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STUDY OF THE INFLUENCE OF GMAW-CMT AND PULSE PROCESSES OF ADDITIVE DEPOSITION OF SILICON BRONZE CuSi3Mn1 ON THE GEOMETRICAL CHARACTERISTICS OF THE SURFACE, STRUCTURE AND STRESS-STRAIN STATE OF FINISHED PRODUCTS

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ABSTRACT

Silicon bronzes of CuSi3Mn1 type (BrKMts3-1) are widely used in the machine-building, aerospace, and mining industries due to their properties. Given the rather high cost of copper-based nonferrous alloys, the use of wire-arc additive manufacturing (WAAM) technologies is relevant. Cold Metal Transfer (CMT) and pulse arc surfacing (Pulse process) are used to prevent overheating and reduce the heat input during surfacing of copper-based alloys. The results of studies of layer-by-layer surfacing of silicon bronze indicate a certain dependence of geometrical characteristics, structural composition, and susceptibility to defect formation on the applied surfacing method (GMAW-CMT/Pulse). Short-circuit surfacing provides a greater height of each bead than with pulse current supply (up to 25 %) and a reduction in the width of each bead, respectively. However, the surface unevenness also increases. The sample deposited by the GMAW-Pulse method contains critical defects in the form of transverse cracks. The stress-strain state modeling for the pulse surfacing method indicates a critical accumulation of normal tensile stresses, which, in combination with the anisotropic structure of the metal, may be the cause of crack formation.

KEYWORDS: WAAM, GMAW, Cold Metal Transfer, pulse arc surfacing, additive technologies, CuSi3Mn1, layer-by-layer surfacing

INTRODUCTION

Silicon bronzes CuSi3Mn1 (BrKMts3-1) are widely used in chemical, petroleum processing and mining industries, due to their high resistance to aggressive media, elasticity and antifriction properties. Production of unit repair parts (bushings, gears) or restoration of the already damaged ones opens up broad possibilities for application of Additive Manufacturing technologies to produce blanks for further finishing treatment instead of the traditional machining operations, as the rather high cost of nonferrous metals, and particularly copper alloys, makes it necessary to reduce machining wastes during manufacture of the finished part or product [1].

Additive synthesis with application of silicon bronze CuSi3Mn1 has already been considered in the sphere of application of concentrated heat sources of the type of Non-Vacuum Electron Beam (NV-EBM) [2]. However, using the laser or electron beam is problematic due to a high coefficient of surface reflection of copper and its alloys [3]. Therefore, application of Wire-Arc Additive Manufacturing (WAAM) technologies is justified from the viewpoint of economic characteristics: relatively low equipment cost and practical absence of limitations on the overall dimensions and shape of synthesized products. Additive layer-by-layer surfacing of CuSi3Mn1 can be performed by basic GMAW technology. Owing to the presence of active deoxidizers (silicon, manganese) in its composition, silicon bronze CuSi3Mn1 lends itself readily to welding and surfacing, although with some limitations on the thickness of the deposited material layer. In view of the high conductivity of copper and alloys on its base, there is the need to use powerful concentrated heat sources. At the same time, the high fluidity of the metal melt and rather high coefficient of thermal expansion ($18 \cdot 10^6$) in combination with a considerable [4] metal shrinkage at crystallization from the liquid state create the prerequisites for accumulation of considerable residual stresses at multilayer deposition. This, in its turn, can lead to formation of critical cracklike defects. Excess heat input also leads to structural growth of columnar grains oriented in the direction of heat removal, resulting in anisotropic mechanical properties. To control the heat input and avoid excess overheating at CuSi3Mn1 deposition, and to produce an equiaxed grain structure, the following variants of GMAW method are used: welding with short-circuiting — Cold Metal Transfer (CMT) process and heat input regulation with pulsed current feed (Pulse process).

A significant number of studies is devoted to GMAW-CMT deposition, using silicon bronze (CuSi3Mn1) as an additional component in tandem with AK5 aluminium alloy (AlSi5-ER4043) with the purpose of lowering the probability of intermetallic phase formation and improvement of mechanical properties of the finished products [5-7]. However, in work [5] there is clearly a problem of excess level of residual shrinkage of the deposited layers of the formed sample, leading to the deposited wall tearing from the copper base. In work [8] the authors considered the influence of deposition mode parameters (heat input level) on shaping and structural changes of layered deposit of CuSi3Mn1. The authors also established the fact of increase of the produced sample surface hardness at current rise. Such behaviour, in particular, increase of silicon bronze hardness, radically differs from low-alloyed steels [9]. At the same time, the roughness (unevenness) of the surface decreases with increase of current from 70 to 110 A, which is logical, as the time of existence of the weld pool melt becomes greater, and it promotes better spreading of liquid metal and leads to greater bead width [8].

In work [10], the influence of the method of short-circuiting surfacing (GMAW-CMT) and pulse surfacing mode (GMAW-Pulse) on the sample structure, using CuSi3Mn1 solid wire, was studied. The authors of work [10] have rather broadly considered the subject of the influence of mechanical transition of electrode metal drops (GMAW-CMT process) and contactless drop detachment at the moment of pulse current feed (GMAW-Pulse process) on the structural changes during weld pool crystallization. We have found that pulse current feed leads to local overheating of the liquid weld pool with a considerable temperature gradient from the melt surface to weld pool bottom. This causes growth of long grains of columnar type at metal crystallization, causing a deterioration of mechanical characteristics of the already deposited metal. Application of GMAW-CMT surfacing with short-circuiting, contrarily, promotes formation of equiaxed grains and their refinement, having a negative impact on mechanical characteristics of the products [10].

However, in works [8] and [10] investigations of the additive process were conducted at deboosted modes of surfacing (from 100 to 110 A) and quite small number of deposited layers (up to 5), which does not allow fully assessing the surface shaping characteristics and the influence on the stress-strain state of the finished product.

Other scientific works are considering application of CuSi3Mn1-containing fillers only as an intermediate material for braze-welding of bimetal compositions of TC4 titanium alloy — austenitic steel E304 [11] and other [12, 13], and are not related to the subject of additive manufacturing of products. Considering the small number of works highlighting complete additive synthesis with application of purely silicon bronzes CuSi3Mn1 by the methods of GMAW-CMT and Pulse surfacing methods, studying this direction is relevant.

The objective of the work is investigation of the possibility of additive manufacturing of 3D spatial products from silicon bronzes CuSi3Mn1 (BrKMts3-1) with application of arc heat sources and their variants in the form of CMT and Pulse processes, as well as their influence on the geometrical characteristics, structure, and tendency to defect formation in the produced samples.

The tasks for reaching the objective:

- perform analysis of literature sources as to the possibility of applying silicon bronzes in the processes of additive manufacturing of products, tendency to defect initiation, features of shape- and structure formation of the layers of the metal deposited using arc heat sources;
- produce samples by layer-by-layer arc surfacing using GMAW-CMT/Pulse methods with solid wire CuSi3Mn1 (BrKMts3-1) in pure argon atmosphere (100 % Ar) on a substrate from austenitic stainless steel E304;
- study the geometrical characteristics of the produced sample surface;
- study the structure of the deposited sample metal, produced by GMAW-CMT/Pulse methods of arc surfacing, and tendency to defect formation.

EXPERIMENTAL PROCEDURE

Experiments on GMAW-CMT/Pulse surfacing were performed in the experimental facility for welding rectilinear welds (*X* axis) with a cantilever for two-coordinate (along axes *Y*, *Z*) positioning of the welding torch (Figure 1, *a*). Fronius TransPulse Synergic 2700 welding source in tandem with PullMig CMT MHP 400i torch was used. As in the previous studies [9], a strategy of deposition in the reciprocal direction for each layer alternatively was selected (Figure 1, *b*). Research work was performed in the facilities of LLC "Science-Production Center "Plazer"".

Investigations of layer-by-layer synthesis were conducted on plates from 6 mm thick austenitic stainless steel AISI 304 (08Kh18N10). Layer-by-layer surfacing was performed by solid electrode wire CuSi3Mn1 (BrKMts3-1) of diameter d_e = 1.2 mm^2. Surfacing at both GMAW-CMT and Pulse processes was carried out at the same deposition rate (V_w = = 600 mm/min) and filler wire feed ($V_{w.f}$= 3.5 m/min). Shielding gas was 100 % argon.

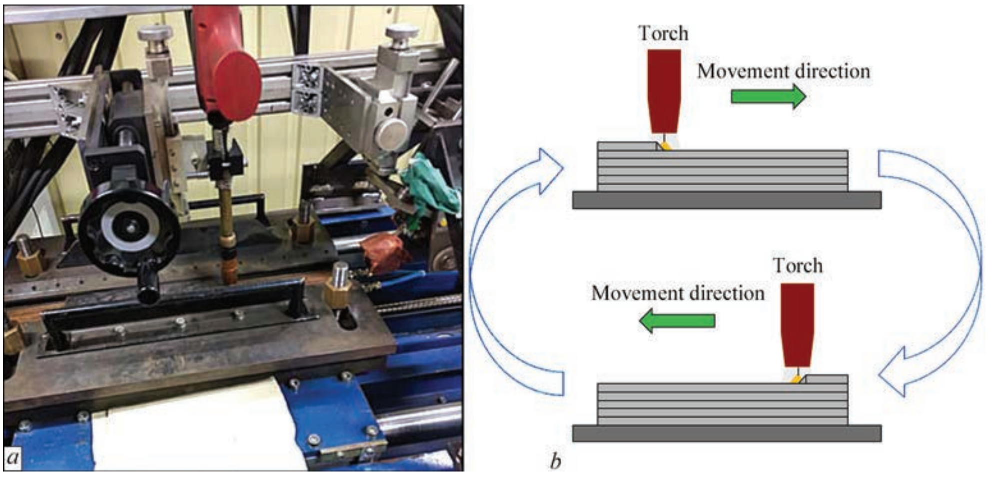

Figure 1. Surfacing equipment and procedure: *a* — facility for straight weld deposition; *b* — direction of torch movement at layer-by-layer deposition

Modes of layer-by-layer surfacing of samples are given in Table 1. Energy input and mode parameters (current, voltage) taken by mean arithmetic values, because of the difficulty of following the current parameters at the moment of pulse feed (Pulse method) and features of GMAW-CMT process with short-circuiting, are described in work [10].

Considering the gradual lowering of heat removal into the base and heat accumulation in the previous layers at alternative layer building up, a strategy of cooling to 120 °C after each layer was selected. It allows eliminating the influence of excess heat on the crystallization process and shaping of each individual layer, protecting the already deposited metal layers from excess overheating, which is confirmed by the results of the previous work [9, 10].

Samples for investigations of macro- and microstructure were prepared by the method of mechanical cutting out of the formed walls with addition of lubricant-coolant fluid to avoid metal overheating with distortion of its structure.

To study the structure, the samples were prepared on high-speed polishing wheels using diamond pastes. The structure of experimental sample metal was revealed by etching in a hot solution of nitric (HNO_3), orthophosphoric (H_3PO_4) and acetic (CH_3COOH) acids in the proportion of 10–30–60 %, respectively.

Structural studies were performed using metallographic microscope Neophot-32. Phase component hardness was determined by Vickers in LECO M-400 hardness meter. The load was 1N (100 g), time of load application was 10 s. Digital photos of the structures were taken with "Olympus C-500" camera.

Finite element method was used to analyze the stress-strain state (SSS) in the deposited samples. Modeling included plotting 3D finite element model of the deposited samples. A model of the type of equilateral triangle with side l = 50 mm having regions of deposition direction reversal was used in the studies. It allows assessment of the influence and distribution of nonuniform thermal load in case of a curvilinear trajectory [14]. The geometrical model of a sample, boundary conditions and finite element grid are shown in Figure 2.

The finite element model was used to perform analysis of the stress-strain state. The system of equations was solved in a series of small steps, beginning from the start of the printing process and up to cooling of the weld to ambient temperature. Each step included calculation of the increments of node displacements using Newton iteration method. The data on the level of stresses and strains were updated after each iteration, and calculation of residual shrinkage force was also performed. The theory of plasticity with kinematic strengthening was used in the model as a characteristic of metal behaviour. Such an approach to modeling provided a detailed understanding and analysis of the processes, occurring during 3D deposition by GMAW-Pulse process.

Table 1. Modes of layer-by-layer surfacing

Method	Filler wire	Shielding gas	Energy input, J/mm	Current, A	Voltage, V	Nozzle diameter, mm	Wire feed rate $V_{w.f}$, m/min	Deposition rate V_w, mm/min	Gas flow rate, l/min
GMAW-CMT	(BrKMts3)	100 % Ar	125	131	12	16	3.5	600	15
GMAW-Pulse			192	120	20				

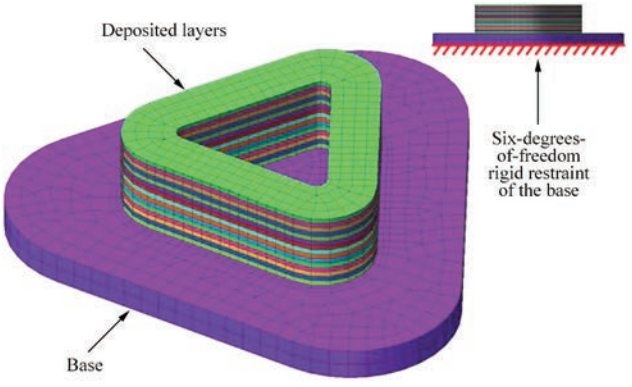

Figure 2. Finite element grid and boundary conditions for finite element modeling of GMAW-Pulse surfacing process

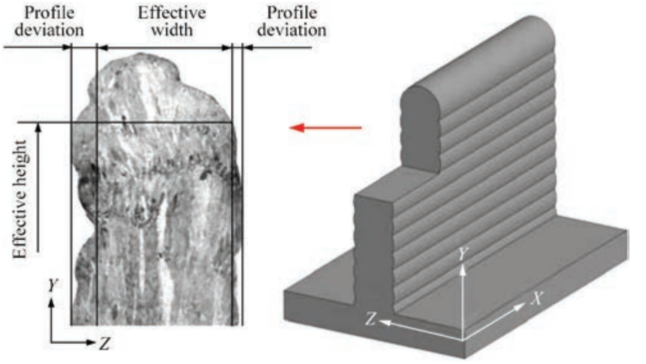

Figure 3. Determination of the parameters of effective height, effective thickness and maximal profile deviation [6]

INVESTIGATION RESULTS AND THEIR DISCUSSION

Figures 4, 5 shows the results of analysis of the dependence of changes in the geometrical characteristics of the produced samples from silicon bronze CuSi3Mn1 (BrKMts3-1) on the applied GMAW-CMT/Pulse surfacing method.

Geometrical characteristics of the surface of the samples were assessed, using an approach with determination of the parameters of effective height and width of the sample wall, which was proposed by the authors in work [15] and was used in previous experiments with low-carbon steels [9]. This approach allows with a rather high degree of accuracy establishing the share of useful deposited metal of the product and the percentage of metal envisaged for allowance for the subsequent finishing treatment. Maximal value of deviation of the wall profile symmetrically from the deposited layer axis (Figure 3) allows evaluation of the unevenness of the finished product surface. Maximal efficiency of metal utilization is achieved at minimal values of its surface unevenness. This is particularly urgent at application of nonferrous metals and copper alloys (CuSi3Mn1), in connection with their high cost compared to low-alloyed and low-carbon steels [12].

The height of 50 deposited layers of silicon bronze (CuSi3Mn1) of samples produced by GMAW-CMT

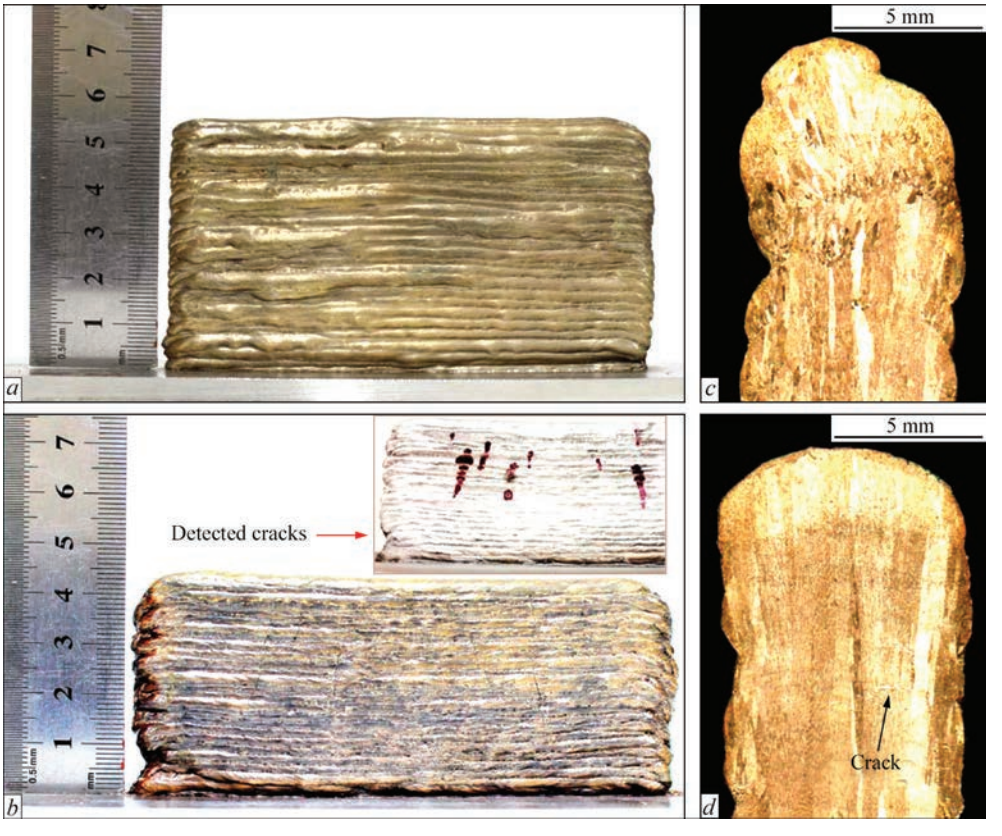

Figure 4. Samples of silicon bronze CuSi3Mn1 (BrKMts3-1) produced by different surfacing methods: *a* — GMAW-CMT; *b* — GMAW-Pulse with cracks detected by liquid-penetrant inspection; *c* — GMAW-CMT, macrostructure; *d* — GMAW-Pulse, macrostructure with cracks present in the transverse section

process (Figure 4, *a*) is 25 % greater (44.9 and 54.9 mm, respectively) at reduction of the effective layer thickness from 9.75 to 8.5 mm, compared to GMAW-Pulse process (Figure 4, *b*).

At GMAW-CMT surfacing method the wall surfaces have clearcut sagging of crystallized metal of individual layers, leading to increase of the characteristic of deviation of side surface profile from 0.5 to 1.13 mm. For GMAW-Pulse method, the unevenness characteristic is smaller, and it is in the range of 0.72–0.82 mm (Figure 4, *b*). On the whole, the parameters of the dependence of unevenness (Figure 5), effective width and height can be regarded as the consequences of the change in the level of the heat input in keeping with the applied GMAW process. The degree of overheating and time of weld pool staying in the liquid state influence the solidification rate with a change in the pattern of weld pool metal spreading.

In samples produced by GMAW-CMT process visual inspection did not reveal any surface defects. However, appearance of critical defects was found at GMAW-Pulse surfacing method. During deposition after reaching the 32nd layer, initiation of cracks is observed which are normal to the surfacing direction (Figure 4, *b*, *d*). Further deposition of new layers causes cracking both in the layers proper and in the previously deposited layers. It may be related to a much higher heat input at pulse current feed than at GMAW-CMT process.

Microstructural analysis of samples was performed on sections enclosing three zones of deposition: last deposited layer, transition zone of fusion of the last and previous layer, and previous layers.

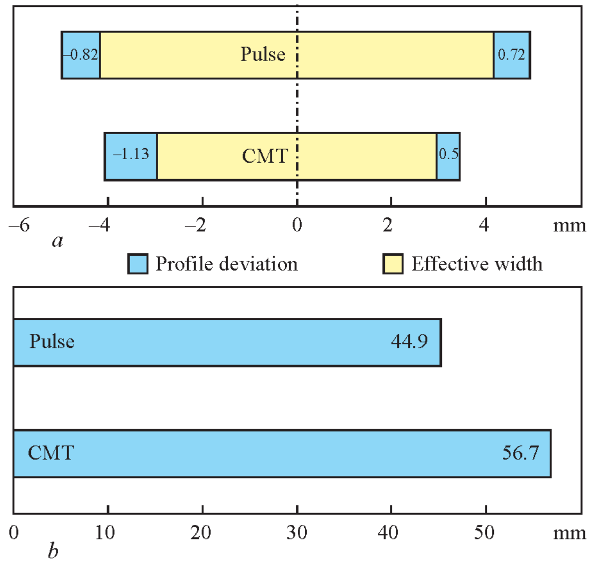

Figure 5. Parameters of the dependence of effective wall thickness (*a*) and effective height (*b*) for different methods of additive GMAW-CMT/pulse surfacing

Fine nonmetallic inclusions of an irregular shape and isolated transparent inclusions of gray-blue colour looking like pores were found on the polished surface of the microsections in all the studied samples. Inclusions are mostly observed along the central axis over the entire height of the studied deposit zones (Figure 6, *a*–*d*). No critical defects were found on the surface of a sample deposited by GMAW-CMT process. The mechanism of silicate inclusion formation during bronze deposition is described in [16] and it is attributed to remelting of CuO and SiO_2 thin films, which appeared as a result of ingress of adsorbed oxygen into the weld pool melt from the previous deposited layer.

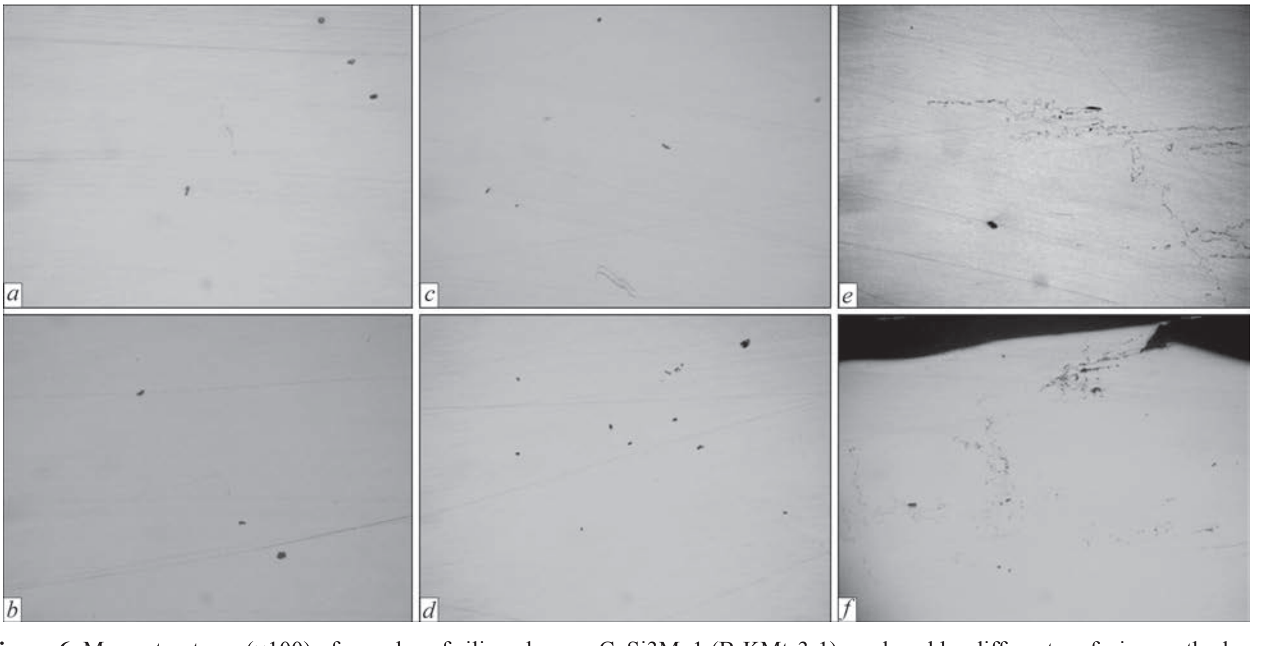

Figure 6. Macrostructures (×100) of samples of silicon bronze CuSi3Mn1 (BrKMts3-1) produced by different surfacing methods: *a*, *b* — GMAW-CMT; *c*, *d* — GMAW-Pulse; *e* — GMAW-Pulse, crack in the sample metal thickness; *f* — GMAW-Pulse, cracking from bead side edge

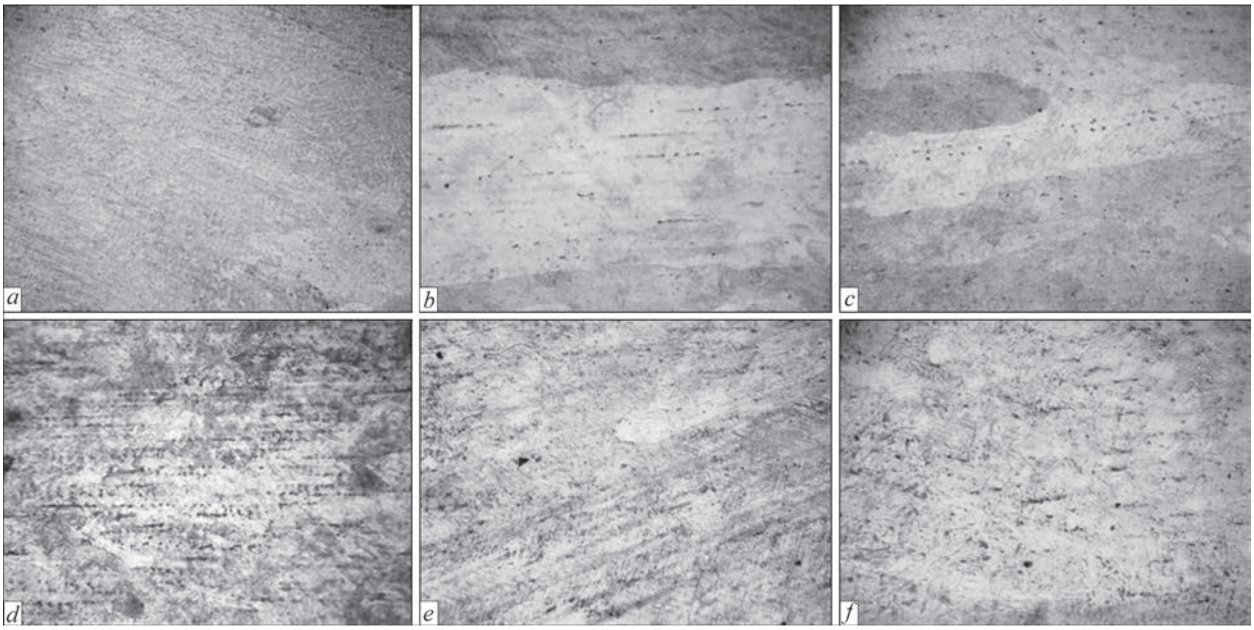

Figure 7. Microstructures (×800) of samples of silicon bronze CuSi3Mn1(BrKMts3-1) produced by different surfacing methods: *a–c* — GMAW-CMT; *d–f* — GMAW-Pulse; *a*, *d* — last deposited layer; *b*, *e* — transition zone; *c*, *f* — previous layers

On the surface of a sample deposited by GMAW-Pulse method numerous microcracks were found both near the side edge (Figure 6, *f*) and closer to the deposited bead center. Microcracks are also observed, which begin at the distance of approximately 6000 μm from the upper edge of the deposited bead and end in the region of the last layer (Figures 6, *e* and 8, *a*, *b*).

Metal of samples produced by GMAW-CMT/Pulse surfacing methods, consists of α-solid solution. For GMAW-CMT method the structure of the last layer is characteristic for multilayer deposits: columnar structure of cast metal points to crystallization direction, and is a fine dendritic structure (Figure 8, *a*). The transition zone structure consists of massive grains elongated along the specimen height and traces of primary structure in the form of intermittent strings of dark globular precipitates of subgrains of 100–150 μm size and substructures with a pronounced orientation (Figure 7, *b*). Structure of previous layers is similar to the transition zone and the last layer. However, a small quantity of a structure with a pronounced orientation appears also in light grains (Figure 7, *c*).

The structure of the last layer of samples produced by GMAW-Pulse surfacing differs from CMT process. No dendritic structure is observed in the last layer. Remains of cast metal in the form of intermittent bands and light matrix are present in the structure. A substructure in the form of plates of a pronounced orientation is observed in some regions of the light matrix (Figure 7, *d*). Structure of the transition layers is similar to the structure characteristic for GMAW-CMT surfacing (Figure 7, *e*). Previous layers have a structure similar to previous zones, remains of cast crystallites and massive grains with different degree of etching are present (Figure 7, *f*). In darker grains the same substructure is observed, as in the transition zone of layer fusion.

In the macrosection of a sample (Figure 4, *d*) deposited with pulse current feed one can see clear interfaces of individual layers with formation of massive columnar grains, which are oriented in the heat removal direction. Such a structure confirms the conclusions reached in work [10] as to residual overheating of the

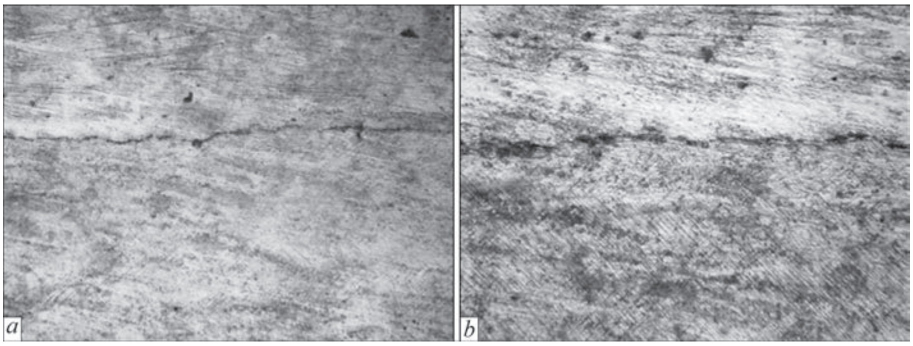

Figure 8. Structures (×200) of zones along the axis of the deposit produced by GMAW-Pulse method in the transition region (*a*) and the last layer (*b*)

weld pool with subsequent formation of an anisotropic structure of the deposited metal. Potentially, it can be the cause for appearance of critical defects of the type of cracks (Figure 8) at deposition of a sufficient number of layers with parallel accumulation of uncompensated tensile stresses from metal shrinkage at crystallization. GMAW-CMT process is characterized by a certain disorientation of the structure grains (Figure 4, *c*).

Microhardness of individual metal zones of the deposited samples is given in Table 2.

Microhardness of individual zones as a whole for Pulse surfacing, compared to CMT method, coincides with the authors' conclusions to some extent, which a given in work [8] in the context of increase of the deposited layer hardness at increase of the heat input.

FINITE ELEMENT MODELING

During creation of products by multilayer 3D printing, cracking can be the result of different factors. One of them is formation of thermal stresses, arising because of temperature difference between the layers during deposition. Technological parameters of the surfacing process also have an important role, in particular deposition rate, heat source power, and sequence of layer deposition. Inconsistency of any of these parameters may lead to cracking and other defects in the finished product.

Stress-strain state of the surfaced products depends on the kinetics of thermal deformation processes, occurring at deposition. At present the Goldak model of

Table 2. Average values of zonal microhardness of deposited samples, MPa

Surfacing method	Last layer	Transition zone	Previous layers
CMT	1190	1120	1190
Pulse	1160	1450	1400

a 3D source with normal distribution of specific heat along all the coordinate axes in the heat flux, having the shape of an ellipsoid, is mainly used in research practice for analysis of thermal processes of arc welding and surfacing.

In order to analyze the stress-strain state and establish the possible causes of cracking in samples deposited by GMAW-Pulse process finite element modeling of layer-by-layer surfacing of a sample from silicon bronze CuSi3Mn1 on the substrate from austenitic stainless steel was performed.

Experimental model has the following geometrical parameters: length of the side of the triangle is 50 mm, substrate thickness is 6 mm, number of layers is 15, layer height (total height) is 1 mm (15 mm total). Material being deposited is CuSi3Mn1, substrate material is austenitic stainless steel AISI 304 (08Kh18N10).

Results of modeling the deposition process show that after achievement of 13–15 layers the level of equivalent and longitudinal normal tensile stresses arising along the trajectory of the torch movement grows significantly, as a result of reheating of previously deposited layers in the selected region (Fig-

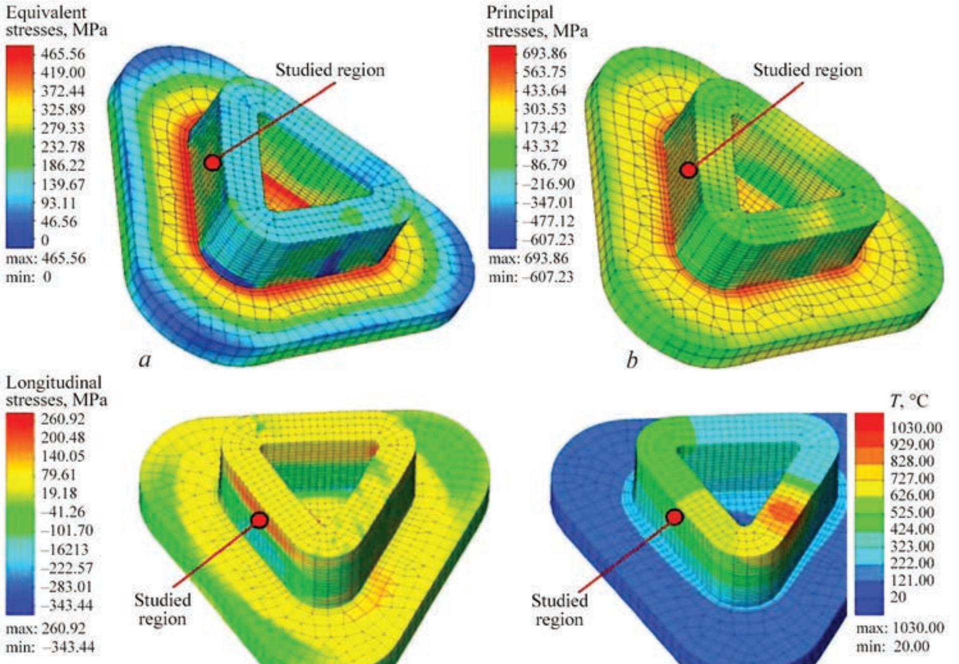

Figure 9. Fields of stress and temperature distribution: *a* — equivalent stresses (MPa); *b* — maximal principal stresses (MPa); *c* — normal stresses in the direction along the deposited layer (MPa); *d* — temperature distribution around the region of crack initiation after deposition of the 13th layer (°C)

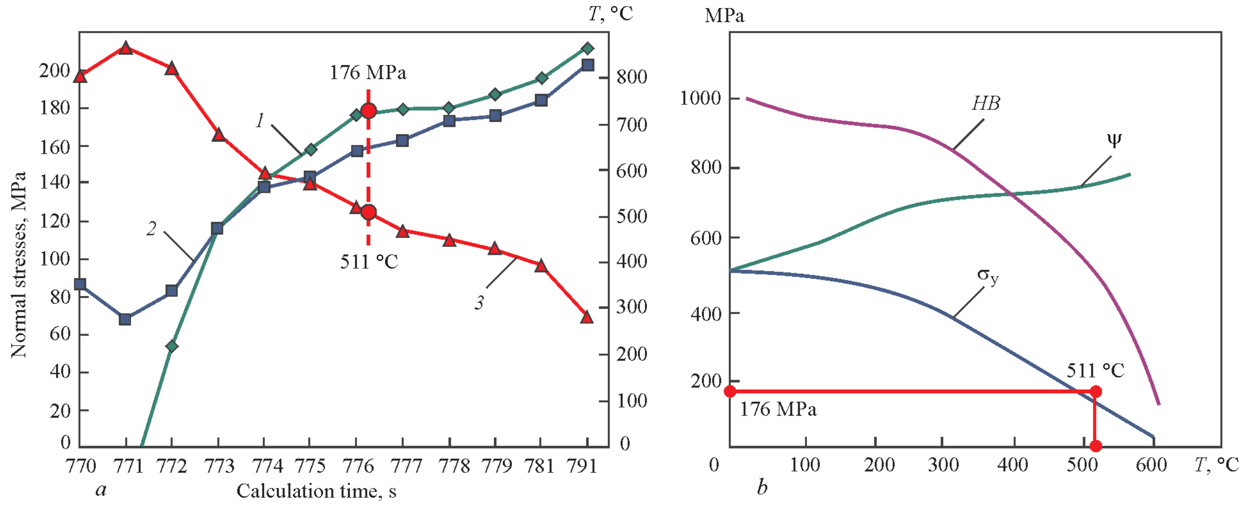

Figure 10. Graph of dependence of normal (*1*), equivalent stresses (*2*) and temperature (*3*) on time after deposition for the region of crack formation (*a*); change of mechanical properties of silicon bronze CuSi3Mn1 (BrKMts3-1), depending on temperature [4] (*b*)

ure 10, *a*). During multiple heating the level of longitudinal tensile stresses exceeds the bronze ultimate strength $\sigma_t \approx 140$ MPa and reaches $\sigma = 176$ MPa at actual temperature in the point of approximately 511 °C (Figures 9, *c* and 10, *a*, *b*).

This effect is observed as a result of reheating of previously deposited layers by the electric arc heat at deposition of the next bead. Analysis of the dependence of stress magnitude and distribution on temperature and time (Figure 10, *a*) shows that normal longitudinal tensile stresses reach the material ultimate strength in the temperature range of 550–490 °C (Figure 10, *b*), which leads to initiation of cracks detected at visual examination of shaping and metal structure.

CONCLUSIONS

The regularities of the influence of GMAW surfacing methods using the electric arc as the heat source on the change of geometrical characteristics and structure of stress-strain state components and probability of defect initiation at additive deposition of silicon bronze CuSi3Mn1were studied. Analysis of the derived data shows that:

1. Surfacing method (GMAW-CMT/Pulse) has an essential influence on geometrical characteristics of the deposited layers. The greatest height and minimal thickness of the deposited samples is ensured by GMAW-CMT method, which is related to smaller heat release, compared to GMAW-Pulse method. Reduction of the heat input leads to decrease of the depth of penetration into the previously deposited layers, lowering of weld pool metal temperature, shortening of the time of melt existence and, consequently, of its spreading.

2. No critical defects in the form of cracks or lacks-of fusion were found at application of GMAW-CMT process. An opposite result was obtained at application of arc Pulse process, in which initiation of transverse cracks along the entire length of the sample is recorded, after reaching the 30th deposited layer and higher. The geometrical shape of each layer, compared to CMT process, has greater width and smaller height of the bead.

3. Analysis of metal microstructure of samples produced by both the surfacing technologies points to formation of a single-phase structure of α-solid solution of a complex chemical composition. The structure of both the deposits mainly consists of massive grains with different degree of etching and orientation, which differ by their hardness. Grain microhardness differs in different deposit regions, and it is in the range of 876–1280 MPa for CMT and 1160–1460 MPa for the Pulse process.

4. The finite element modeling method revealed that crack formation in samples made by GMAW-Pulse method, is associated with greater heat input compared to GMAW-CMT surfacing, which leads to a significant increase in the level of longitudinal tensile stresses, reaching the material ultimate strength in the temperature range of 490–550 °C.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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