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INVOLMENT OF METALLIC NICKEL WASTE IN THE CHARGE FOR THE SMELTING OF HEAT-RESISTANT NICKEL ALLOYS

ЗАЛУЧЕННЯ МЕТАЛЕВИХ НІКЕЛЕВИХ ВІДХОДІВ У ШИХТУ ДЛЯ ВИПЛАВЛЕННЯ ЖАРОМІЦНИХ НІКЕЛЕВИХ СПЛАВІВ

Nesterenko T.M. / Нестеренко Т.М.
c.t.s., as. prof. /к.т.н., доц.
ORCID: 0000-0001-7900-8512
Zaporizhzhia National University, Zaporizhzhia, Zhukovskogo str.,66, 69600
Запорізький національний університет, м. Запоріжжя, Жуковського, 66, 69600
Nesterenko O.M. / Нестеренко О.М.
Didenko L.M. / Діденко Л.М.
researchers / наукові співробітники
Zaporizhzhia Machine-Building Design Bureau IVCHENKO-PROGRESS State Enterprise Named after Academician A.G. Ivchenko, Zaporizhzhia, Ivanova str., 2, 69068
ДП «Запорізьке машинобудівне конструкторське бюро «Івченко-Прогрес» ім. акад. О.Г. Івченко, м. Запоріжжя, Іванова, 2, 69068
Ivannikov S.V. / Іванніков С.В.
student / студент
Zaporizhzhia National University, Zaporizhzhia, Zhukovskogo str.,66, 69600
Запорізький національний університет, м. Запоріжжя, Жуковського, 66, 69600

Abstract. *An analysis of modern technologies and equipment for smelting heat-resistant nickel alloys, ways of processing waste from the production and consumption of nickel with their involvement in a closed cycle was carried out. The technology of refining electron-beam remelting in combination with vacuum-induction remelting was chosen for the processing of metal casting waste and menders aircraft blades made of heat-resistant nickel alloy. The peculiarities of the technology of obtaining single crystal nickel castings are analyzed. Experimental studies have confirmed the expediency and cost-effectiveness of adding 50% of the heat-resistant ЖС26-ВІ alloy, obtained by electron-beam remelting of metal nickel waste of our own production, to the charge for the production of castings by the method of high-speed directional crystallization. The variant of the charge for casting production from the ЖС26-ВІ alloy with the addition of 50 % of metal waste of the original alloy has the most optimal combination of properties for short-term rupture and long-term strength. It was experimentally established that the microstructure of the ЖС26-ВІ alloy produced with the addition of nickel waste does not differ significantly from the structure of the ЖС26-ВІ alloy obtained by the method of vacuum induction remelting and is a γ-solid solution strengthened by the γ-phase and carbides. The directions for improving the processing of heat-resistant nickel alloys metal waste have been identified.*

Keywords: *casting, heat-resistant nickel alloy, directional crystallization, metallic nickel waste, melting, microstructure.*

Introduction.

Heat-resistant nickel alloys of the ЖС type are distinguished by a very complex alloying system and, accordingly, high cost. Modern economic conditions require a reduction in the cost of any product while maintaining the level of its operational properties and reliability.

One of the areas of resource conservation is the development of new alloys that meet high operational and economic requirements. At the same time, they have high corrosion resistance, as a result of which it is not necessary to additionally apply a corrosion coating to the blades [1-6]. However, the creation of new alloys with improved characteristics compared to the used alloys is a rather long and costly process, as it is closely related to the creation of a new material with a new chemical composition and properties, as well as the development of a new technology, the selection of new equipment, etc. On this way, it is possible to have failed tests, when the expected results are not justified.

Another promising way to reduce the cost of castings from heat-resistant nickel alloys is the use of technological waste of own production in the charge.

The aim of the project work is the researching the chemical composition and material properties of the ЖС26-ВІ alloy on samples made with the addition of different amounts of heat-resistant nickel alloy waste to the charge.

The object of the research is heat-resistant nickel ЖС26-ВІ alloy, obtained by the method of double remelting with the involvement of metallic nickel waste of our own production.

The subject of the research is the influence of the amount of metallic nickel waste on the quality and properties of the metal in the obtained castings from the ЖС26-ВІ alloy.

Literature review.

The development of many branches of mechanical engineering, and above all, the sphere of the aviation cluster, poses new challenges for improving the quality, reliability and durability of parts operating at high temperatures and stresses in modern gas turbine engines (GTE). Responsible castings for power plants of energy and aviation engineering are made of expensive complex alloyed heat-resistant nickel alloys. In the field of nickel heat-resistant alloys, in world practice, there is a tendency to increase the level of heat-resistant properties of cast alloys due to more complex alloying [1,7-9].

Heat-resistant nickel alloy ЖС26-ВІ is widely used for the manufacture of turbine blades of modern gas turbines. This alloy is characterized by a very complex alloying system and, accordingly, high cost (Table 1).

Table 1 - The chemical composition of some monocrystalline heat-resistant nickel alloys

Alloy	Mass fraction of the element, %										
	Cr	Ti	Mo	W	Re	Ta	Al	Co	Nb	Hf	Others
ЖС32-ВІ	5,0	–	1,0	8,3	4,0	4,0	6,0	9,0	1,5	–	0,15 C, 0,02 B
ЖС26-ВІ	5,0	1,0	1,1	11,7	–	–	5,8	9,0	1,6	–	0,12 C, 0,015 B, 1,0 V
CMSX-10	2,0	0,2	0,4	5,0	6,0	8,0	5,7	3,0	0,1	0,03	–
TMS-138	3,2	–	2,8	5,9	5,0	5,6	5,9	5,8	–	0,1	2,0 Ru
TMS-162	2,9	–	3,9	5,8	4,9	5,6	5,8	5,8	–	0,1	6,0 Ru
Note. Nickel is the base.											

Resource [1,7-10]

To ensure a high level of heat-resistant properties in the production of working blades of modern GTE in Ukraine and abroad, the technology of directional crystallization is used, which ensures obtaining a monocrystalline structure (without grain boundaries) in the blades with a given crystallographic orientation.

The feature of the monocrystalline structure is the absence of grain boundary strengthening, therefore, in alloys developed for single crystal casting, as a rule, there are no elements (Hf, Zr) that form carbides and are responsible for grain boundary strengthening, and carbon is reduced to the technologically possible minimum (0.002-0.004%) [7-11]. Blades with a monocrystalline structure have increased strength properties, which allows you to increase the service life of products by 2-3 times compared to the usual technological process, which allows you to obtain blades with an equiaxed structure.

The features of the technology of obtaining single crystal nickel castings are analyzed. In order to create optimal conditions for obtaining a monocrystalline structure of castings (blades), it is expedient to make the seed from alloys of the Ni–W system, pure nickel, and from the same nickel alloy as the castings. Liquid aluminum is used as a medium for crystallization of single crystal nickel castings.

Recently, the duplex process scheme has become widespread for the production of ingots from heat-resistant alloys. Various variants of the duplex process, in which electron beam, electroslag and plasma melting are used, are promising for heat-resistant nickel alloys. Heat-resistant nickel alloys of almost any chemical composition can be smelted in vacuum induction furnaces.

During the manufacture of blades for aircraft engines and after the operation of the engines, a significant amount of nickel metal waste is generated - waste and return of sprue systems, rejected and used blades. Such metal wastes of nickel alloys are multicomponent systems containing up to 12 alloying and microalloying elements. Now, resource-saving technologies of refining vacuum remelting of nickel waste are being created. New technologies will make it possible to completely return heat-resistant nickel alloy waste to the production of alloys that are not inferior to alloys made from primary nickel raw materials.

Research materials and methods.

Turbine blades of modern both aviation and power ground units are made, as a rule, from heat-resistant nickel ЖС26-ВІ alloy. Castings from this alloy are produced by high-speed directional crystallization (HSDC) on units of the УВНК-8П type. ЖС26-ВІ alloy is distinguished by a very complex alloying system and, accordingly, high cost. Modern economic conditions require a reduction in the cost of any product while maintaining the level of its operational properties and reliability.

When casting turbine blades of aviation engines using the casting method according to molten models, a significant amount of nickel metal waste of own production accumulates in the form of technological waste, which includes waste from shower systems and defective blades. In production, the direct use of such waste in the charge without prior cleaning causes the accumulation of non-metallic inclusions in castings, as a result of which the melting properties of the alloy deteriorate, and also comes to the formation of defects in castings. In addition, after removal of ceramic rods in alkaline solutions, traces of sodium and potassium aluminates remain on the inner surface of defective blades. Therefore, a special high-gradient technology of directional crystallization and special equipment for smelting monocrystalline turbine blades are being developed in order to involve in the production of metal nickel waste from our own production of heat-resistant nickel alloys and obtain high-quality metal.

As metal waste of heat-resistant nickel alloys for research, technological waste of in-house production of aircraft blades made of nickel alloy ЖС26-ВІ is used: rejected castings and sprue system elements – collectors, bowls, inlets, risers (Figure 1).

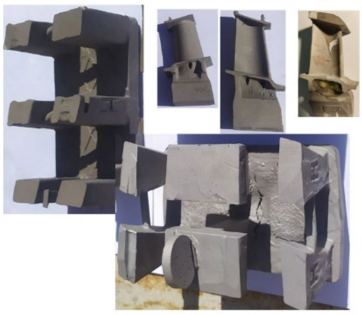

Figure 1 - Metal waste of heat-resistant nickel ЖС26-ВІ alloy

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It is established that the technological wastes correspond to the alloy ЖС26-ВІ (Table 1) in terms of chemical composition according to TU 1-92-177-91 and in terms of mechanical properties and long-term strength tests to the established requirements (Table 2).

Table 2 - Mechanical properties of the ЖС26-ВІ alloy at a temperature of 20 °C and long-term strength of the blade material tested on casting samples obtained by the HSDC method using the technology of the corresponding part

Mechanical properties of the alloy at a temperature of 20 °C		Long-term strength at a temperature of 975 °C	
Indexe	Value	Indexe	Value
Temporary resistance σ_B, N/mm^2 (kg/mm^2), not less	830 (85)	Constant added stress σ, N/mm^2 (kg/mm^2)	255 (26)
Relative elongation δ, %, not less	6	Time to destruction τ, hours, no less	40
Note. Tests for long-term strength should be performed before the destruction of the samples.			

To work out the industrial technology of obtaining blades for aviation gas turbine engines (GTE), power plants and responsible castings of other parts from special heat-resistant alloys, the vacuum УВНК-8П unit (Figure 2) is used for high-speed directional crystallization at high thermal gradients.

The main functional unit of the УВНК-8П unit is the melting chamber (Figure 2), which houses an induction melting furnace, a mold heating furnace and a crystallizer with liquid aluminium.

Blanks of alloys ЖС26-ВІ and ЖС26-ВІ (EBR) are supplied by the factory-supplier in the form of bars or measured blanks with a diameter of 90 mm.

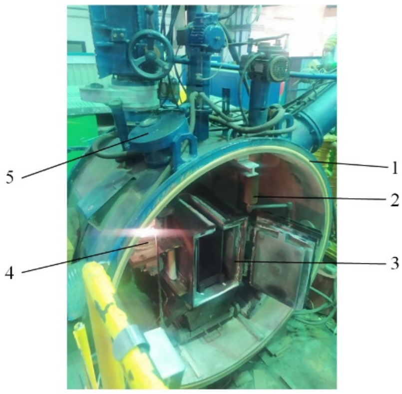

Figure 2 – The melting chamber of the УВНК-8П unit

1 – melting chamber; 2 – door turning mechanism; 3 – mold heating furnace; 4 – induction furnace; 5 – nozzle with a viewing window

Author's working

Each blank of the original melting, which arrived with a certificate, is checked by spectral analysis on the Expert 02L analyzer for compliance with the grade of ЖС26-ВІ alloy. With positive test results, one of the blanks is submitted for input control of the starting alloy by casting samples for mechanical tests and taking chips for checking the composition by chemical analysis.

With positive results of the input control (spectral and chemical analysis, heat-resistant and mechanical tests), the output melt is launched into production.

The measured billet is loaded into the induction melting furnace through the loading device of the УВНК-8П unit.

After obtaining blade castings by the HSDC method on the УВНК-8П unit, the block of castings is subjected to thermostating, cooling, and processing of castings is carried out by freeing the castings from the ceramic shell by punching, blowing with electrocorundum, cutting off the castings from the sprue system, cleaning.

Cleaned castings (Figure 3) are subjected to etching to control the macrostructure. The macrostructure of the samples must be monocrystalline or directional (the number of crystals from 2 to 8 pieces), the permissible inclination of the crystal boundaries relative to the longitudinal axis of the sample is no more than 10 degrees.

Figure 3 - Casting of blades obtained by the HSDC method

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Control of the crystallographic orientation (COR) of single-crystal samples of nickel alloy is carried out by the X-ray diffraction method on the ДРОН-3М diffractometer according to the standard method. Crystallographic orientation is determined on single-crystal samples, which are used as starting cones of parts, seeds, teplets, cut from the feather of the working vanes, perpendicular to the Z axis, etc. Samples (Figure 4) should be etched to a noticeable dendritic structure.

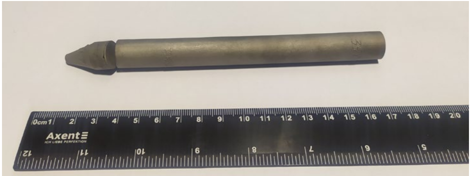

Figure 4 - General appearance of a nickel alloy sample

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The mechanical properties and long-term strength of castings are investigated after heat treatment. Testing of samples of nickel alloys for long-term strength is carried out in accordance with DSTU 10145 «Metals. Method and test for long-term strength». Testing of samples of nickel alloys for short-term stretching is carried out in accordance with DSTU 1497 «Metals. Method and tensile test».

Research results.

In order to process the metal nickel waste of our own production of the heat-resistant ЖС26-ВІ alloy and use it as part of a batch measurement blank, the waste was refined by remelting using electron beam technology. The alloy blank obtained by such preparation will be conventionally designated as ЖС26-ВІ (EBR). The appearance of such a nickel alloy blank under investigation is shown in Figure 5. Templates (template 1 and template 2) with a thickness of about 10 mm were cut from the two ends of the rod, on which the chemical composition, including the carbon content, and microanalysis of the material were examined to assess the quality of the microstructure and the presence of casting defects.

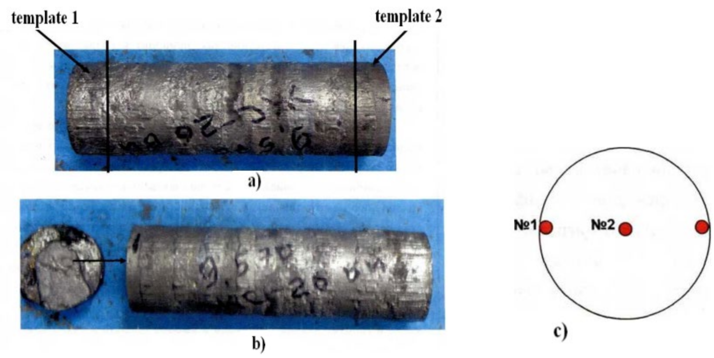

Figure 5 - General view of a solidly cast (a), with a cut-off template (b) of the ЖС26-ВІ (EBR) alloy blank and a diagram of the spectral analysis zones on template 1

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The chemical composition was determined on each template (marked 1 and 2), corresponding to the upper and lower casting zones. On template 1, the chemical composition was controlled in three zones: in the core of the template and on two diametrically located peripheral areas (Figure 5, c). The results of the spectral analysis of the cut fragment of the alloy blank are given in Table 3. It was established that the chemical composition of the templates meets the requirements of the Certificate norms and indicates the chemical macro-homogeneity of the ingot.

Table 3 - The results of determining the chemical composition of the cut fragment of the alloy blank

Sample type		Mass fraction of the element, %									
		Al	Ti	V	Cr	Fe	Co	Ni	Nb	Mo	W
Template 1		5,88	0,82	1,12	4,30	0,50	9,43	Base	1,8	1,07	12,08
Template 2		5,92	0,62	1,17	4,416	0,46	9,50	Base	1,8	1,09	12,33
Template 1	p.1	5,80	0,70	1,19	4,70	0,60	9,60	Base	1,7	1,1	12,2
	p.2	5,80	0,76	1,17	4,90	0,60	9,50	Base	1,7	1,1	12,12
	p.3	5,98	0,76	1,14	4,80	0,60	9,40	Base	1,7	1,1	12,07
Certificate		5,5-6,2	0,8-1,2	0,8-1,2	4,3-5,6	<1,2	8-10	Base	1,4-1,8	0,8-1,4	10,0-12,5

Author's working

Control of the carbon content showed that in the upper part of the ingot it is within 0.125 %, in the lower part - 0.13 %, which meets the requirements of the Certificate (0.13-0.18 %). The variation of carbon content within one fragment is slightly more than 0.05 %.

Microanalysis of the samples cut from the casting of the remelted ЖС26-BI (EBR) alloy showed that the microstructure of the alloy is characteristic of the ЖС26-BI alloy in the non-heat-treated state, there is unevenness in the dispersion and distribution of the γ′-phase (Figure 6).

With the use of the ЖС26-BI (EBR) alloy blank, which was obtained by electron beam remelting of metal technological waste of our own production, two variants of charge compositions were made for research: 1) with 50 % of the original ЖС26-BI alloy and 50 % of the ЖС26-BI (EBR) alloy; 2) from 100 % ЖС26-BI (EBR) alloy, from which castings were obtained by the HSDC method. Sample castings underwent all technological operations and types of control provided by the technological process.

According to the results of the control of the macrostructure of the samples, it was found that:

1) out of 9 units of castings obtained from 100 % ЖС26-BI (EBR) that came for control, 8 units were recognized as suitable by macrostructure, of which 5 units have a single crystal structure and 3 units have a DC-structure, 1 unit is defective. The yield of suitable material according to the macrostructure was 89 %.

2) out of 9 units, obtained using 50 % of the original alloy and 50 % of ЖС26-BI (EBR), which came for control, 9 units were recognized as suitable by macrostructure, of which 8 units have a single crystal structure and 1 unit has a DC-structure. The yield of suitable material according to the macrostructure was 100 %.

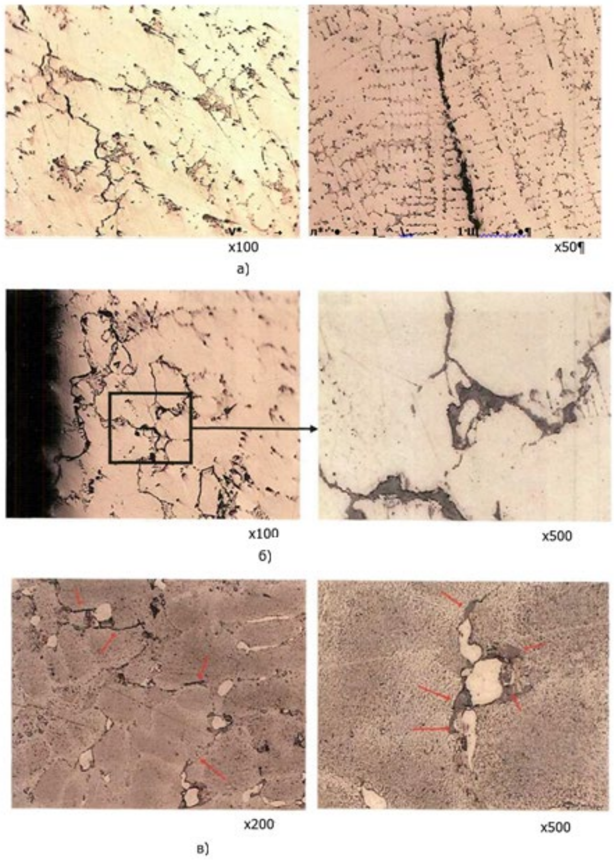

Figure 6 - Defects in the structure of the ЖС26-ВІ (EBR) alloy blank
a – cracks in the ingot; b – films in an ingot; c – oxidation along grain boundaries
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All castings of samples with a single crystal structure have deviations from the specified COR [001] up to 5 degrees, which meets the requirements of the technological process. The averaged test results of blade samples cast from two variants of the charge with the addition of remelted waste of our own production to the charge are given in Table 4 and Table 5.

Based on the analysis of the data presented in Tables 4 − 6, it was established that:

1) the properties of samples of both variants of castings meet the requirements of TU 1-92-177-91 for the ЖС26-ВІ alloy and the requirements of the TU for the part (turbine blade), and according to the characteristics of the short-term rupture test, they are significantly higher than the standards;

2) on samples made of 100 % alloy ЖС26-ВІ (EBR) after heat treatment, the level of properties of the tensile strength limit σ_B, temporary resistance $\sigma_{0.2}$ at room temperature and long-term strength increased slightly. At the same time, the relative elongation turned out to be somewhat lower, and the relative narrowing remained at the same level.

After testing of mechanical properties of the samples the investigation of fractures in the places of failure of the samples were performed:

- study of fractures at the place of destruction under a binocular microscope;
- microanalysis of the material for the quality of the microstructure and the presence of casting defects;
- determination of the chemical composition by the spectral method according to

the main elements, except for carbon, for each variant of castings (on burst samples).

Table 4 - The averaged results of testing the mechanical properties of ЖС26-ВІ alloy samples after EBR and with the addition of technological waste of own production

Melting conditions of the sample	Sample condition	Mechanical properties				
		The nature of the microstructure	Tensile strength limit σ_B, kg/mm^2	Temporary resistance $\sigma_{0.2}$, kg/mm^2	Relative elongation δ, %	Elongation at break Ψ, %
100 % ЖС26-ВІ (EBR)	Casting, dc	Average	96,1	70,9	16,8	16,0
	After heat treatment	Average	114	70,8	14,3	16,8
50 % ЖС26-ВІ (EBR) + 50 % of the original alloy ЖС26-ВІ	Casting, dc	Average	116,1	84,0	11	12
	After heat treatment	Average	113,3	79,2	12,5	15,7
TU for blade	Casting, dc		255		≥ 6	
TU 1-92-177-91	After heat treatment		≥ 85		≥ 8	

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Table 5 - The averaged results of the long-term strength test of ЖС26-ВІ alloy samples after EBR and with the addition of technological waste of own production

Melting conditions of the sample	Sample condition	Lasting strength, hours
100 % ЖС26-ВІ (EBR)	Casting, dc	73 hours
	After heat treatment	75 hours 30 minutes
50 % ЖС26-ВІ (EBR) + 50 % of the original alloy ЖС26-ВІ	Casting, dc	72 hours 50 minutes
	After heat treatment	90 hours 48 minutes
TU for blade	Casting, dc	≥ 40 hours
TU 1-92-177-91	After heat treatment	≥ 40 hours

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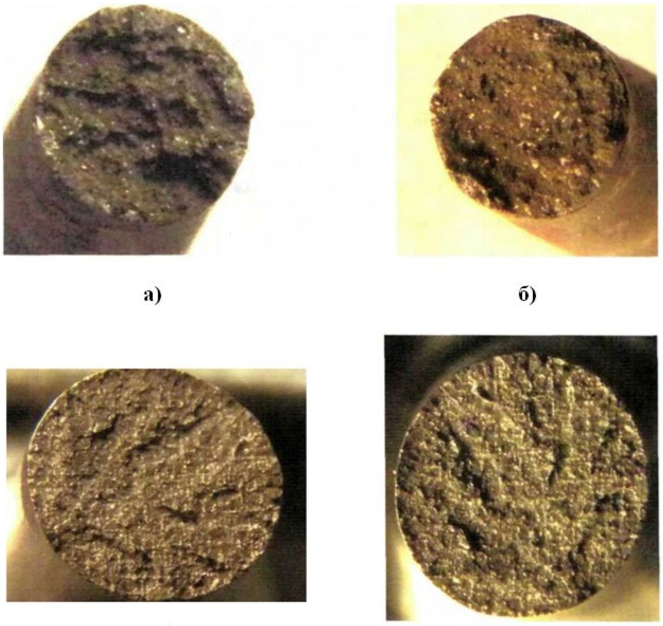
Microanalysis was performed on longitudinal samples in the fracture zone using an OLYMPUS IX70 optical microscope. The study of fractures in the places of destruction of samples during the test for tearing at room temperature and long-term strength was carried out at a temperature of 975 °C and a load of 26 kg/mm^2. The appearance of fractures is shown in Figure 7.

According to the results of the study of sample fractures (Table 6), it was established that the sample failure occurred within the calculated length.

Fractures of the samples after destruction are identical for both variants of castings, have a fine-crystalline structure without pronounced dendriticity, typical for heat-resistant tests. There are no pronounced foci of destruction, as well as fracture zones, the structure of the fractures is the same throughout the entire cross-section of the destruction. Fractures oxidized to a dark brown color, no oxide inclusions or other casting defects were detected. No significant difference in fracture structure was found on samples with high and reduced survivability (Figure 7, a and b).



а) б)

в) г)

Figure 7 - Fractures at the points of failure of the samples during the long-term strength test (a, b) and tearing (c, d)

a – sample I16, m 5; b – sample I1, dc 1°;

c – sample I16, m 5°; d – sample I5, m 4°

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Fractures of the samples after the test with destruction are similar for both variants of castings, typical for the destruction of samples with COR [001], no oxide inclusions or other casting defects were detected (Figure 7, c and d).

Analysis of the microstructure of heat-resistant samples revealed no significant difference in the microstructure of samples cast from 100 % ЖС26-ВІ (EBR) and in the case of adding 50 % of the original ЖС26-ВІ alloy to the charge.

In the as-cast state, the structure is characterized by inhomogeneity in the dispersion and distribution of the γ′-phase – greater in the interdendritic spaces compared to the dendrite axes. There is a large amount of γ′-eutectic in the interdendritic spaces. After heat treatment, the structure did not change significantly, in particular, the unevenness of the dispersion of the γ′-phase remained practically at the same level. After heat treatment, the difference in the dispersion of the γ′-phase is somewhat equalized.

Table 6 - Results of analysis of the microstructure of ЖС26-ВІ alloy samples after EBR and with the addition of technological waste of own production

Melting conditions of the sample	Time to destruction of the sample, hours	Area of the sample damaged by transverse micro-cracks, mm (counting from the fracture)
Sample I12, m 2° (50 % ЖС26-ВІ (EBR) + 50 % of the original alloy ЖС26-ВІ), casting	75	1,6
Sample I13, m 5° (50 % ЖС26-ВІ (EBR) + 50 % of the original alloy ЖС26-ВІ), after heat treatment (with minimal heat resistance)	81	0,8
Sample I16, m °5 (50 % ЖС26-ВІ (EBR) + 50 % of the original alloy ЖС26-ВІ), after heat treatment (with minimal heat resistance)	102	3,4

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Table 7 - Comparison of the results of the chemical composition of castings of turbine blades melted from different charge compositions

Sample type	Mass fraction of the element, %									
	Al	Ti	V	Cr	Fe	Co	Ni	Nb	Mo	W
100 % ЖС26-ВІ (EBR), casting	5,7	1,07	0,95	4,50	0,14	8,60	Base	1,76	1,06	12,75
100 % ЖС26-ВІ (EBR), after heat treatment	6,1	0,90	1,10	4,25	0,17	8, 65	Base	1,72	1,04	11,60
50 % ЖС26-ВІ (EBR) + 50 % of the original alloy, casting	5,7	0,95	0,98	4,30	0,10	8,65	Base	1,77	1,02	11,73
50 % ЖС26-ВІ (EBR) + 50 % of the original alloy, after heat treatment	5,7	0,96	1,06	4,40	0,14	8,66	Base	1,68	0,96	11,72
TU 1-92-177-91	5,6–6,1	0,8–1,2	0,8–1,2	4,3–5,3	≤0,5	8,7–9,3	Base	1,4–1,8	0,8–1,2	11,2–12,0
Note. Carbon was not observed on these samples.										

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Spectral analysis of the chemical composition of the metal of blade castings obtained by the method of high-speed directional crystallization (HSDC) established that the chemical composition of both versions of the castings in terms of the main elements meets the requirements of the ЖС26-ВІ alloy Certificate. No significant difference between the variants of batch compositions with the addition of different amounts of technological waste of own production was found (Table 7).

Conclusions.

Both variants of charge compositions can be used to obtain high-quality material for castings from the ЖС26-ВІ alloy by the method of double remelting of heat-resistant nickel alloy waste. The properties of the samples obtained with the addition of 100 % and 50 % of ЖС26-ВІ alloy to the charge, made by electron beam remelting of nickel metal waste of our own production, both variants of castings meet the regulatory requirements for the ЖС26-ВІ alloy and parts (blades).

According to the results of the spectral analysis of the metal composition of turbine blade castings obtained by the HSDC method, it was established that the chemical composition of castings made from both variants of charge compositions meets the requirements of the ЖС26-ВІ alloy Certificate for the main elements. No significant difference was found between samples of alloy materials made from both variants of charge compositions.

The variant of the charge for obtaining a casting from the ЖС26-ВІ alloy with the addition of 50% of metal waste of the original alloy has the most optimal combination of properties for short-term rupture and long-term strength. According to the results of tests on short-term rupture of samples obtained with the involvement of nickel metal waste, it was established that the properties of such samples exceed the established norms.

It was experimentally established that the microstructure of the ЖС26-ВІ alloy obtained with the addition of nickel waste does not significantly differ from the structure of the ЖС26-ВІ alloy obtained by the method of vacuum induction remelting and is a γ-solid solution strengthened by the γ-phase and carbides. There are significant amounts of γ'-eutectics in the interdendritic spaces. In the as-cast state, non-uniformity with respect to the dispersion and distribution of the γ′-phase is observed. Experimental studies have confirmed the expediency and cost-effectiveness of adding 50 % of ЖС26-ВІ alloy, obtained by EBR of nickel metal waste of our own production, to the charge for the production of castings by the HSDC method.

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Анотація. *Проведено аналіз сучасних технологій та обладнання для виплавлення жароміцних нікелевих сплавів, шляхів переробки відходів виробництва і споживання нікелю із залученням їх у замкнутий цикл. Для переробки металевих відходів лиття і бракованих авіаційних лопаток із жароміцного нікелевого сплаву вибрано технологію рафінувального електронно-променевого переплавляння у поєднанні з вакуумно-індукційним переплавленням. Проаналізовано особливості технології отримання монокристалічних нікелевих виливків. Експериментальними дослідженнями підтверджено доцільність та економічність додавання 50 % жароміцного сплаву ЖС26-ВІ, отриманого шляхом електронно-променевого переплавляння металевих нікелевих відходів власного виробництва, у шихту для виготовлення виливків методом високошвидкісної спрямованої кристалізації. Варіант шихти для отримання виливка із сплаву ЖС26-ВІ із додавання 50 % металевих відходів вихідного сплаву має найбільш оптимальне поєднання властивостей при короткочасному розриванні та тривалої міцності. Експериментально встановлено, що мікроструктура сплаву ЖС26-ВІ, отриманого із додаванням нікелевих відходів, суттєво не відрізняється від структуры сплаву ЖС26-ВІ, отриманого методом вакуумно-індукційного переплаву та є γ-твердим розчином, зміцненим γ-фазою і карбідами. Виявлено напрями вдосконалення переробки металевих відходів жароміцних нікелевих сплавів.*

Ключові слова: *виливок, жароміцний нікелевий сплав, спрямована кристалізація, металеві нікелеві відходи, плавлення, мікроструктура.*

Supervisor of studies: c.t.s., as. prof. Nesterenko T.M.
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