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Developing technology of directed energy deposition of workpieces of parts of aircraft engines from heat-resistant nickel alloys by means of using layer-by-layer microplasma surfacing method

K. Balushok[1] • **S. Chygileichyk**[1] • **I. Petryk**[1] • **S. Sakhno**[1] • **R. Kulykovskyi**[2]

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Abstract. *The article presents the technology of the Directed Energy Deposition (DED) process using the method of layer-by-layer microplasma surfacing with powder and wire made from a heat-resistant nickel-based high-chromium alloy of the Ni-Cr-Ti-Al system (γ′ = 3–5 %), which is used for manufacturing workpieces of gas turbine engine parts, while ensuring a given level of mechanical properties required for the parts' further operation. The article discusses the equipment and characteristic features of the DED technology using the continuous (layer-by-layer) microplasma surfacing method. The additive deposition was implemented on the STARWELD 190H robotic installation for microplasma powder surfacing and on the integrated installation based on the FANUC robot and the SBI plasma equipment by means of using wire made from a nickel-based alloy of the Ni-Cr-Ti-Al system (γ′ = 3–5 %). Following the deposition, such operations as the heat treatment (aging 900 °C, exposure 16 hours), the machining and the quality control were conducted. A set of studies was conducted to develop the evidence base for the purpose of determining the possibility of installing deposited workpieces in engines, with the studies being as follows: determining the chemical composition of workpieces deposited by means of a technology similar to depositing workpieces; implementing metallographic studies and mechanical tests. The authors state that studies conducted showed that the chemical composition of the deposited metal is in compliance with the requirements set forth in the regulatory documentation, and the microstructure of the deposited metal after the heat treatment corresponds to the normally heat-treated state of a low-aging nickel-based high-chromium alloy of the Ni-Cr-Ti-Al system (γ′ = 3–5 %),while the level of mechanical properties of the deposited alloy followed by the serial heat treatment (aging 900 °C, holding for 16 hours) is not lower than the level of the forging implemented in the serial production of this type of parts.*

Keywords: *depositing workpieces, powder, wire, mechanical properties, chemical composition, weld metal.*

Introduction

The Directed Energy Deposition (DED) method is one of modern additive technologies in manufacturing and repairing metal parts and can, in some cases, replace conventional methods such as casting, stamping and forging. One can highlight that with the use of the automated computer control made it possible to manufacture new products on layer-by-layer (continuous) principle as per products' 3D models: this feature is one the main advantages of the DED technology. At the same time, the DED technology significantly reduces both time and costs required for manufacturing new products by eliminating intermediate stages of manufacturing tooling and molds, which, in turn, makes it possible to implement a design project experimentally (when designing new products or modifying existing products to improve their characteristics) with minimal costs in 2–3 weeks [1], [2].

In some cases, the relatively high material utilization rate (MUR) compared to forging, makes it possible to implement the DED technology in manufacturing workpieces on commercial scale with a significant positive economic effect.

The microplasma surfacing method is optimal among existing DED technologies for the purposes of manufacturing nonrotational parts of gas turbine engines from heat-resistant nickel alloys, which is due to a) large dimensions of products above (diameters ranging from 500 mm to 1500 mm); b) the fact that, in case with heat-resistant nickel alloys, a high-temperature heat treatment (1,000+ °C)

✉ *K. Balushok*
motor@motorsich.com

[1] *Motor Sich JSC, Zaporizhzhia, Ukraine*
[2] *National University "Zaporizhzhia Polytechnic", Zaporizhzhia, Ukraine*

is required to relieve stress and obtain the required strength and special service properties after depositing; and c) to metallurgical characteristics of heat-resistant nickel alloys, since reducing the likelihood of cracks requires the possibility of both the precise control of the input heat during the deposition process and the restrain of the overheating of deposited layers [7]–[9].

The microplasma surfacing method using powders and wires is in compliance with the criteria above for depositing workpieces of nonrotational parts of gas turbine engines, which are made from heat-resistant nickel alloys.

The purpose of the research is developing a technology for manufacturing workpieces from a nickel-based heat-resistant high-chromium alloy of the Ni-Cr-Ti-Al system (γ' = 3–5 %) by using microplasma surfacing with powder and wire while ensuring mechanical properties required for the further operation of gas turbine engine non-rotational parts.

Materials & Research Methods

Research subjects: rectangular samples [130×70×14 mm (Fig. 1)] obtained by additive depositing by means of microplasma surfacing with wire and powder under regimes corresponding to regimes of depositing the workpiece of a ring that is a part of a turbojet bypass engine.

The powders implemented were made from a heat-resistant nickel-based high-chromium alloy of the Ni-Cr-Ti-Al system (γ'=3–5 %), with the alloy obtained by plasma centrifugal atomization (produced by Multiflex LLC, Ukraine), with its fraction being 63–160 microns.

The chemical composition of powders made from a heat-resistant nickel-based high-chromium alloy of the Ni-Cr-Ti-Al system (γ' = 3–5 %) is in compliance with the requirements set forth in the TU14-143-527-2003 technical regulations.

Welding wire with a diameter of 1 mm made from a heat-resistant nickel-based high-chromium alloy of the Ni-Cr-Ti-Al system (γ' = 3–5 %) is in compliance with the requirements set forth in the TU 14-1-2234 technical regulations.

Samples were deposited from the powder on the STARWELD 190H specialized robotic installation, and from wire on the installation the based on the FANUC robot and the SBI plasma equipment.

All powders were dried in an oven (temperature of 250 °C) for 1 hour before being loaded into the installation metering unit.

The wire for the deposition process was on in-line wound spools; the surface of the wire shall be clean and smooth with no cracks, traces of delamination or grease.

Samples were subjected to heat treatment as per the following regime (for the deformed state) upon undergoing the deposition process:

– T_Q= 1140 °C, τ = 1 hour, air cooling;
– T_A = 900 °C, τ = 16 hours, air cooling.

The SPECTROMAX optical emission spectrometer (SPECTRO) was used for spectral analysis of the deposited metal.

Mechanical properties of the alloy obtained by means of the additive deposition using microplasma surfacing were determined with the help of standard cylindrical samples as per the following regulatory documentation DSTU ISO 6892-1:2019 "Metal materials. Tensile Testing. Part 1. Method of test at room temperature"; DSTU ISO 6892-2:2020 Metallic materials. Tensile tests. Part 2. Test methods at elevated temperatures"; "DSTU ISO 204:2018 METALLIC MATERIALS UNIAXIAL CREEP TESTING IN TENSION METHOD OF TEST".

Samples were cut out in the longitudinal and transverse directions relative to deposition layers (see Fig. 1) following the heat treatment as per the regime above.

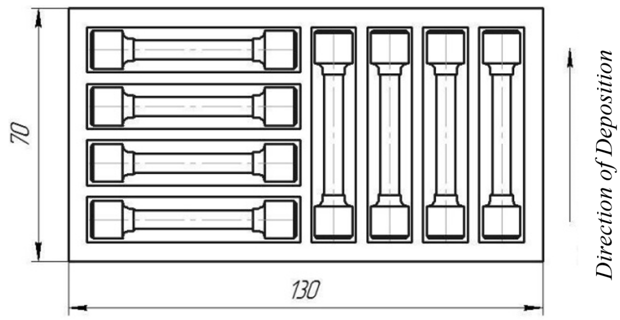


Fig. 1. Scheme of Cutting Samples for Mechanical Testing

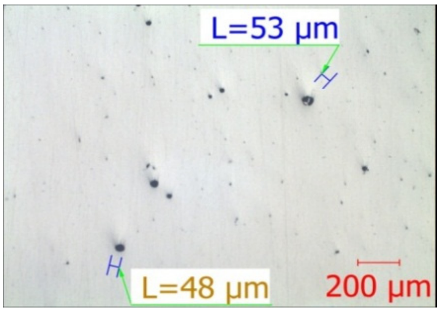
Metallographic studies of microslices were conducted using the Axio Observer MAT. D1m optical metallographic microscope by Carl Zeiss GmbH (Germany).

Research Results and Discussion

The microstructural analysis was conducted on slices made in the longitudinal and transverse directions relative to the growth layers.

The metallographic examination of non-etched slices showed that the samples' metal was dense; the following was registered in field of vision: a) the presence of microporosity up to 80 µm in size in samples deposited from powder (Fig. 2 *a*, *b*); and b) single pores up to 20 µm in size in samples deposited from wire (see Fig. 2 *c*, *d*). The greater amount of microporosity on samples deposited from powder compared to those deposited from wire is explained by the presence of micropores in powders, since micropores pass into the sample material when deposited. No metallurgical defects in the form of either lacks of fusions or cracks were found.

The study of slices upon their undergoing etching in a reagent for electrolytic etching of heat-resistant alloys (H_3PO_4 – 800 ml + CrO_3 – 100 ml) showed that the microstructure of initial samples (i.e. prior to heat treatment) that were deposited from powder and wire was not significantly



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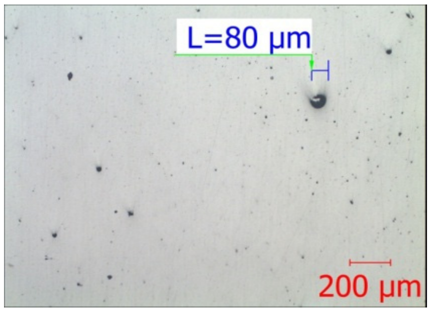

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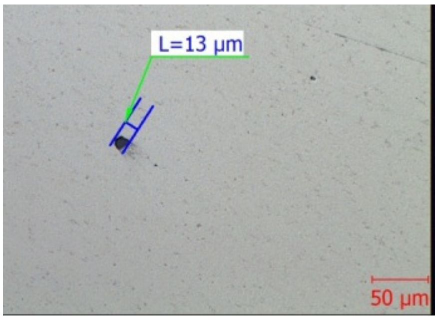

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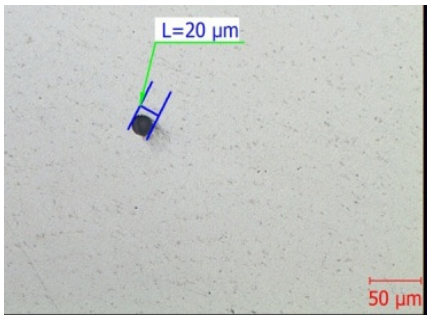

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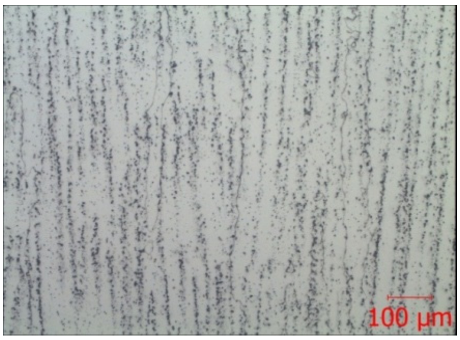
Fig. 2. Non-etched Slices: *a*, *b* – Powder; *c*, *d* – Wire

different. The microstructure has a dendritic structure with elongated grains in the direction of heat release across layers (Fig. 3, 4); the microstructure above is a γ-solid solution with the presence of carbides and nitrides arranged in an orderly manner in the direction of heat release during the deposition process. When analyzing the microstructure, fusion lines are not visible; the structure is homogeneous.



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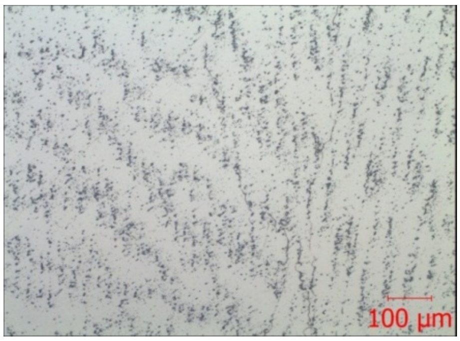

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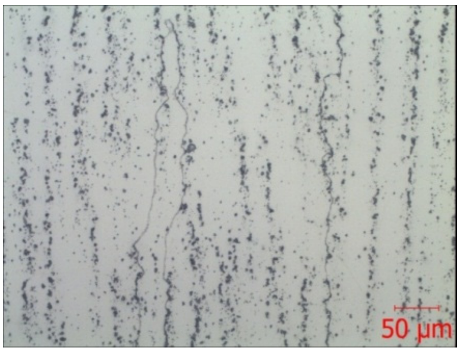

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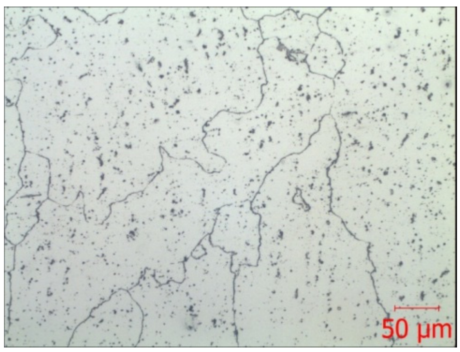

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Fig. 3. Structure of Samples Deposited from Powder upon Etching Process: *a*, *c* – Traverse; *b*, *d* – Longitudinal (Prior to Heat Treatment)

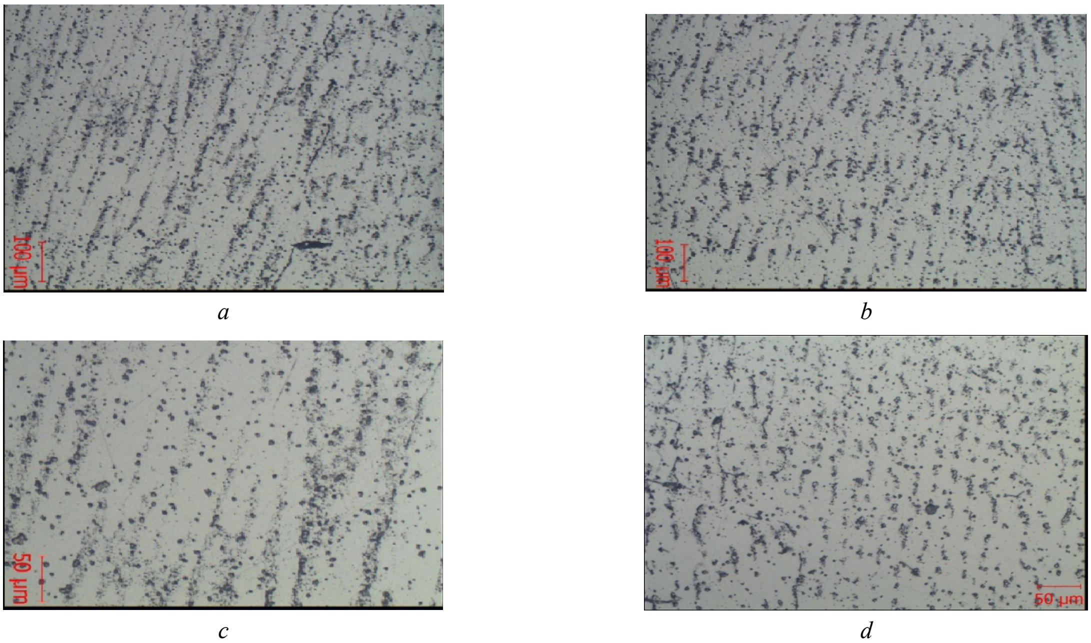


Fig. 4. Structure of Samples Deposited from Wire Upon Etching Process: *a*, *c* – Traverse, *b*, *c* – Longitudinal (Prior to Heat Treatment)

The structure of the resulting material (without heat treatment) is characteristic of a quenched cast heat-resistant nickel-based low-aging high-chromium alloy of the Ni-Cr-Ti-Al system (γ′ = 3–5 %).

The study of etched sections (electrolytic etching) made in the longitudinal and transverse directions showed and wire also does not differ significantly (Fig. 5, 6) after the that the microstructure of samples made from powder heat treatment. The microstructure of the dendritic structure is characterized by heterogeneity and the presence of elongated grains in the direction of heat removal. The microstructure is a γ-solid solution with the presence of intermetallic compounds, carbides, nitrides and particles of acicular morphology of an excess chromium- based (α-Cr) phase. There is the same orientation of their location in the direction of heat removal during the deposition process (across layers) as prior to the heat treatment. The microstructure corresponds to the normally heat-treated state of a low-aging high-chromium nickel-based alloy of the Ni-Cr-Ti-Al system (γ′ = 3–5 %).

The manufactured samples were subjected to determining a) mechanical properties (σ_v, $\sigma_{0.2}$, δ, ψ) at room temperature, mechanical properties (σ_v, δ, ψ) at a temperature of 800 °C (short-term), and b) long-term strength at T = 450 °C following the heat treatment as per the regime above.

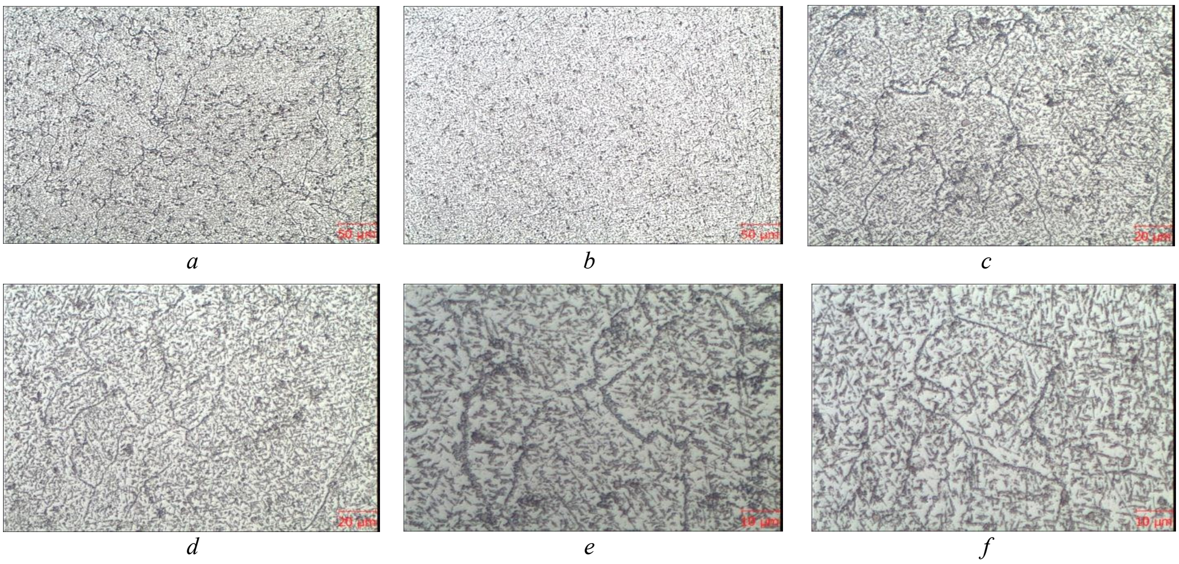


Fig. 5. Structure of Samples Deposited from Powder Upon Pickling Process: *a*, *c*, *e* – Traverse; *b*, *d*, *f* – Longitudinal (Prior to Heat Treatment)

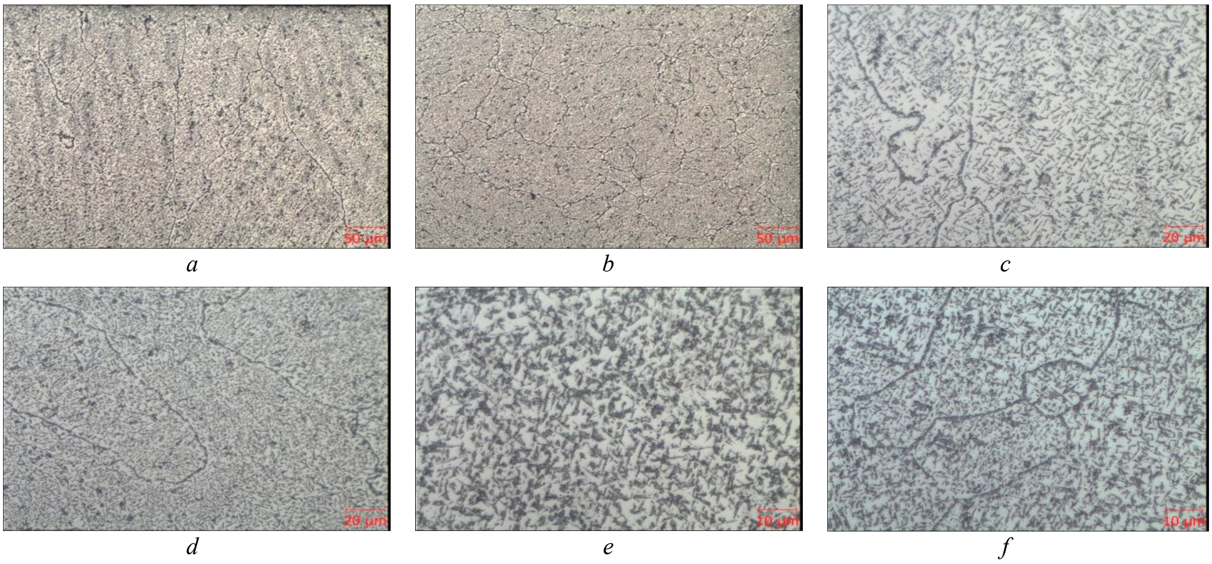


Fig. 6. Structure of Samples Deposited from Wire Upon Pickling Process: *a*, *c*, *e* – Traverse; *b*, *d*, *f* – Longitudinal (Prior to Heat Treatment)

Table 1. Mechanical Properties of Deposited Samples (T = 20 °C)

Semi-Finished Product Type (TU Standards)	Maximum Strength, kgf/mm^2	Yield Point, kgf/mm^2	δ, %	ψ, %
		Transversal Direction		
	90.3	65.9	22.3	22.9
	91.3	63.9	22.8	26.3
	92.2	63.7	31.2	37.6
	92.7	65.2	20.8	24.3
Deposited by Plasma Powder Surfacing	**90.8**	**64.6**	**24.3**	**26.1**
		Longitudinal Direction		
	81.0	61.1	11.4	11.6
	81.2	62.6	11.8	12.4
	83.2	63.4	12.3	13.8
	85.1	65.1	12.8	15.4
	82.5	**63.1**	**12.1**	**13.3**
		Transversal Direction		
	93,7	56.0	25.2	27.7
	91,0	55.6	21.6	19.7
	85,9	58.1	26.0	26.6
	82.5	56.0	16.0	19.0
Deposited by Plasma Wire Surfacing	**87.5**	**57.0**	**21.8**	**23.5**
		Longitudinal Direction		
	86.1	63.7	8.0	19.0
	79.5	61.1	5.2	11.6
	83.2	63.4	5.6	12.0
	85.2	63.9	8.4	12.0
	83.5	**63.0**	**6.8**	**13.7**
Standards TU 14-1-3046-80 (Rod)	**≥ 80**	**≥ 35**	**≥ 25**	–
Standards OST 1 90126-85 (Casting)	**≥ 80**	–	**≥ 4**	–

Note. **Bold** marked are average values.

The results of mechanical tests at room temperature are processed and given in Table 1.

For comparison, Table 1 shows the TU standards and the OST for serial semi-finished products manufactured in the form of rods and castings from a low-aging high-chromium nickel-based alloy of the Ni-Cr-Ti-Al system (γ′ = 3–5 %).

Table 1 shows that mechanical properties at room temperature of the material [that is a) deposited by micro-plasma surfacing with powder and wire, and b) heat-treated as per the quenching regime with T = 1140 °C, holding for 1 hour and aging at T = 900 °C, holding for 16 hours and cooling at air] is:

– In full compliance with the requirements for a cast nickel-based alloy of the Ni-Cr-Ti-Al system (γ′ = 3–5 %);

– In compliance with the requirements set forth in the regulatory documentation for deformed metal (rod) in terms of strength characteristics, while being almost identical in terms of plastic properties (δ) in the transverse direction, and is 50 % inferior in the longitudinal direction.

Mechanical properties (σ_v, δ, ψ) at temperature T = 800 °C are given in Table 2. For comparison, Table 2 shows standards of the TU specifications for a serial semi-finished product manufactured in the form of rods from a high-chromium nickel-based alloy of the Ni-Al-Ti-Al system (γ′=3–5 %).

The data specified in Table 2 clearly show that average mechanical properties of samples (deposited using powder and wire at a temperature of 800 °C) are in full compliance with the requirements set forth in the regulatory documentation for rods, both in longitudinal and transverse directions.

Long-term strength tests were conducted at 450 °C, the operating temperature of the part. The results of long-term strength tests are processed and given in Table 3.

Table 3 shows that samples deposited using powder and wire underwent long-term strength tests at a temperature of 450 °C for 300 hours (with the necessary requirement being at least 100 hours), after which they were removed (without destruction). The visual inspection of samples showed no cracks or other defects.

The visual inspection of samples following the tests at room temperature showed that the surface of all samples changed during plastic deformation and became wavy with varying degree of thinning. Samples are fractured with the formation of a neck, which indicates the ductile fracture. The appearance of samples upon mechanical tests is shown in Fig. 7.

Table 2. Mechanical Properties of Samples (T = 800 °C)

Semi-Finished Product Type (TU Standards)	σ_v, kgf/mm^2	δ, %	ψ, %
Deposited by Plasma Powder Surfacing		Longitudinal Direction	
	79.0	12.4	26.0
	74.9	15.3	36.0
	77.0	**13.9**	**31.0**
		Transversal Direction	
	67.5	3.8	11.7
	73.4	22.4	26.0
	72.1	17.1	29.5
	71.0	**14.4**	**22.4**
Deposited by Plasma Wire Surfacing		Longitudinal Direction	
	68.0	21,8	50.9
		Transversal Direction	
	69.1	23.2	53.7
Standards TU 14-1-3046-80 (Rod)	≥ 35	≥ 13	≥ 18

Note. **Bold** marked are average values.

Table 3. Results Testing Deposited Samples for Long-Term Strength

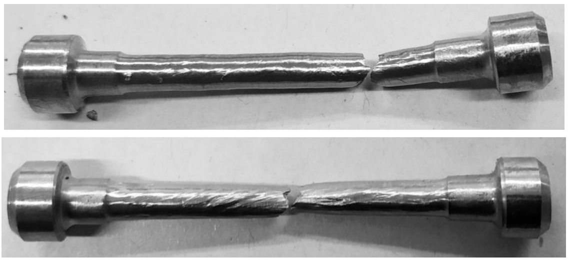
Sample	Test Temperature, °C	Load kgf/mm^2	Exposure, hours	Note
Longitudinal (Wire)	450	73	300	Removed
Longitudinal (Powder)	450	73	300	Removed
Transverse (Wire)	450	73	300	Removed
Transverse (Powder)	450	73	300	Removed
Designer's Requirements	450	73	100	–

Table 4. Chemical Composition of Deposited Sample

	Al	W	Ti	Cr	Nb	Mo	Mn	Fe	C
Chemical Composition as per Regulatory Documentation [6]	0.5–1.1	4.3–5.3	0.5–1.1	32.0–35.0	0.5–1.1	2.3–3.3	≤ 0.5	≤ 4.0	≤ 0.1
Sample	0.88	4.88	0.83	32.6	0.84	2.87	< 0,5	< 4.0	–

The examination of fractures of tensile samples using a binocular microscope showed no defects of a metallurgical nature (Fig. 8); the fractures have a dimple nature.

a



b

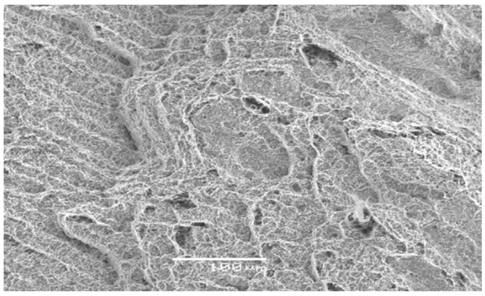
Fig. 7. Appearance of Samples upon Testing at Room Temperature: *a* – Powder; *b* – Wire

a

b

Fig. 8. Appearance of Fractures of Tensile Samples: *a* – Longitudinal; *b* – Traverse

Fractograms of fractures of tensile samples, which were obtained on an electron microscope, show a cellular structure of the fracture surface (Fig. 9), which is characteristic of plastic-acting materials.



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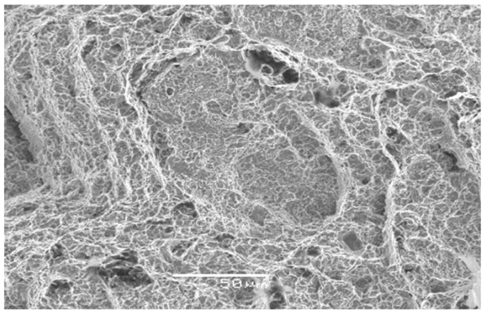

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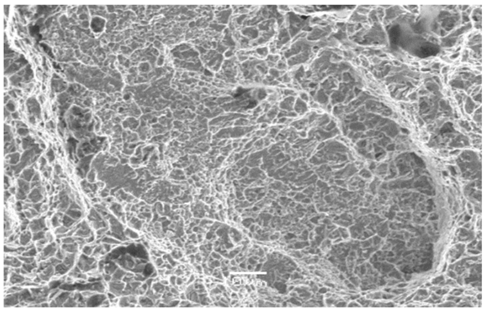

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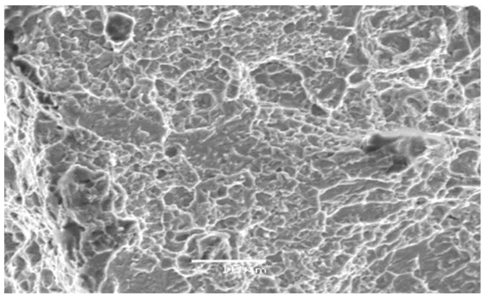

d

Fig. 9. Fracture Patterns of Fractures of Tensile Samples: *a*, *b* – Transverse; *c*, *d* – Longitudal

Data of the quantitative spectral analysis show that the material of the samples deposited by microplasma surfacing with powder and wire corresponds to a low-aging high-chromium nickel-based alloy of the Ni-Cr-Ti-Al system (γ' = 3–5 %). Test results are given in Table 4.

Implementation Experience

Following the results of works conducted, a technology was implemented for depositing a ring workpiece that is a part of a turbojet bypass engine, with the technology implemented foreseeing the microplasma surfacing with powder and wire made from a heat-resistant low-aging high-chromium nickel-based alloy of the Ni-Cr-Ti-Al system (γ' = 3–5 %).

The sketch of the workpiece with allowances (Fig. 10) made it possible to develop a mathematical model for further machining (Fig. 11).

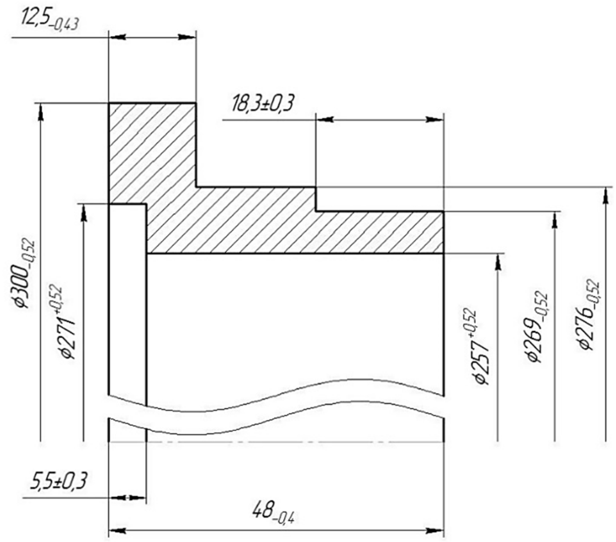

Fig. 10. Workpiece for Depositing: Sketch

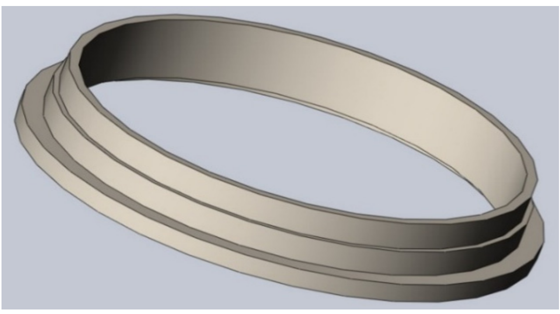

Fig. 11. Workpiece for Depositing: Mathematical Model

A workpiece was produced (Fig. 12) using sample deposition regimes before undergoing a) a heat treatment (T_Q = 1140 °C, τ = 1 hour, air cooling; T_A = 900 °C, τ = 16 hours, air cooling) and b) the machining operation (Fig. 13).

Fig. 12. Appearance of Deposited Workpice

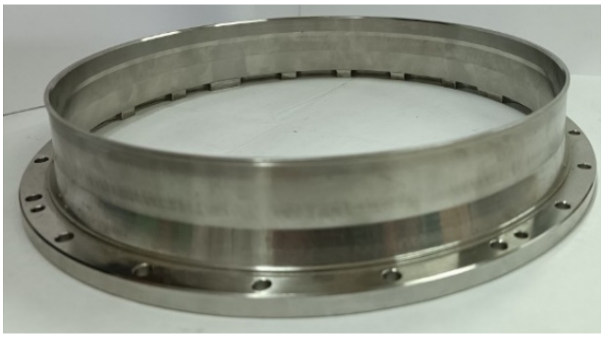

Fig. 13. Appearance of Deposited Workpice Upon Machining

The X-ray inspection and the capillary inspection (OST 1 90282) did not show any defects in the form of pores, cracks or lacks of fusions. The part then underwent successful trials as part of a technological engine. The part is at MOTOR SICH JSC facilities at the moment.

Conclusion

1. The microplasma surfacing method makes it possible to obtain high-level mechanical properties of workpieces deposited from nickel-based alloys of the Ni-Cr-Ti-Al system (γ' = 3–5 %).

2. The advantages of the chosen technology compared to other deposition processes have been identified.

3. Mechanical properties of samples deposited from powder and wire are in full compliance with the requirements for a cast alloy on a nickel base of the Ni-Cr-Ti-Al system (γ' = 3–5 %).

4. The resulting structure of workpieces (made from powder and wire) when deposited is a γ-solid solution with the presence of intermetallic compounds, carbides, nitrides and particles of acicular morphology of the excess chromium-based (α-Cr) phase released during the aging process. When analyzing the microstructure, fusion lines are not visible; the structure a) is homogeneous with the mutual growth of grains and dendrites between layers, and b) corresponds to the normally heat-treated state of the alloy made from a heat-resistant, low-aging, high-chromium nickel-based alloy of the Ni-Cr-Ti-Al system (γ' = 3–5 %).

Statement

The evidence base has been developed regarding the process maintainability, mechanical properties and the ensuring of stable quality of workpieces deposited by micro-plasma surfacing with powder and wire, which made it possible to implement the technology presented through a) manufacturing new parts on commercial scale, and b) conducting repair activities after operation.

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Розробка технології спрямованого енергетичного осадження заготовок деталей авіаційних двигунів з жароміцних нікелевих сплавів методом пошарового мікроплазмового наплавлення

К. Балушок[1] • С. Чігілейчик[2] • І. Петрик[1] • С. Сахно[1] • Р. Куликовський[2]

[1] АТ "Мотор Січ", Запоріжжя, Україна

[2] Національний університет "Запорізька політехніка", Запоріжжя, Україна

Анотація. *У статті представлено технологію процесу спрямованого енергетичного осадження (СЕО) методом пошарового мікроплазмового наплавлення порошком і дротом з жароміцного високохромового сплаву на основі нікелю системи Ni-Cr-Ti-Al (γ′ = 3–5 %), який використовується для виготовлення заготовок деталей газотурбінних двигунів, із забезпеченням заданого рівня механічних властивостей, необхідних для подальшої експлуатації деталей. У статті розглянуто обладнання та характерні особливості технології СЕО з використанням методу безперервного (пошарового) мікроплазмового наплавлення. Адитивне осадження здійснювали на роботизованій установці для мікроплазмового порошкового наплавлення STARWELD 190H та на інтегрованій установці на базі робота FANUC і плазмового обладнання SBI з використанням дроту, виготовленого зі сплаву на основі нікелю системи Ni-Cr-Ti-Al (γ′ = 3–5 %). Після осадження були проведені такі операції, як термічна обробка (старіння 900 °C, витримка 16 годин), механічна обробка та контроль якості. Для формування доказової бази з метою визначення можливості встановлення наплавлених заготовок у двигунах було проведено комплекс досліджень, який включав: визначення хімічного складу заготовок, наплавлених за технологією, аналогічною до наплавлення заготовок; проведення металографічних досліджень та механічних випробувань. Автори стверджують, що проведені дослідження показали, що хімічний склад наплавленого металу відповідає вимогам нормативної документації, а мікроструктура наплавленого металу після термічної обробки відповідає нормально термічно обробленому стану низьколегованого високохромового сплаву на основі нікелю системи Ni-Cr-Ti-Al (γ′ = 3–5 %), а рівень механічних властивостей наплавленого сплаву після серійної термічної обробки (витримка 900 °C, витримка 16 годин) не нижчий за рівень поковок, що реалізуються в серійному виробництві даного типу деталей.*

Ключові слова: *наплавлювані заготовки, порошок, дріт, механічні властивості, хімічний склад, метал шва.*