau}^2\right)}} \times \exp\left[-\frac{\left(2\overline{x}'^2 + \overline{\upsilon}'\tau\right)^2}{4\left(\overline{c}'^2 + \overline{\tau}^2\right)} - \frac{\overline{y}^2}{\overline{b}^2 + \overline{t}^2} - \frac{\overline{z}^2}{\overline{t}^2}\right] d\tau, \tag{3}$$

where $\overline{T}=16\sqrt{\pi KrT}/PA_0$; $\overline{\upsilon}=\upsilon_r/2a$; $\overline{x}'=\frac{x}{r}$; $\overline{y}'=\frac{y}{r}$; $\overline{z}'=\frac{z}{r}$; $\overline{c}'=\frac{c}{r}$; $\overline{b}'=\frac{b}{r}$; $r^2=cb$; A_0 – scattering capacity of the workpiece; P – heat source power; b, c – parameters of energy density distribution in the cross section of thermal influence.

The change in temperature will be determined by the ratio:

$$T(x,y,z,t)=\frac{P}{\pi\frac{1}{2}\rho c}\int_0^t\frac{e^{\frac{(x-v(t-z))^2}{4\alpha\tau+A^2}\frac{y^2}{4\alpha\tau+B^2}}}{\left[\left(4\alpha\tau+A^2\right)\left(4\alpha\tau+B^2\right)\alpha\tau\right]^{1/2}}\times \tag{4}$$
$$\times\left[\begin{array}{l}e^{-\frac{z^2}{4\alpha\tau}}-\eta(\pi\alpha\tau)^{1/2}erfc\left(\frac{z}{2(\alpha\tau)^{1/2}}+\eta(\alpha\tau)^{1/2}\right)\times\\ e^{\eta z+\eta^2\alpha\tau}\end{array}\right]d\tau,$$

x, y, z – coordinates; t – time; η – heat transfer coefficient from the surface of the workpiece; a – thermal conductivity; A and B – larger and smaller axes of the heating area.

The depth of heating a determine the equation

$$T(t)=T_{\max}-\frac{q_l\delta}{\lambda}\left[\begin{array}{l}\frac{2}{\sqrt{\pi}}\frac{\sqrt{a(t-\tau)}}{\delta}+\\ +\exp\left(\frac{a(t-\tau)}{\delta^2}\right)erfc\left(\frac{\sqrt{a(t-\tau)}}{\delta}\right)\end{array}\right] \tag{5}$$

The energy balance, taking into account the melt of the material and its partial evaporation, will take the form:

$$P(t)dt=\rho\cdot L_u\pi\cdot\tau^2(t)dh+\rho\cdot L_{nл}\cdot 2\pi\cdot\tau(t)h(t)dr \tag{6}$$

where the first term is the energy expended on evaporation and the second is the energy expended on melting.

The dynamics of the movement of the working body along the teaching surface was modeled by known relations that describe the behavior of a mechanical system with concentrated masses on elastic–elastic bonds.

Mathematical modeling of the surfacing process allowed us to conclude that in addition to the feed factor of the filler metal (expressed through the speed of the wire v_{nn}), the parameters of the roller are influenced by electrical characteristics of the arc, in particular, current I, surface conditions (v_e); the wavyness of the seam χ, $\chi=h_{max}-h_{min}$, mm, is also determined by the surface where the material is laid. When laid out on a flat base, the wavyness χ is formed due to the manifestation of dynamic phenomena of the supply system, as well as the pulsating action of the electric arc, Fig. 3; in the future, the base, which already has a non-planarity, leads to an increase in undulation and under certain conditions can cause a violation of the combustion of the arc.

This requires additional study of the phenomena of arc combustion in conditions where the base is not flat, but has the initial spatial deviations.

To establish the patterns of formation of the surfacing roller in the process of reproducing a given 3–d model used a manipulation system of the machine model 6R13F3 with CNC system NC210 and the electric arc was created using a power supply Fronius Magicwave 3000, which allowed at a voltage U=10,1–22 V to provide a current I=155–215 A. As an additive used wire ∅ 3,0 mm Titanium Grade 5; he electrode was set at the optimal distance from the surface L=3–7 mm, its diameter ∅ 2,5 mm. Shielding gas – argon.

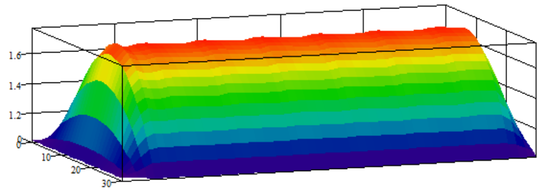


Fig. 3 Formation of the surfacing roller when laying on a flat base

Modeling results and experimental research

To obtain the regression dependences that determine the shape of the seam, as well as to predict the accuracy parameters of the additive product, we denote its geometric characteristics, respectively, 2: e – width of the weld, h – its height, g – depth of penetration.

Analysis of the obtained models in the form of static expressions of regression equations shows that they reflect the deterministic dependences of the weld size on the main modes of argon arc welding and do not contradict the existing notion of weld formation [13-14]. However, to lay out the circular seam and reproduce the three–dimensional model, it is necessary to adjust the corresponding coefficients; in addition, the corresponding models in the first stage can be in the form of linear functions; in addition to relations (3), there must be another equation that takes into account the wavy surface of the seam χ. Must be another equation that takes into account the wavy surface of the seam χ.

$$\begin{array}{l}h=f(V_w,\ d_w,V\ ,I\ ,d_e\ ,L_a)\\ e=f(V_w,\ d_w,V\ ,I\ ,d_e\ ,L_a)\\ c=f(V_w,\ d_w,V\ ,I\ ,d_e,L_a)\\ g=f(V_w,\ d_w,V\ ,I\ ,d_e\ ,L_a)\end{array} \tag{7}$$

When planning the required number of experiments for the response function – by planning a multifactorial experiment of type 2^4 by the Box–Wilson method, it is necessary to make a regression equation. In the study of the process of forming the seam took into account the influence of the following parameters of the welding mode: I – welding current strength; U – arc voltage; L_a – arc length ($L_a = L_a + f_d$, where f_d – exciting effects along the length of the arc caused b the characteristics of the surfacing surface); V – welding speed; V_w – the feed rate of the filler wire; d_e – the diameter of the tungsten electrode; d_w – wire diameter, mm. When choosing the ranges of variation of the factors of functions provided by the experimental plan, the results of modeling the heating process and the possibility of reproducing such levels in practice were taken into account.

It was assumed that for the equipment used d_e and d_w were selected according to the recommendations [1], and d_e=2,5 mm, та d_w= 3 mm, and the arc voltage was provided by the adopted inverter model Fronius MagicWave 3000, U =10.1–22 V. The values of the factors taken into account are given in table 1. To conduct planning on the basis of a full–factor experiment of type 2^4 a matrix of experiment planning was compiled, which is given in table 2 [6]. As a result of plans realization of experiment the regression equations allowing to estimate influence of the factors, which were taken into account on effective parameters h, e, g, χ are received.

From the Pareto diagram it is seen that the greatest influence on the height of the welded roller h has the speed v, the wire feed speed and the total effect of these two factors. With increasing speed v the height of the weld will decrease, and with increasing wire feed speed v_w – increase. Increasing the current I, the length of the arc L_a leads to a slight decrease in the height of the seam, table 1.

The width of the weld roller is influenced by three factors: the length of the arc L_a, the speed v and the current I. The greatest influence is the length of the arc and the speed of movement. From the Pareto diagram shown in table 1, it is seen that the greatest influence on the depth of the melt of the roller have the length of the arc, velocity and current. With increasing arc length and velocity, the depth of penetration of the weld decreases, and with increasing current – increases.

The last line of Table.1 shows the response surface of the objective function – the depth of penetration of the weld g, mm, and their two-dimensional cross sections in the planes of the impact parameters, which can clearly illustrate the dependence of this parameter g on individual factors – I, L_a, V.

The level of undulation was rather weak from the conditions of processing. It was found that the maximum values of χ, mm, acquires at the initial moment of time (when the arc is ignited) and when the arc is turned off. Significant perturbation can be considered a change in the conditions of movement of the head: so when you change the direction of movement associated with the formation of certain layers of the reproducible model, the ripple increases; a decrease in the parameter χ is observed at steady motion.

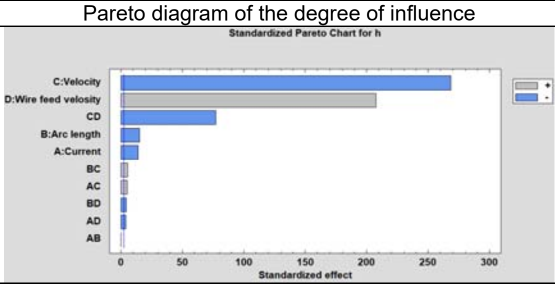
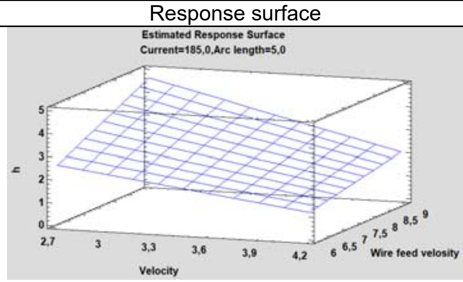
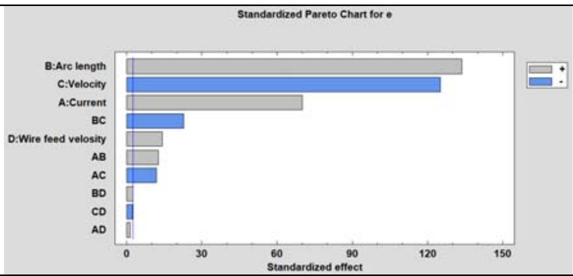
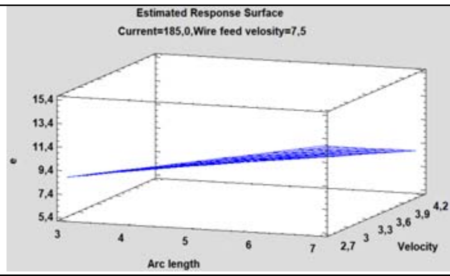
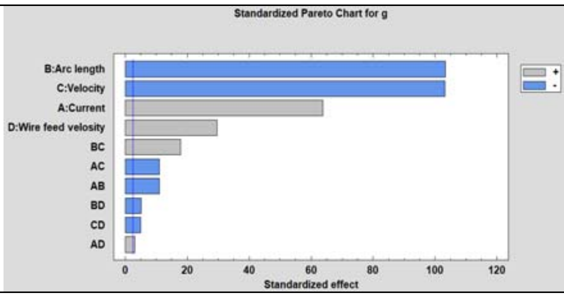
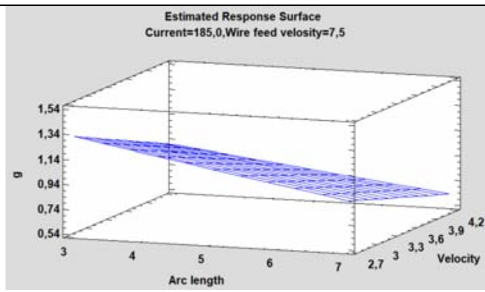
Microelectronic study of the cross section of the seam proves that under conditions of relatively low speeds of the head (up to 10…15 mm/s) the laying of rollers is quite dense (Fig. 4, a, b). In this case, when shifting the trajectories of the head (Fig. 2, b, option 2), the density is the highest, otherwise the cavities are significant and close to the cavities when laying plastic (Fig. 4, c). On the right microphoto (Fig. 4, b) separate cavities and defects of connection of layers are observed.

Comparison of interlayer and inter-roller laying of materials by FDM–process and WAAM-process proves that the density in the latter case is up to 97% of the density of the source material, while in WAAM the density can reach 99.2 %.

Comparison of interlayer and inter-roller laying of materials by FDM–process and WAAM-process proves that the density in the latter case is up to 97 % of the density of the source material, while in WAAM the density can reach 99.2 %.

It can be argued that improving the quality of products obtained by processes based on argon-arc welding, is seen in the optimization of methods of forming rollers, in particular, ensuring appropriate overlap of trajectories on the layers of 0.5e, arc, as well as maintaining the mode of dynamic constancy of arc combustion. Further research should be aimed at determining the patterns of solidification of the metal in the melt bath, as well as to study the dynamic phenomena of wave processes under the action of a system of forces during the formation of the surfacing roller.

Table 1. Results of the statistical analysis given to the experiment

<table>
<tr><th>P_i</th><th>Pareto diagram of the degree of influence</th><th>Response surface</th></tr>
<tr><td rowspan="2">h, mm</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">$h = -2{,}59376 - 0{,}0410349 \cdot L_{\partial} + 0{,}365082 \cdot V + 1{,}48785 \cdot V_{n\partial} - 0{,}259977 \cdot V \cdot V_{n\partial}$</td></tr>
<tr><td rowspan="2">e,
mm</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">$e = 1{,}03241 + 0{,}0367745 \cdot I + 0{,}940488 \cdot L_{\partial} + 0{,}296303 \cdot V$</td></tr>
<tr><td rowspan="2">g, mm</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">$g = 0{,}688702 + 0{,}0068816 \cdot I - 0{,}0763948 \cdot L_{\partial} - 0{,}12007 \cdot V + 0{,}0506604 \cdot V_{n\partial}$</td></tr>
</table>

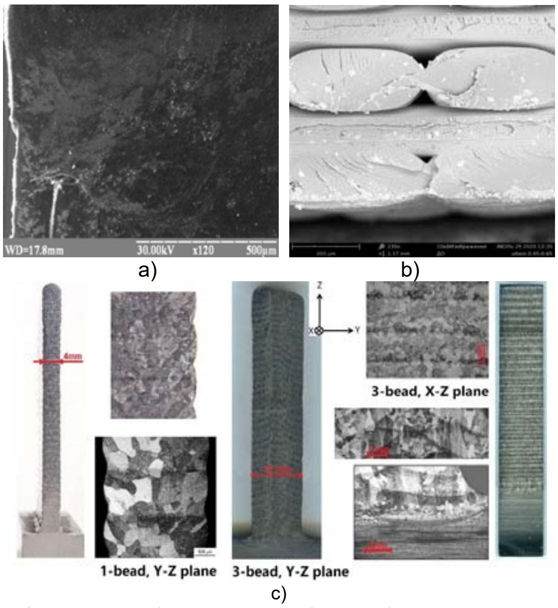


Fig. 4 Comparison of end sections of model fragments obtained by surfacing (a), FDM–printing with plastic (b) and additive technology xBeam 3D Metal Printing (c). Microphoto (b) – ULTEM 9085 plastic, element created on the STRATAsys FORTUS 380 printer. Cavities and defects of the open end face are observed on the sections

Conclusions

A set of theoretical and experimental studies aimed at improving the quality of products created by the WAAM process. It is shown that this process can be successfully used for the manufacture of single workpieces for further machining by traditional methods. Due to the application of the multifactor experiment planning method, a regression equation is obtained, which allows to determine the main parameters of the roller formed by argon-arc welding from the main process parameters – arc length, current, head speed and wire feed rate.

It was found that the height of the weld is most affected by speed, wire feed speed and a combination of these factors. The width of the weld is most influenced by the length of the arc, speed and current, and these factors have the greatest impact on the depth of penetration of the weld.

The influence of these factors on the undulation of the roller surface is negligible; it is concluded that the parameter χ results in dynamic phenomena of wave processes that develop under the action of a system of forces during the formation of the surfacing roller. Improving the quality of products is seen in the optimization of methods of forming rollers, ensuring dynamic constancy of the working head, ensuring appropriate overlap of trajectories in the layers by 0.5*e*, ensuring dynamic constancy of the working head, establishing a rational arc length and maintaining dynamic combustion constancy arc.

The response surfaces of objective functions in the planes of influence parameters are constructed, which allow to visually illustrate the dependence of the controlled geometrical parameters of the seam on individual influence parameters.

It is shown that the improvement of product quality, first of all, by reducing the surface roughness, is possible by optimizing the methods of forming rollers, in particular, providing appropriate overlap of trajectories on the layers by 0.5*e*, arc, as well as maintaining the mode of dynamic constancy of arc combustion.

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