КОНСТРУКЦІЙНІ І ФУНКЦІОНАЛЬНІ МАТЕРІАЛИ

STRUCTURAL AND FUNCTIONAL MATERIALS

UDC 669.715:669.018.25:620.186

Serhii Puchek — Postgraduate student of the Department of Transport Technologies, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: puchek777@gmail.com,* ORCID: 0009-0007-8077-6106

Sergiy Byelikov — Doctor of Technical Sciences, Professor of the Department of Transport Technologies, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: belikov@zp.edu.ua,* ORCID: 0000-0002-9510-8190

STRUCTURE AND PROPERTIES OF HEAT-RESISTANT ALLOY ZHS-26VI FOR THE PRODUCTION OF RELEVANT PARTS OF GAS TURBINE ENGINES

Purpose*. To study the macro- and microstructural state of a series of research samples of the heat-resistant alloy ZhS26-VI for the production of critical components of a gas turbine engine, namely rotor blades of a high-pressure turbine (HPT), and to evaluate the mechanical properties and heat resistance in accordance with the technical specifications of the materials of the gas turbine hot part .*

Research methods*. Macro- and microstructural analysis and phase composition studies were carried out by optical metallography using an optical microscope. Mechanical properties at room temperature were determined in accordance with ISO 6892-84 and ST SEV 471-88. Tensile tests were carried out on a ZDMY30 machine.*

Results*. The structure and properties of samples of experimental melts of the ZhS-26VI alloy obtained in the FM-1-2-100 vacuum furnace of the "ULMAC" company by the method of equiaxed crystallization were studied. Significant grinding of the macrograin was established due to intensive heat removal and high crystallization rate. The microstructure of the samples before heat treatment corresponds to the cast state of the alloy, and after heat treatment in the standard mode satisfies the technical conditions and corresponds to the approved microstructure scale. The mechanical and heat-resistant properties of the samples meet the requirements of the regulatory documentation for responsible heat-resistant casting.*

Scientific novelty*. New data on the structure and phase state of the ZhS26-VI alloy of experimental and serial melts were obtained. The fine structure of the nickel-based heat-resistant alloy, which is traditionally used to produce high-pressure turbine blades of an aviation gas turbine engine, was studied.*

Practical value*. The results obtained provide an opportunity to expand the use of the ZhS26-VI heat-resistant alloy for the production of castings for critical purposes.*

Key words*: heat-resistant alloy, macro- and microstructure, heat treatment, mechanical properties, heat resistance, gas turbine blade.*

Introduction

The development of new-generation gas turbine engines (GTEs) requires improved performance characteristics, including power, service life, reliability, durability, and fuel efficiency. Achieving the required GTE performance is ensured by the application of heat-resistant nickel alloys as the primary materials for hot-gas path components [1-5]. Heat-resistant alloys used in gas turbine construction must have an optimal combination of mechanical properties and heat resistance with sufficient ductility, which generally ensures high component performance under conditions of uneven stress distribution across the cross-section. In the works [1–6, 10, 11] special attention was paid to the study and improvement of the long-term strength and creep properties of heat-resistant alloys, and the authors [7–9, 12, 13] paid special attention to the development of principles for alloying heat-resistant alloys operating in high-temperature corrosive environments, which is more typical for gas turbine units in land and marine engine building, although it is also inherent in aircraft engines operating in marine environments or desert regions [8, 9]. Ensuring improved characteristics of hot tract parts and, in general, the operational life of a gas turbine engine is usually carried out in two main directions: the development of new complex heat-resistant alloys with a high content of elements, having low diffusion coefficients under high temperature conditions and increasing the range of service characteristics through additional alloying, modification and microalloying of industrial alloys that have demonstrated reliability in long-term operation [16].

DOI 10.15588/1607-6885-2025-4-2

For modern gas turbine engines, the base material for both uncooled and air-cooled blades are high-strength cast nickel alloys, which, in addition to the nickel base, may contain chromium, cobalt, titanium, aluminum, tungsten, and other elements. An example of such alloys is the nickel alloy ZhS26-VI [14].

Material and Methodology

Fragments of a rod blank produced in a ULMAC FM-1-2-100 vacuum furnace using equiaxed crystallization of the ZhS26-VI alloy were studied.

The chemical composition of the material, as well as the macro- and microstructure of the test samples, were determined. The macrostructure was revealed by chemical etching in a reagent consisting of 80 % HCl and 20 % H_2O_2.

Using high-speed directional solidification, 15mm-diameter, 135mm-long specimens were cast from 90mm-diameter rod blanks of ZhS26-VI alloy obtained from fresh components to determine their mechanical and heat-resistant properties.

The mechanical and heat-resistant properties were determined on unheat-treated specimens, as well as after heat treatment using the standard mode—homogenization at 1265 ± 100 °C in a vacuum.

After processing according to the specified options, the blanks were machined to ensure the dimensions specified in the technical documentation for the manufacture of mechanical testing specimens. Mechanical properties at room temperature (tensile strength, yield strength, elongation, and reduction in area) were determined in accordance with ISO 6892-84 and ST SEV 471-88. Tensile testing was performed on a ZDVY30 testing machine.

Long-term strength testing was conducted in accordance with DSTU ISO 204:2019 using an Instron M3 testing machine at 945 °C and a load of 260 MPa until complete failure of the specimens.

Research Results and Discussion

The chemical composition of the ZhS26-VI alloy for all tested variants, with respect to the main elements, meets the requirements of the scientific and technical documentation for the material (Table 1).The macrostructure of the transverse cut of fragments of workpieces, taken from a vacuum furnace FM-1-2 from OLVAC using the equiaxial crystallization method, is presented in Fig. 1.The structure of the workpiece-fork is presented by the following crystallization zones:

- Zone of fine subcortical crystals;
- Zone of columnar crystals;
- Zone of equiaxed crystals.

The zone of columnar crystals, which expand from the surface of the samples to the central zone at a 12–23 mm distance (Fig. 1). According to the authors [15, 16], this zone is formed under influence of cobalt aluminate, which is introduced into the first ceramic-shaped working layer and ensures increased thermal conductivity [16, 17]. The advancing zone is the zone of equiaxed grains, grown at the center of the fork with a diameter of 4–61 mm. Intensive fragmentation of grains in this zone can be associated with the action of dispersed particles of titanium carbides, which are additional centers of crystallization, which promotes the formation of a more finely dispersed structure of the alloy [16].

Table 1 – Chemical composition of tested variants of ZhS26-VI nickel-based alloy

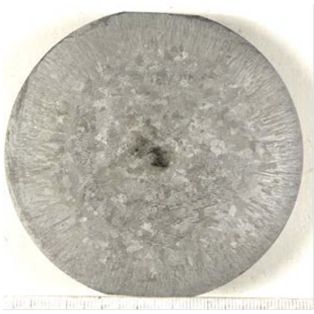
№	Content of elements, %															
melt	C	Cr	Co	W	Al	Ti	Mo	Fe	Nb	V	Si	Mn	S	P	B	Ni
1	0,144	5,08	9,05	11,54	5,86	0,98	0,98	0,06	1,54	1,03	0,090	0,008	0,003	0,005		Base
2	0,16	5,10	9,06	11,58	5,90	0,99	1,01	0,06	1,54	1,00	0,080	0,006	0,005	0,004		Base
3	0,144	4,95	9,10	11,46	5,84	1,02	1,06	0,06	1,60	1,05	0,080	0,009	0,005	0,004	0,014	Base
4	0,143	4,98	8,93	11,52	5,90	1,00	1,03	0,06	1,60	1,04	0,080	0,010	0,005	0,004	0,012	Base
5	0,14	5,03	9,00	11,45	5,76	1,02	1,04	0,06	1,65	1,03	0,080	0,010	0,005	0,004	0,011	Base
6	0,143	5,12	9,13	11,51	5,77	1,02	1,06	0,06	1,65	1,05	0,070	0,009	0,005	0,004	0,014	Base
7	0,144	5,16	9,15	11,42	5,66	1,02	1,05	0,06	1,63	1,07	0,080	0,009	0,005	0,004	0,014	Base
8	0,14	4,98	9,03	11,59	5,82	1,05	1,09	0,06	1,60	0,99	0,085	0,008	0,005	0,004	0,013	Base
9	0,15	5,02	9,10	11,49	5,78	1,09	1,11	0,06	1,71	1,08	0,065	0,009	0,005	0,004	0,015	Base
10	0,133	4,80	8,84	11,75	6,05	0,92	1,00	0,06	1,50	1,00	0,10	0,008	0,005	0,004	0,010	Base
11 Series	0,15	5,04	8,89	11,65	5,86	0,93	1,00	0,06	1,63	0,99	0,11	0,009	0,005	0,004	0,010	Base
Norms TU 1-92-177-91	0,12-0,17	4,3-5,3	8,7-9,3	11,2-12,0	5,6-6,1	0,8-1,2	0,8-1,2	≤0,5	1,4-1,8	0,8-1,2	≤0,2	≤0,3	≤ 0,005	≤ 0,010	≤ 0,015	Base

DOI 10.15588/1607-6885-2025-4-2

a

b

c



d

e

Figure 1. Macrostructure in the cross-section of the bar blank of the ZhS26-VI alloy samples:
a – variant 1 before heat treatment; *b* – variant 1 after heat treatment; *c* – variant 2 in the initial state; *d* – variant 10 in the initial state; *e* – variant 11 in the initial state

The results of measuring the parameters of the macrostructure of the blanks of different variants of the melts of the ZhS26-VI alloy samples are given in Table 2.

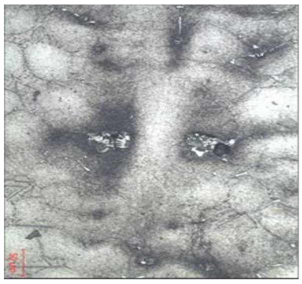
Table 2 – Parameters of the macrostructure of the blanks made of ZhS26-VI metal in the initial state

Option number	Size of crystallization zones, mm			macrograin, size mm
	zone of fine subcortical crystals	columnar crystal zone	zone of equiaxed crystals	
1	1…2	17…23	44…56	3,0…8,0
2	1…2	12…15	52…58	2,0…10,0
10	1…3	18…20	47…51	2,0…5,0
11	1…2	10…12	57…61	1,0…2,5

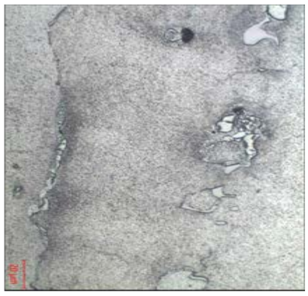
Metallographic examination of the test samples revealed no metal contamination in the form of films, coarse slag inclusions, or accumulations thereof.

The microstructure of the alloy samples cast made of the ZhS26-VI alloy, in all test variants, is a γ-solid solution with an intermetallic γ′- phase and a eutectic (γ-γ′) phase with carbides and carbonitrides, corresponding to the as-cast state of the ZhS26-VI alloy (Fig. 2).

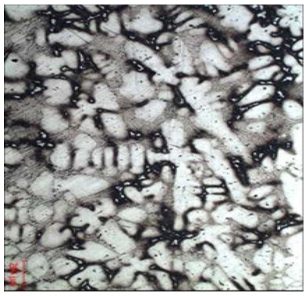
a × 50



b × 200



c × 500



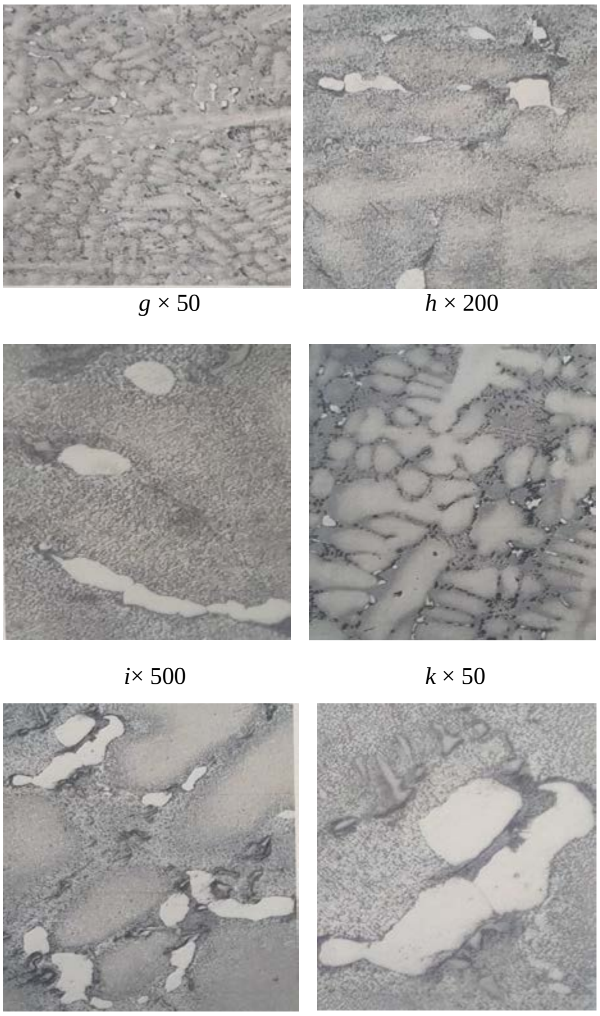
d × 50

e × 200

f × 500

Figure 2. Microstructure in the edge (*a*, *b*, *c*) and central (*d*, *e*, *f*) zones of sample 1

DOI 10.15588/1607-6885-2025-4-2



g × 50 *h* × 200

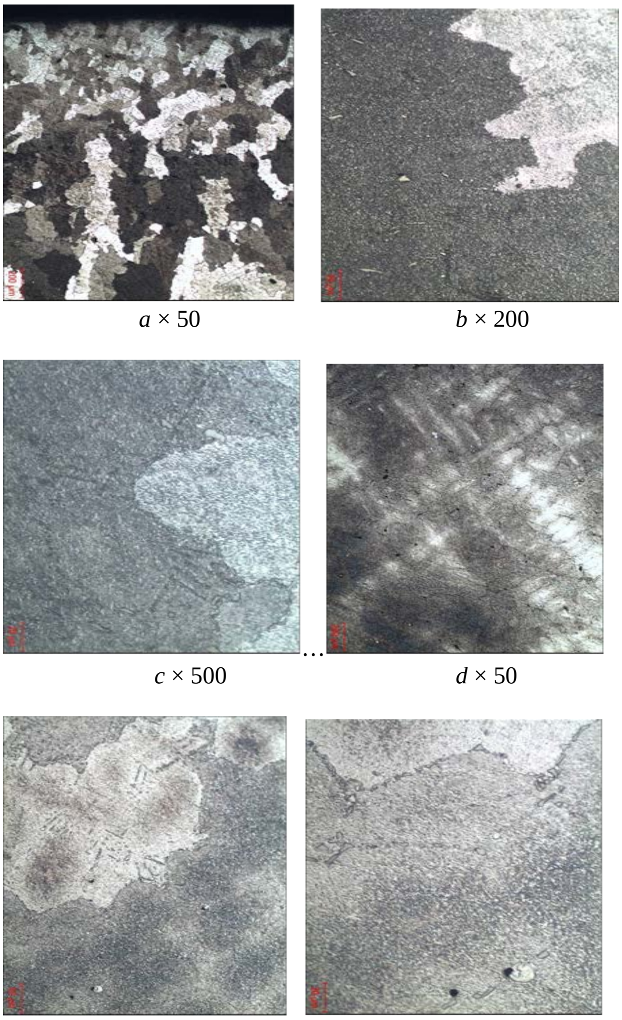
i× 500 *k* × 50

l × 200 *m* × 500

Figure 2. Continuation, in the edge (*g*, *h*, *i*) and central zones of sample 2 (*k*, *l*, *m*) before heat treatment

The microstructure after heat treatment is characterized by greater homogeneity due to the equalization of the particle sizes of the intermetallic γ′- phase between the axes and interaxial space of the dendrites and almost complete dissolution of the eutectic (γ-γ′) -phase in the γ-solid solution (Fig. 3). It can be considered that the microstructure of all samples is satisfactory for a normally heat-treated condition of this alloy.

TCP phases were not detected in the studied alloy samples (either before or after heat treatment according to the standard mode). To determine the mechanical and heat-resistant properties, samples (diameter 15 mm, length 135 mm) were cast from rod blanks with a diameter of 90 mm using the high-speed directional crystallization method.



a × 50 *b* × 200

c × 500 *d* × 50

f × 200 *e* × 500

Figure 3. Microstructure in the edge (*a*, *b*, *c*) and central (*d*, *f*, *e*) zones of sample 1

Mechanical and heat-resistant properties were determined according to 18T-TU-165 on unheat-treated samples, as well as after heat treatment using the standard mode (homogenization at 1265 ± 100 °C for 1 hour 15 minutes, in a vacuum). The results of mechanical tests, including long-term strength tests, are presented in Table 3.

Mechanical tests showed that all studied variants provide mechanical properties that meet the requirements of regulatory and technical documentation. The most pronounced indicators of material ductility are those obtained, as the obtained values exceed the requirements by 1.5 to 3 times (see Table 3).

DOI 10.15588/1607-6885-2025-4-2

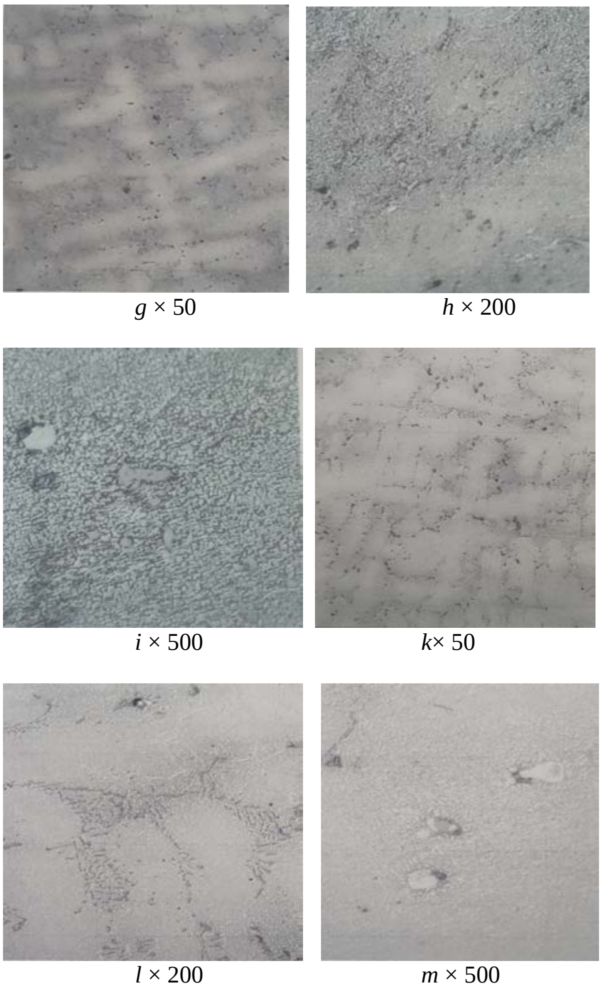


Figure 3. Continuation, as well as in the edge (*g*, *h*, *i*) and central (*k*, *l*, *m*) zones of the sample 2 after heat treatment

The time to high-temperature failure of the studied samples also complies with regulatory requirements and exceeds them by 1.5 to 2.5 times (see Table 3). The favorable morphology of grain-boundary carbides and the uniform distribution of the carbonitride component throughout the alloys, along with traditional strengthening by the intermetallic γ′- phase, characteristic of alloys of this class, were the reasons for the high time to failure.

The sizes of the structural components in the original 90mm diameter blank of the ZhS26-VI alloy, as well as in the samples (15mm in diameter and 135mm in length) before and after heat treatment, are presented in Table 4.

In the alloy structure, carbides and carbonitrides are present as small, dispersed particles of spherical and plate-like shapes, generally uniformly distributed throughout the material. Standard calculations of the quantitative and dimensional properties of the intermetallic γ′- phase did not reveal any significant differences between the alloys studied.

Table 3 – Mechanical and high-temperature properties of studied metals

Melt number	State of the material	Mechanical properties at 20°C		Hour before the failure (at Tisp = 9 75°C and Ϭ = 260 MPa), τ_f, hour
		$Ϭ_в$, МПа	δ, %	
1	without heat treatment	914	10,0	94^{15}
	after heat treatment	875	9,4	100^{30}
2	without heat treatment	1094	8,6	72^{30}
	after heat treatment	913	9,8	82^{30}
3	without heat treatment	928	9,2	40^{00}
4	without heat treatment	874	14,8	40^{00}
5	without heat treatment	727	24,8	91^{00}
6	without heat treatment	1108	13,2	67^{30}
7	without heat treatment	1085	10,8	53^{30}
8	without heat treatment	897	17,0	79^{30}
9	without heat treatment	866	17,2	68^{30}
Norms of TC		≥ 850	≥ 6,0	≥ 40^{00}

Conclusions

A series of experimental melts of ZhS26-VI alloy samples revealed significant macrograin refinement due to intensive heat removal and high crystallization rates. The macrostructure of all studied samples is satisfactory and meets technical specifications. The microstructure of the samples before heat treatment corresponds to the as-cast state of the alloy, and after heat treatment under standard conditions, it also meets technical specifications and conforms to the approved microstructure scale

It can be concluded that the normally heat-treated structure of the studied samples was achieved due to the conformity of the alloy's chemical composition. Heat treatment and hot isostatic pressing completely eliminated internal microporosity. The structure of all studied alloys exhibited the precipitation of carbides and carbonitrides in the form of small particles of spherical and lamellar morphology, generally distributed uniformly throughout the material.

DOI 10.15588/1607-6885-2025-4-2

The mechanical and high-temperature properties of the samples meet the requirements of regulatory documentation for critical heat-resistant castings. To confirm the sufficiency of the demonstrated level of mechanical properties, it is recommended to conduct technical tests (motor, full-scale) of parts as part of a gas turbine engine according to the accepted methodology of aviation regulations.

Table 4 – Dimensions of structural components for work pieces with a diameter of 90 mm and in samples (diameter 15 mm, depth 135 mm) of studied alloys

Melt number	Naymenuvannya	State of the material	Place of measurement	Size of structural components, microns			Distance between axes of 2nd order dendrites, μm
				carbides		Eutectic type (γ-γ')	
				Globular type MeC	Plate type Me_6C		
11	Workpiece, diameter 90mm	without h/t	edge	1,5…6	6…27	4…18	25…35
			center	2…8	6…30	9…65	65…90
		after h/t	edge	1,5…6	6…25	-	25…35
			center	2…8	6…30	До 16	65…90
	sample, diameter 15 mm	without h/t	center	3…12	5…25	7…60	50…90
		after h/t	center	3…9	5…28	-	50…90
22	Workpiece, diameter 90 mm	without h/t	edge	3…11	4…34	11…52	20…40
			center	2…13	6…32	15…50	45…90
		after h/t	center	4…9	3…30	-	20…40
			center	2…9	6…30	5…22	45…90
	Sample, diameter 15 mm	without h/t	center	3…9	7…44	8…43	60…90
			center	3…18	7…40	-	60…90

References

1. Okada, I., Torigoe, T., Takahashi, K., & Izutsu, D. (2004). Development of Ni base superalloy for industrial gas turbine. Proceedings of the International Symposium on Superalloys, 707–712.

2. Perrut, M., Caron, P., Thomas, M., & Couret, A. (2018). High temperature materials for aerospace applications: Ni-based superalloys and γ-TiAl alloys. Comptes Rendus Physique, 19(8), 657–671. https://doi.org/10.1016/j.crhy.2018.10.003

3. Sims, C. T., Stoloff, N. S., & Hagel, W. C. (1987). Superalloys II: High-temperature materials for aerospace and industrial power (2nd ed.). John Wiley & Sons, 615.

4. Epishin, A., Link, T., Nazmy, M., et al. (2008). Microstructural degradation of CMSX-4: Kinetics and effect on mechanical properties. Proceedings of the International Symposium on Superalloys, 725–731.

5. Reed, R. C. (2006). The superalloys: Fundamentals and applications. Cambridge University Press, 372.

6. Paton, B. E. (1987). Zharoprochnost' liteynykh nikelevykh splavov i zashchita ikh ot okisleniya [Heat resistance of cast nickel alloys and their protection against oxidation]. Naukova Dumka, 256.

7. Koval, A. D., Belikov, S. B., Sanchugov, E. L., & Andrienko, A. G. (1990). Nauchnyye osnovy legirovaniya zharoprochnykh nikelevykh splavov, stoykikh protiv vysokotemperaturnoy korrozii (VTK) [Scientific foundations of alloying heat-resistant nickel alloys resistant to high-temperature corrosion]. UKMK VO, 56.

8. Bielikov, S. B. (1996). Rozvytok naukovykh pryntsypiv lehuvannia lyvarnykh zharomitsnykh nikelevykh splaviv z metoiu pidvyshchennia korozijnoi stijkosti detalei v umovakh vysokotemperaturnoho seredovyshcha hazoturbinnykh ustanovok [Development of scientific principles of alloying cast heat-resistant nickel alloys to improve the corrosion resistance of parts in the high-temperature environment of gas turbine installations] [Doctoral dissertation, Zaporizhzhia National Technical University], 439.

9. Koval, A. D., Belikov, S. B., & Sanchugov, E. L. (2001). Principles of alloying of high-temperature nickel alloys resistant to high-temperature corrosion. Metal Science and Heat Treatment, 43(9–10), 373–377. https://doi.org/10.1023/A:1013245225944, 9, 373–377.

10. Boguslaev, V. A., Muravchenko, F. M., Zhemanyuk, P. D., et al. (2007). Tekhnolohichne zabezpechennia ekspluatatsiinykh kharakterystyk detalei

DOI 10.15588/1607-6885-2025-4-2

HTD. Lopatky turbyny. Chastyna 2 [Technological assurance of operational characteristics of GTE parts. Turbine blades. Part 2]. Zaporizhzhia, 493.

11. Solntsev, Yu. P., Bielikov, S. B., Volchok, I. P., & Sheiko, S. P. (2010). Spetsialni konstruktsiini materialy [Special structural materials]. Valpis-Polihraf, 536.

12. Gaiduk, S. V., & Belikov, S. B. (2017). Nauchnyye osnovy proyektirovaniya liteynykh zharoprochnykh nikelevykh splavov s neobkhodimym kompleksom sluzhebnykh svoystv [Scientific basis for the design of cast heat-resistant nickel alloys with the necessary set of service properties]. Zaporizhzhia National Technical University, 79.

13. Gaiduk, S. V. (2018). Razvitiye i primeneniye nauchnykh printsipov legirovaniya dlya razrabotki zharoprochnykh nikelevykh splavov s garantirovannymi svoystvami [Development and application of scientific principles of alloying for the development of heat-resistant nickel alloys with guaranteed properties] [Doctoral dissertation, Zaporizhzhia National Technical University], 404.

14. Zhemanyuk, P. D., Klochikhin, V. V., Lysenko, N. A., & Naumik, V. V. (2015). Structure and properties of cast blades of aircraft engines made of heat-resistant nickel alloy ZhS26-VI after hot isostatic pressing. Bulletin of Engine Building, (1), 139–146.

15. Zhemanyuk, P. D., Pedash, A. A., Tsivirko, E. I., & Pedash, A. F. (2013). Combination of modification in the production of gas turbine engine parts. Bulletin of Engine Building, (1), 75–78.

16. Danilov, S., Pedash, O., Naumik, V., Tyomkin, D., & Naumik, O. (2024). Complex modification of a heat-resistant nickel alloy with dispersed parts of refractory joints. New Materials: Technologies in Metallurgy and Mechanical Eng, 4, 6–14.

17. Pedash, A. A., Bialik, G. A., & Tsivirko, E. I. (2015). Increasing the thermal conductivity of local ceramic molds with cobalt aluminate. Aviation and Space Technology and Technology, (10), 40–44.

Received 14.10.2025
Accepted 03.11.2025

СТРУКТУРА ТА ВЛАСТИВОСТІ ЖАРОМІЦНОГО СПЛАВУ ЖС-26ВІ ДЛЯ ВИРОБНИЦТВА ВІДПОВІДАЛЬНИХ ДЕТАЛЕЙ ГАЗОТУРБІННИХ ДВИГУНІВ

Сергій Пучек — аспірант кафедри транспортних технологій Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: puchek777@gmail.com*, ORCID: 0009-0007-8077-6106

Сергій Бєліков — д-р техн. наук, професор, професор кафедри транспортних технологій Національного університету «Запорізька політехніка», м. Запоріжжя, Україна, *e-mail: belikov@zp.edu.ua*, ORCID: 0000-0002-9510-8190

Мета роботи*. Вивчити макро- та мікроструктурний стан серії дослідницьких зразків жароміцного сплаву ЖС26-ВІ для виробництва критичних компонентів газотурбінного двигуна, а саме роторних лопаток турбіни високого тиску (ТВТ), та оцінити механічні властивості та жароміцність у відповідності до технічних специфікацій матеріалів гарячої частини газової турбіни.*

Методи дослідження*. Макро- і мікроструктурний аналіз та дослідження фазового складу проводили методом оптичної металографії на оптичному мікроскопі. Механічні властивості при кімнатній температурі визначали у відповідності до ISO 6892-84 та СТ СЭВ 471-88. Випробування на розрив здійснювали на машині ZDMY30.*

Отримані результати*. Проведено дослідження структури та властивостей зразків дослідних плавок сплава ЖС-26ВІ, отриманих у вакуумній печі FM-1-2-100 фірми «ULMAC» методом рівновісної кристалізації. Установлене суттєве подрібнення макрозерна за рахунок інтенсивного тепловідводу та високої швидкості кристалізації. Мікроструктура зразків до термічної обробки відповідає литому стану сплава, а після термообробки по стандартному режиму задовольняє технічні умови та відповідає затвердженій шкалі мікроструктури. Механічні та жароміцні властивості зразків відповідають вимогам нормативної документації до відповідального жароміцного лиття.*

Наукова новизна*. Одержано нові дані щодо структури та фазового стану сплаву ЖС26-ВІ дослідних та серійних плавок. Вивчено тонку будову жароміцного сплаву на основі нікелю, що традиційно використовується для отримання лопаток турбіни високого тиску газотурбінного двигуна авіаційного призначення.*

Практична цінність*. Отримані результати надають можливість розширити використання жароміцного сплаву ЖС26-ВІ для виробництва виливків відповідального призначення.*

Ключові слова*: жароміцний сплав, макро- та мікроструктура, термічна обробка, механічні властивості, жароміцність, лопатка газової турбіни.*

DOI 10.15588/1607-6885-2025-4-2

Список літератури

1. Development of Ni Base Superalloy for Industrial Gas Turbine [Text] / I. Okada, T. Torigoe, K. Takahashi, D. Izutsu // Proceedings of the International Symposium on Superalloys. – 2004. – P. 707–712.

2. High temperature materials for aerospace applications: Ni-based superalloys and γ- TiAl alloys / M. Perrut, P. Caron, M. Thomas, A. Couret // Comptes Rendus Physique. – 2018. – No. 19. – P. 657–671.

3. Sims, Ch.T. Superalloys II: High-Temperature Materials for Aerospace and Industrial Power (2nd edition) [Text] / Ch.T. Sims, Norman S. Stoloff, William C. Hagel. - New York: John Wiley & Sons, 1987. – 615 p.

4. Microstructural Degradation of CMSX-4: Kinetics and Effect on Mechanical Properties / A. Epishin, T. Link, M. Nazmy et al. // Proceedings of the International Symposium on Superalloys. – 2008. - P. 725–731.

5. Reed R. C. The Superalloys: Fundamentals and Applications / R. C. Reed. – Cambridge, University Press. - 2006. – 372 p.

6. Патон Б. Е. Жаропрочность литейных никелевых сплавов ы защита их от окисления. - К., Наукова думка. – 1987. – 256 с.

7. Научные основы легирования жаропрочных никелевых сплавов, стойких против высокотемпературной коррозии (ВТК): Научное издание – препринт / А. Д. Коваль, С. Б. Беликов, Е. Л. Санчугов, А. Г. Андриенко, ЗМИ. – К. : УМК ВО, 1990. – 56 с.

8. Бєліков С. Б. Розвиток наукових принципів легування ливарних жароміцних нікельових сплавів з метою підвищення корозійної стійкості деталей в умовах високотемпературного середовища газотурбінних установок : дис. докт. техн. наук: 05.02.01 / С. Б. Бєліков. – Запоріжжя :ЗНТУ, 1996. – 439 с.

9. Koval A.D. Principles of Alloying of High-Temperature Nickel Alloys Resistant to High-Temperature Corrosion / A. D. Koval, S. B. Belikov, E. L. Sanchugov // Metal science and heat treatment. – 2001. – No. 9–10. – P. 373–377.

10. Технологическое обеспечение эксплуатационных характеристик деталей ГТД. Лопатки турбины. Часть 2: монография [Текст] / Богуслаев В. А., Муравченко Ф. М., Жеманюк П. Д. и др. – Запорожье, 2007. – 493 с.

11. Спеціальні конструкційні матеріали : підручник / Ю. П. Солнцев, С. Б. Бєліков, І. П. Волчок, С. П. Шейко; ред.: І. П. Волчок. – Запоріжжя : Валпіс-Поліграф, 2010. – 536 с.

12. Гайдук, С. В. Научные основы проектирования литейных жаропрочных никелевых сплавов с необходимым комплексом служебных свойств / С. В. Гайдук, Беликов С. Б. – Запорожье, ЗНТУ. – 2017. – 79 с.

13. Гайдук, С. В. Развитие и применение научных принципов легирования для разработки жаропрочных никелевых сплавов с гарантированными свойствами [Текст]: дис. д-ра техн. наук: 05.02.01 / Гайдук С.В. Запорож. нац. техн. ун-т.- Запорожье, 2018. – 404 с.

14. Structure and properties of cast blades of aircraft engines made of heat-resistant nickel alloy ZhS26-VI after hot isostatic pressing / P. D. Zhemanyuk, V. V. Klochikhin, N. A. Lysenko, V. V. Naumik // Bulletin of Engine Building. – 2015. – No. 1. – P. 139–146.

15. Combination of modification in the production of gas turbine engine parts [Text] / P. D. Zhemanyuk, A. A. Pedash, E. I. Tsivirko, A. F. Pedash // Bulletin of Engine Building. – 2013. – No. 1. – P. 75–78.

16. Complex modification of a heat-resistant nickel alloy with dispersed parts of refractory joints [Text] / S. Danilov, O. Pedash, V. Naumik, D. et al. // New materials: technologies in metallurgy and mechanical engineering. – 2024. – No. 4. – P. 6–14.

17. Pedash A. A. Increasing the thermal conductivity of local ceramic molds with cobalt aluminate [Text] / A. A. Pedash, G. A. Bialik, E. I. Tsivirko //Aviation and space technology and technology. – 2015. – No. 10. – P. 40–44.

DOI 10.15588/1607-6885-2025-4-2