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DETECTING THE INFLUENCE OF HEAT SOURCES ON MATERIAL PROPERTIES WHEN PRODUCING AVIATION PARTS BY A DIRECT ENERGY DEPOSITION METHOD

M. Gnatenko
Postgraduate student*
E-mail: jane070air594@gmail.com
P. Zhemaniuk
PhD, Deputy Chairman of the Board of Directors,
Technical Director***
I. Petrik
PhD, Chief Welder***
S. Sakhno
Technological Engineer***
S. Chigileichik
Chief of the Bureau of Welding***
V. Naumyk
Doctor of Technical Sciences*
O. Ovchinnikov
Doctor of Technical Sciences, Professor, Head of the Department
Department of Equipment and Technology of Welding Production**
M. Matkovska
Postgraduate student*
*Department of Machines and Technologies of Foundry**
**Zaporizhia National Technical University
Zhukovskoho str., 64, Zaporizhia, Ukraine, 69063
***Motor Sich JSC
Motorobudivnykiv str., 15,
Zaporizhia, Ukraine, 69068

Досліджено якість матеріалу, отриманого методом прямого вирощування (Direct Energy Deposition) із застосуванням трьох джерел нагріву: плазмової дуги, електричної зварювальної дуги, зварювальної дуги з холодним перенесенням металу (Cold Metal transfer). У якості присадного матеріалу використовувався дріт зі сплаву AlMg5.

Дослідження проводилося з метою визначити, при якому з джерел нагрівання наплавлений матеріал буде мати вищі значення фізико-механічних характеристик, а процес буде мати вищу продуктивність. Також слід було оцінити якість, розмір і рівномірність розподілу наплавлених слоїв, оскільки дані показники визначають точність отримуваного виробу і дозволяють зменшити припуск на механічну обробку.

Виявлено вплив джерел нагріву на формування поверхні наплавлених пластин: зразки, отримані методом плазмового наплавлення, мають виступання наплавлених шарів бічній поверхні на висоту до 2 мм, зразки, отримані методом електродугової і CMT наплавлення, – на висоту до 0,5 мм. Отримані дані дозволять визначити мінімальний допустимий припуск на механічну обробку.

Аналіз хімічного складу показав, що кожне джерело нагріву дозволяє забезпечити хімічний склад готового виробу, відповідний хімічному складу початкового матеріалу. Розподіл легуючих елементів рівномірний між наплавленими шарами. Однак процес CMT забезпечив найбільш точний розподіл легуючих елементів.

Фізико-механічні властивості пластин, отриманих методом прямого вирощування, знаходяться приблизно на одному рівні з матеріалами, які були отримані традиційними методами лиття та штампування.

Найвищі значення механічних властивостей мають зразки, отримані методом плазмового наплавлення: $\sigma_в$*=28 мПа;* $\sigma_{0,2}$*=15; мПа;* δ*=30,4 %, що можна пояснити більш дисперсної структурою і високим рівнем сплаву шарів.*

Отримані дані дозволять визначити, яке джерело нагріву доцільніше використовувати для отримання необхідних конкретному технологічному процесу властивостей. Вони також дозволяють оцінити застосовність методу прямого вирощування з використанням дугових джерел нагріву при серійному виробництві деталей

Ключові слова: адитивні технології, плазмове наплавлння, пряме вирощування, холодне перенесення металу

1. Introduction

Over the past decades, additive produce (AP) has grown and spread throughout the world to a multi-billion dollar industry encompassing a variety of technologies and types of materials. AP methods form a group of new technologies that make it possible to create functional three-dimensional objects from a series of materials including aluminum alloys by layer-by-layer application of material to achieve final form [1].

Main advantages of this technology include significant reduction of time and cost of making new products by eliminating intermediate stages of preparation of rigging and mold tools [2]. Current aluminum products manufactured by AP methods mostly relate to selective sintering using laser or electron beam heat sources and aluminum alloy powders applied in layers by stereolithography techniques. However, other AP methods using aluminum alloy wire are also gaining popularity [1].

One such method is directed energy deposition (DED) method. This is an AP process in which focused thermal energy (from laser, electron beam, electric arc or plasma arc heat sources) is used to melt wire or powder materials with further solidification [3].

This method advantage consists in ability not only to manufacture parts but also repair them. The DED method provides restoration of parts after their operation, correction of casting and stamping defects as well as production of parts using the combined method when a part of the product is manufactured by conventional methods with further growing.

Based on study [4], it can be said that the processes using wire as a filler material have greater productivity, are more economical (due to almost 100 % efficiency of wire use) compared to the processes in which powders are used as a filler material [4].

Among the heat sources, laser and electron beam are common since they enable high manufacturing accuracy though they are expensive. Equipment for plasma and electric arc surfacing is less expensive. Evaluation of quality and accuracy of material formation using aluminum wires is not yet fully understood. Comparison of quality of the material obtained by plasma, electric arc and CMT surfacing as well as assessment of interchangeability and applicability of these surfacing processes in serial production of aircraft parts of aluminum alloys is an urgent task.

2. Literature review and problem statement

Results of study of the technology of additive manufacture of aluminum products using welding wire (wire+arc additive manufacture (WAAM)) were presented in [5]. Large-sized functional components of ribs and cones of aluminum alloy were grown. As a result, it was found that the WAAM process is suitable for the production of large-sized aluminum parts [6].

It was shown that introduction of conventional welding process for aluminum WAAM is currently limited because of flaws arising during solidification of the deposited material, such as pores and cracks [7]. These flaws, to some extent, have a negative effect on mechanical properties. Porosity is the major problem in aluminum alloys which are much more susceptible to this flaw than other metals. This is explained by the fact that the residual amount of hydrogen often exceeds the threshold concentration sufficient for bubble formation in the weld pool [8].

Thus, parts of aluminum alloys produced by the method of growing are prone to porosity. However, when using a combination of high-quality welding wire and correct welding modes, porosity may be limited [5, 9]. Specifically, the cold metal transfer (CMT) process developed by Fronius GmbH (Germany) is a modified version of gas arc welding. This method makes it possible to obtain finer grains and uniform distribution of oxygen due to the low level of heat input [5].

Besides the WAAM and CMT processes, the process of plasma surfacing is also promising for growing blanks for parts using wires. The use of plasma and microplasma surfacing has some advantages in formation of multilayer blanks. It provides regulation of fusion depth and width in a wide range. Thermal and force effects of the arc in the surfacing zone are also controllable [10].

However, the problems associated with application of these technologies not only in pilot and single-part production but also in mass production of parts from aluminum alloys as well as potential of interchangeability of these processes have remained unresolved.

All this suggests that it is necessary to conduct studies of materials obtained by plasma and electric arc surfacing and the CMT method. Comparative analysis of the material obtained using each of the heat sources should be made pertaining to such parameters as:

– formation of layers, since accuracy of the grown product affects machining allowance and, consequently, cost of the product;

– maximum possible surfacing rate which will ensure performance determination;

– chemical composition and distribution of alloying elements in the deposited material;

– values of mechanical properties and characteristics of the metal structure that determine these parameters.

3. The aim and objectives of the study

The study objective was to establish effect of plasma, electric arc and CMT heat sources on formation of deposited layers, chemical composition, physical and mechanical properties and structure of the material, determine applicability and interchangeability of these processes in the mass production of parts (on the example of AlMg5 alloy).

To achieve this objective, the following tasks were set:

– grow specimen blanks and conduct visual inspection of surfaced plates, assess their formation quality and size of overlay protrusion;

– conduct studies of chemical composition after surfacing to assess distribution of alloying elements;

– perform mechanical tests, assess the effect of structure on mechanical properties of the alloy and evaluate the material quality based on the results obtained.

4. Materials and methods to study aluminum alloy deposited by direct growing

4. 1. The methods used for studying the deposited material

To perform the tasks set in this study, we used the methods of studying chemical composition, structure and properties of experimental alloys. We used methods for qualitative and quantitative evaluation of structural components at macro and micro levels and determination of physical, mechanical and structural properties of the material under study.

AlMg5 alloy grown using three heat sources was chosen as the study object. The resulting alloy must meet all requirements of relevant regulatory and technical documentation on physical, mechanical and operational properties [11].

Compliance of structural components was quantitatively assessed according to requirements of ISO 18273 to aluminum alloys [12].

The following main property indicators of the aluminum alloy were determined in the experiment: tensile strength (σ_t), yield strength ($\sigma_{0.2}$), elongation (δ).

4. 2. Surfacing procedure. Test materials and equipment used in the experiment

Surfacing of test specimens using AlMg5 filler wire was carried out in three stages.

The specimen No. 1, 1.6 mm dia. wire, was manufactured by SBI Company for Motor Sich Company using plasma surfacing on PMI 500 TL semiautomatic machine using CNC of SWD 3000 machine (SBI, Austria). Surfacing mode was as follows. Current: 120–100A, voltage: 25 V, surfacing rate: 18–45 mm/s, gas consumption: 12 l/min, wire extension: 17 mm, arc length: 2 mm.

The specimen No. 2, a plate made from 1.2 mm dia. wire was made by the method of electric arc surfacing using MagicWave 1700 semi-automatic machine equipped with Fanuc robot. Surfacing mode was as follows. Current: 65–70 A, voltage: 12.6 V, deposition rate: 18–30 mm/s, gas consumption: 8 l/min, wire extension: 20 mm, arc length: 5 mm.

The specimen No. 3 was made by Fronius GmbH for Motor Sich Company using the CMT surfacing method with the help of Trans Plus Synergic 2700 CMT semi-automatic machine equipped with Motoman robot. 1.2 mm dia. Wire. Surfacing mode was as follows. Current: 80–40 A, voltage: 11–14 V, deposition rate 20–30 mm/s, gas consumption 8 l/min, wire extension: 15 mm, arc length 3 mm.

Chemical and spectral analysis methods were used to control chemical composition of the alloy, its structure and physical and mechanical properties.

Macrostructure and microstructure of the surfaced specimens of the aluminum based alloy were examined. Structure components of the alloys were determined by methods of qualitative and quantitative metallography.

Mechanical grinding and polishing operations were used to prepare microsections of the studied metals and alloys.

Structure of the specimens of aluminum alloys was revealed by etching microsections with Marble reagent (4 g of copper vitriol, 20 ml of concentrated hydrochloric acid, 20 ml of distilled water).

Chemical composition was determined by X-ray fluorescence analysis with the help of EDX 6000B spectrometer (Skyray Instrument, USA).

Quantity, color, shape, size, location and other characteristics of the structural components were determined by means of Stemi 200-c, Observer.D1m (Zeiss, Germany) metallographic microscopes at magnifications from 100× to 1000×.

Studies were performed using REM-106I and JEOL JSM-6360LA (FEI, Holland) scanning electron microscopes at magnifications from 1000× to 10,000×. Element composition of local areas was determined using the X-ray microanalyzer (energy dispersion and wave spectrometers).

5. Results of studying the grown plates

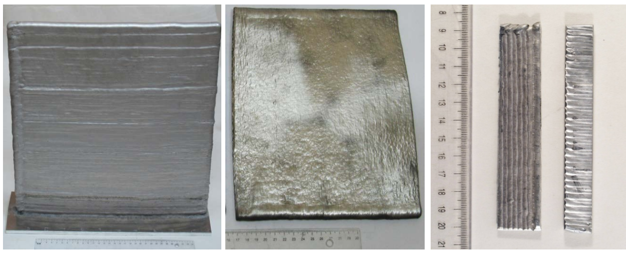
This study was conducted with three specimens obtained using AlMg5 filler wire applying different heat sources (Fig. 1).

Specimen No. 1 was obtained by the method of plasma surfacing. Dimensions: 360×250×12 mm.

Specimen No. 2 was obtained by electric arc (MIG) surfacing. Dimensions: 350×300×12 mm.

Specimen No. 3 was obtained by CMT method. Dimensions: 120×25×10 mm and 150×30×10 mm.

Visual inspection has shown that the side surface of the plates had a predominantly even surface. The deposited layers protruded to a height of no more than 1–2 mm in the specimen No. 1 (Fig. 1, *a*), to a height of 0.3–0.5 mm in the specimen No. 2 (Fig. 1, *b*) and to a height of 1–1.5 mm in the specimen No. 3. Width of the surfaced plates of the specimen No. 3 (10 mm) was made to demonstrate ability of the CMT process to ensure narrow surfaces of small parts escaping overheating (Fig. 1, *c*).



a *b* *c*

Fig. 1. Specimens obtained by the DED method with various heat sources: specimen No. 1 was obtained by the method of plasma surfacing (*a*); specimen No. 2 was obtained by the method of MIG surfacing (*b*); specimen No. 3 was obtained by the method of MIG/CMT surfacing (*c*)

According to the data of quantitative spectral analysis, chemical composition of the specimens obtained by all three surfacing methods met requirements of AWSA5.10 to AlMg5 (ER5356) alloy and was close to composition of AMg5 alloy (GOST 4784-74) with the exception of manganese and magnesium (Table 1).

Table 1

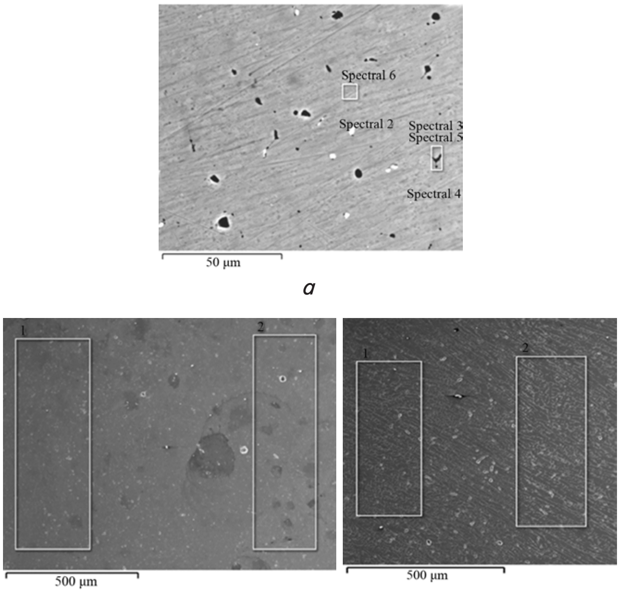
Comparative analysis of chemical composition of the material obtained

Product name	Content, %				
	Si	Fe	Cu	Mn	Mg
No. 1. Plasma surfacing	0.05	0.08	0.03	0.1	4.75
No. 2. MIG surfacing	0.04	0.09	0.01	0.09	5.10
No. 3. MIG-CMT surfacing	0.02	0.1	0.005	0.17	4.97
AWS A5.10 norms for AlMg5(ER5356) alloy	≥0.25	≥0.4	0.10	0.05–0.20	4.5–5.5
GOST 4784-74* norms for AMr5 alloy	≥0.5	≥0.5		0.3–0.8	4.8–5.8

*Note: * – for reference purposes, not applied to AlMg5(ER5356) alloy*

X-ray microanalysis (X-ray SMA) has shown that in the specimen material obtained by plasma surfacing, there was concentration inhomogeneity in the content of Fe, Mg, Mn found at locations of precipitation of hardening phases which is characteristic of this alloy in the deformed state (Fig. 6). Spectral analysis was carried out in randomly selected areas of microsections (Table 2).

Distribution of chemical elements was uniform in each of the three specimens, (Table 2).



a

b *c*

Fig. 2. Zones of distribution of elements in the area of specimens: microsection of specimen No. 1 (*a*); microsection of specimen No. 2 (*b*); microsection of specimen No. 3 (*c*)

Table 2

Quantitative distribution of elements

Surfacing method	Analysis zone	Element, wt. %				
		Mg	Al	Si	Mn	Fe
Plasma	Spectrum 2	5.19	93.0	0.05	0.22	1.53
	Spectrum 3	4.72	95.03	0	0.16	0.09
	Spectrum 4	2.55	97.25	0	0.11	0.09
	Spectrum 5	9.81	90.08	0	0.10	0
	Spectrum 6	2.94	96.89	0	0.13	0.04
MIG	Spectrum 1	4.85	95.16	0	0	0
	Spectrum 2	4.98	95.02	0	0	0
MIG/CMT	Spectrum 1	4,95	95.05	0	0	0
	Spectrum 2	4.95	95.05	0	0	0

Mechanical properties of the grown specimens were tested on tensile specimens cut along and across the deposited layers in initial state (after surfacing). Mechanical properties are presented in Table 3.

As can be seen from Table 2, 90 % of the specimens obtained with the use of three heat sources complied with standards EN ISO 18273 for aluminum alloys. Mechanical properties of the surfaced specimens were approximately 10 % inferior to those specified in GOST 4784-74 for wrought metal plates.

It is characteristic of the material obtained by the use of each heat source that the specimens cut across the deposited layers (1.1, 1.2, 1.3, 2.1, 2.2, 2.3, 3.1, 3.2, 3.3) had mechanical properties superior to those cut lengthwise (1.4, 1.5, 1.6, 2.4, 2.5, 2.6, 3.4, 3.5, 3.6).

As can be seen from Table 3 and Fig. 3, specimens No. 1 had the highest strength, relative elongation, and yield values. Values of strength and yield of specimens No. 3 were 10 % lower and values of relative elongation were 40 % lower than those of specimens No. 1 and 2 (Table 3).

Table 3

Mechanical properties of deposited materials

Heat source	Specimen reference name	Cutting direction	Mechanical properties		
			σ_t, mPa	$\sigma_{0,2}$, mPa	δ, %
Plasma surfacing	1.1	transverse	27.7	14.8	29.2
	1.2		28.5	14.9	30.0
	1.3		28.3	15.4	30.4
	1.4	longitudinal	26.9	16.27	12.4
	1.5		27.6	17.32	17.6
	1.6		25.3	13.9	11.6
	Mean value	–	27.4	15.4	25.2
MIG surfacing	2.1	transverse	27.0	13.2	34.0
	2.2		27.0	12.6	24.0
	2.3		27.0	15.1	28.0
	2.4	longitudinal	24.0	12.0	16.0
	2.5		26.9	14.0	24.0
	2.6		26.8	13.1	20
	Mean value	–	2645	13.3	24.3
MIG/CMT surfacing	3.1	transverse	26.7	12.3	15.2
	3.2		27.0	12.9	14.4
	3.3		26.8	13,9	14.0
	3.4	longitudinal	26.6	11.9	13.0
	3.5		26.0	11.7	13.0
	3.6		25.7	12	12.8
	Mean value	–	26.1	12.45	13/7
–	Norms* of GOST 17232-99	–	≥27.0	≥12.0	≥13.0
–	Norms of EN ISO 18273	–	25	12	8

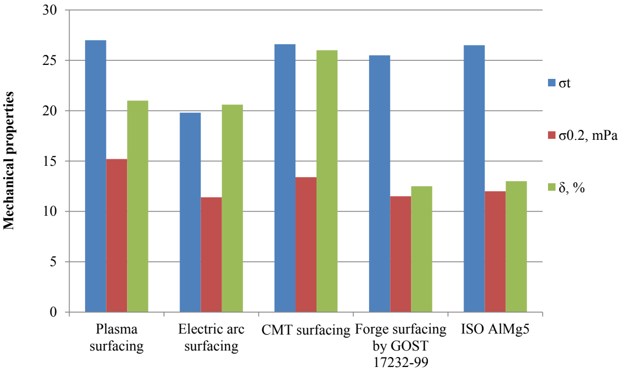
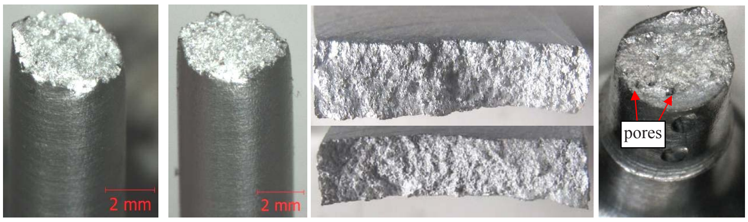


Fig. 3. Comparative analysis of mechanical properties of materials

Specimens No. 3 had strength values superior to those of specimens No. 2 but inferior to specimens No. 1. Yield and relative elongation values were lower than those of specimens Nos. 1, 3. The low value of mechanical properties for specimen No. 1.6 can be explained by accumulation of micro pores in the specimen fracture (Fig. 4).

Mechanical tests of plates Nos. 1, 2 were carried out with cylindrical specimens and plate No. 3 was tested with rectangular specimens (Fig. 4).

Macrostructure was examined in plates grown with the use of three different heat sources cut along and across the deposited layers and along the specimen height.

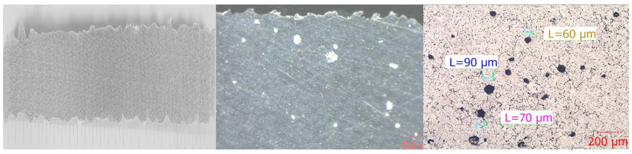


a *b* *c* *d*

Fig. 4. Fractures in specimens after mechanical testing: fracture of specimen No. 1 (*a*), fracture of specimen No. 2 (*b*), fracture of specimen No. 3 (*c*), fracture of specimen No. 1.6 with pores (*d*)

Structure of all three specimens was examined on microsections cut in longitudinal and transverse directions relative to the fusion line.

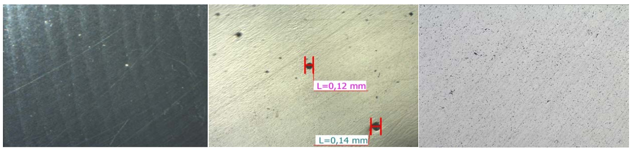
Visual inspection have shown that macrostructure of specimen No. 1 had a uniform matte etching background without manifestation of macro-grains and lines of fusion of deposited layers (Fig. 5, *a*). It should be noted that there were small 60...90 μm dia. round pores in the specimen structure throughout the cross section (Fig. 5, *b*).



a *b* *c*

Fig. 5. The specimen obtained by the metod of plasma surfacing: without magnification (*a*); 6.5 magnification (*b*); 50 magnification (*c*)

Visual inspection has shown that 1.5...2.0 mm thick deposited layers with a clear interface are visible in specimen No. 2 (Fig. 6, *a*). With the use of binocular microscope, it was revealed that the structure had a matte background without macro-grain manifestation. Small 12...14 μm dia. pores were observed in some parts of the specimen (Fig. 6, *b*).



a *b* *c*

Fig. 6. The specimen obtained by MIG surfacing: without magnification (*a*); 6.5 magnification (*b*); 50 magnification

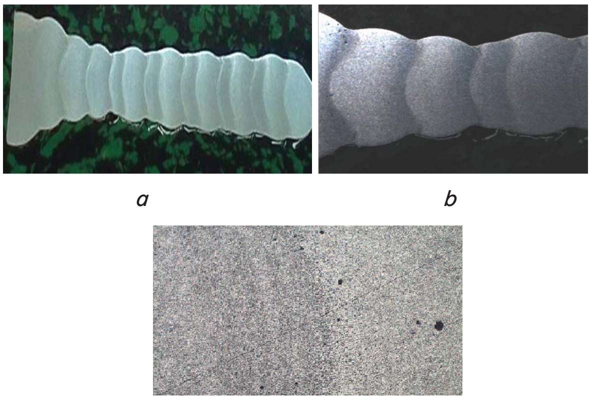
Macrostructure of the tensile specimen No. 3 obtained by the MIG-CMT method was tested on the surface and in a cross section along the deposited layer. Macrostructure and microstructure were examined on microsections cut in longitudinal and transverse directions relative to the fusion lines.

Visual inspection and examination using a binocular microscope have shown that the specimen also had layers of transverse orientation. There were fine 30–50 μm pores (Fig. 7, *c*) which could worsen mechanical properties (Table 3).

Microstructure of specimen No. 1 obtained by plasma surfacing was not uniform across the section. Metal structure was characteristic of overheated state in the specimen surface along the layer fusion line. Farther in the specimen cross section, it consisted of more dispersed precipitates of hardening phases in α solid solution typical of AlMg type alloys (Fig. 8, *a*).

Microstructure of the deposited material of specimen No. 2, both in the zone of fusion line and in the layers, was identical: it was an α solid solution and hardening phases which is typical of AlMg alloys (Fig. 8, *b*).

Microstructure of specimen No. 3, both in the fusion line zone and in the layers was identical: it was an α solid solution and hardening phases which is typical of AlMg-type alloys. Microstructure of the specimen material was identical to the surfaced plate and typical of AlMg-type alloys (Fig. 8, *d*).

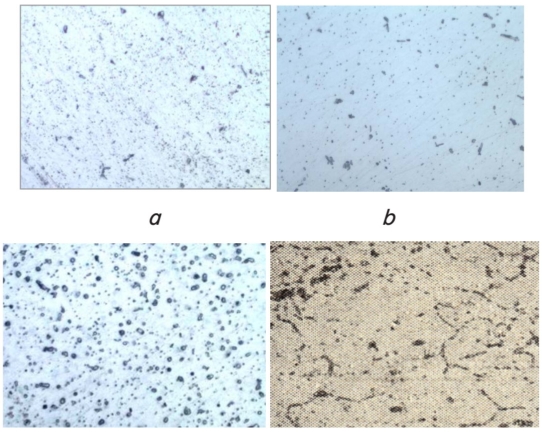


a *b*

c

Fig. 7. The specimen obtained by MIG-CMT surfacing method: without magnification (*a*); 6.5 magnification (*b*); 50 magnification (*c*)

Size of the hardening phases in the specimens deposited with the help of plasma and arc heat sources was smaller than that of the specimens grown by the CMT method which has made it possible to provide higher values of mechanical properties for specimens No. 1, 2. Number of hardening phases in each of the specimens was approximately at the same level (Fig. 8).



a *b*

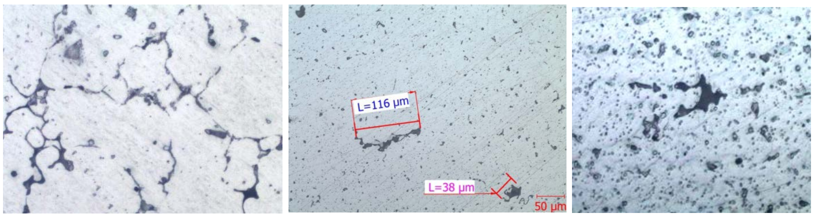
c *d*

Fig. 8. Comparative analysis of structures: structure obtained by plasma surfacing at 500 magnification (*a*); structure obtained by MIG-surfacing at 500 magnification (*b*); structure obtained by CMT/MIG- surfacing (*c*); structure of wrought aluminum AMg5 (*d*)

An overheated zone was revealed along the line of fusion of metal layers in the surface of specimen No. 1. The structure was characteristic of the superheated state. The superheated layer was at a depth of ~1.0 mm (Fig. 9, *a*).

In some places of the specimen No. 2 surface, material discontinuity lines were visible. They reached length of up to 116 μm (Fig. 9, *b*).

Microanalysis of the discontinuous specimen No. 3 also revealed 16...61 μm dia. discontinuities (Fig. 9, *c*).



a *b* *c*

Fig. 9. Flaws in the surface of a specimen obtained by the method of direct deposition: plasma at 500 magnification (*a*); MIG at 200 magnification (*b*); MIG/CMT at 500 magnification (*c*)

The same defects for other metallurgical processes were characteristic of the growing methods. During the study, such defects as gas pores, overheating, discontinuities in a form of slag inclusions were found in the grown specimens.

6. Discussion of results of studying the influence of heat sources on the grown material quality

Each of the three specimens was obtained at currents of 75–120 A to heat the metal and ensure fusion with the substrate and 45–100 A directly during growth of a simulator plate. The plasma heat source has enabled use of high surfacing rates and had the highest productivity, up to 45 mm/s, due to deep penetration and a concentrated arc. Specimens obtained by electric arc and CMT surfacing have a maximum speed of up to 30 mm/s.

Lines of deposited layers were clearly seen by the naked eye in specimens No. 1 and No. 3.

The specimens obtained by the method of plasma surfacing had the greatest surface roughness of up to 2 mm which adversely affects machining allowance.

The specimens obtained by electric arc surfacing had surface similar to the cast metal surface. The deposited layers protruded to a height of no more than 0.5 mm which is the best indicator of the surface quality compared to other specimens. This method will make it possible to obtain parts with a minimum machining allowance.

Specimens obtained by the CMT method had layers height of 1–1.5 mm. This allowance is higher than that of specimens No. 2, however, these dimensions were obtained on narrow surfaces during surfacing of ±50 mm long sections and at more correct modes. The CMT method enabled obtaining of a surface wall with a minimum allowance of up to 0.5.

Each heat source has made it possible to ensure chemical composition of the finished product corresponding to the chemical composition of the initial material.

X-ray microanalysis has shown that distribution of alloying elements in the specimen material was uniform between the deposited layers. However, the CMT process provided the most accurate distribution of alloying elements.

Specimens obtained by the method of plasma surfacing had the highest values of mechanical properties despite the presence of micropores in some parts of the specimens. The lines of fusion of the deposited layers were not traced in the cross section of the specimens obtained by the method of plasma surfacing which indicates a deep fusion penetration in the material.

There was an overheating line in the surface of specimen No. 1 at a depth of 1 mm which can be explained by the fact that each subsequent applied layer anneals the previous one. It could also cause higher mechanical properties for specimens No. 1 (mechanical tests were carried out on specimens made from a material taken below the overheating zone). If adjustment of modes does not eliminate this process feature, then the depth of the overheated layer should be taken into consideration when introducing a machining operation.

The specimens grown by electric arc surfacing had a minimum porosity of up to 14 μm as compared with other specimens corresponding to the normative values of mechanical properties and qualitative structure characteristic of AlMg alloys with a clear manifestation of deposited layers.

Mechanical properties of the material grown by the CMT method which are inferior to those of the rest of specimens can be explained by presence of micropores up to 30 μm and also by the fact that the surfaced blanks had significantly smaller width (about three times) than other surfaced plates.

It should be noted that the CMT method makes it possible to grow products up to 10 mm wide without manifestation of metal overheating and with a high-quality metal structure. Obtaining of such narrow surfaces by electric arc and plasma surfacing is problematic since the deposited metal may become overheated and flow off the surface.

7. Conclusions

1. A surface of highest quality which makes it possible to set minimum machining allowance at the smallest height of layer protrusion up to 0.5 mm was obtained by arc welding. The maximum protrusion height of 2 mm was obtained by plasma surfacing.

2. Chemical composition of specimens prepared by direct growth with the use of various heat sources (plasma, electric arc, CMT) met requirements of AWSA5.10 to AlMg5 alloy (ER5356) and was close to composition of AMg5 alloy by GOST 4784-74. Each heat source has made it possible to provide chemical composition of the finished product corresponding to the chemical composition of the original material. X-ray microanalysis has shown that distribution of alloying elements in the specimen material was uniform in the deposited layers. However, the CMT process provided the most accurate distribution of alloying elements.

3. Mechanical properties of the specimens deposited by plasma, electric arc and CMT surfacing met requirements of GOST 17232-99 for deformed AMg5 alloy plates and requirements of EN ISO 1827 standard. The grown material had structure characteristic of the AMg5 alloy which is an α solid solution and hardening phases. Maximum values of mechanical properties of the grown material were provided by

the plasma heat source: σ_t=28 MPa; $\sigma_{0.2}$=15 MPa; δ=30.4 % which can be explained by the presence of the most dispersed structure compared to other specimens. The studied heat sources have made it possible to grow critical aviation parts with physical and mechanical properties corresponding to quality of wrought and cast blanks.

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