КОНСТРУКЦІЙНІ І ФУНКЦІОНАЛЬНІ МАТЕРІАЛИ

STRUCTURAL AND FUNCTIONAL MATERIALS

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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

STUDY OF THE STRUCTURE AND PROPERTIES OF WORKING BLADES OF AIRCRAFT GAS TURBINE ENGINES MADE OF HEAT-RESISTANT NICKEL ALLOY ZhS26-VI

Purpose. *To study the macro- and microstructural condition of VK-2500 gas turbine engine rotor blades in their original condition and after various processing stages. To evaluate their mechanical properties and long-term strength.*

Research methods*. The material quality of first-stage gas turbine engine rotor blades made of Zhs26-VI heat-resistant nickel alloy was studied in their original condition and after hot isostatic pressing (HIP), as well as after HIP and standard heat treatment. Luminescence testing of the blades was performed using the LUM1-OV method. Microstructure examination was performed using optical microscopy (Neophot-32 microscope) and scanning electron microscopy (JSM T-300 microscope).*

Mechanical properties at room temperature were determined in accordance with ISO 6892-84 and ST SEV 471-88, and heat resistance parameters were determined in accordance with DSTU ISO 204:2019.

Results*. Metallographic studies revealed that the microstructure of the rotor blades is single-crystalline, with the main structural components being: γ'- solid solution with the presence of the intermetallic γ'- phase, the eutectic (γ-γ') phase, carbides, and carbonitrides. A reduction in the size of the structural components is observed in the microstructure of the blades after HIP.*

Scientific novelty*. New data on the structure and phase composition of the rotor blade material for aircraft gas turbine engines have been obtained. Heat treatment under standard conditions after HIP corresponds to almost complete recrystallization of the strengthening intermetallic γ'- phase, which consists of dissolution of the γ'- phase in the γ- matrix and its re-precipitation as dispersed particles of cubic morphology.*

Practical value*. It has been shown that hot isostatic pressing in combination with standard heat treatment provides the most favorable combination of strength and ductility properties, as well as long-term durability of blades.*

Key words*: superalloys, gas turbine blades, homogenization, hot isostatic pressing, intermetallic γ'-phase.*

Introduction

The development of aircraft and stationary gas turbine engineering requires improved performance parameters for gas turbine engines (GTEs), specifically turbine inlet temperatures, increased specific power, and increased efficiency and service life [1].

The reliability and durability of a GTE primarily depend on the performance parameters of the materials used to manufacture the most critical GTE components – the rotor blades and nozzle vanes. Heat-resistant nickel-based alloys are the most common materials used to manufacture these components. Such materials are typically referred to as “superalloys” [2–7].

Technological support for the performance characteristics of GTE components shapes approaches to achieving the required material parameters for GTEs [8–10]. For modern GTEs, the optimal material for both cooled and uncooled rotor blades is high-strength cast nickel alloys, one of which is the ZhS26-VI alloy [10, 15].

One of the characteristic defects of the cast structure of blades with very complex geometry is the presence of internal shrinkage defects [13]. Hot isostatic pressing (HIP) is often used to eliminate such defects [12, 14].

Material and Methodology

The chemical composition of the experimental alloys was determined using a spectral analyzer on an ARL-4460 quantometer.

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The material quality of first-stage rotor blades for the VK-2500 gas turbine engine, cast from ZhS26-VI heat-resistant nickel alloy using high-speed directional solidification (HSDS), was studied:

Variant “1” – after hot isostatic pressing (HIP);

Variant “2” – after HIP and heat treatment using the standard procedure (homogenization at 1265±10°C for 1 hour 15 minutes, vacuum).

The studies were compared to similar blades without the HIP procedure – variant “0”.

The HIP process was conducted under actual production conditions at Motor Sich JSC using the following procedure [10]:

- Initial pressure in the high-pressure furnace: 51 MPa;
- Heating from room temperature to T=1040±10 °C at a rate of 90 °C/min;
- Holding at 1040 °C for 1 hour;
- Pressure in the high-pressure furnace at 1040 °C: 120 MPa;
- Heating to 1250±10 °C at a rate of 5 °C/min;
- Holding at 1250±10 °C for 1.5 hours;
- Pressure in the high-pressure furnace at 1250 °C: 170 MPa;
- Cooling of castings to 800 °C at a rate of 30 °C/min.

The chemical composition of the rotor blades received for testing (variant “0”, “1”, and “2”) is presented in Table 1.

Luminescence testing of the root axial section and the airfoil cross-section was performed using the LUM1-OV method.

Microstructure was examined using optical (Neophat-32 microscope) and scanning electron microscopy (JSM T-300 microscope) on unetched and etched microsections cut from rotor blades.

The state of the strengthening intermetallic γ′- phase in the axes and interaxial spaces of the airfoil and airfoil dendrites of rotor blades tested in variants “0”, “1” and “2” was studied on microsections after electrolytic etching in a reagent consisting of 80 ml of H_3PO_4 and 10g of CrO_3, using a JSM T-300 scanning electron microscope.

Mechanical properties at room temperature (tensile strength, relative elongation and contraction) were determined in accordance with DSTU ISO 6892-84 and ST SEV 471-88, and heat resistance indicators in accordance with DSTU ISO 204:2019 on a DST-500 test bench at a temperature of 975 °C and a load of 260 MPa until complete destruction.

Research Results

Inspection of the blades received for testing revealed that the blade surfaces before HIP (variant “0”) and after HIP and heat treatment (variant “2”) had a light gray matte color (Fig.1*a*, *b*, *d*, *e*, *f*). After HIP (variant “1”), the blade surfaces were dark gray (Fig.1c, d).

A metallographic examination of the blade surfaces after hot isostatic pressing (variant “1”) revealed dark-gray non-metallic inclusions, characteristic for oxides, penetrating to a depth of ~10 μm (Fig. 2).

The blade surfaces before HIP (variant “0”) and after HIP + heat treatment at 1265 °C (variant “2”) show virtually no oxidation. The absence of oxidation on the surfaces of parts processed using variant 2 is due to the use of micropowder blasting on the outer surface during preparation of the blades for heat treatment, as well as vacuum cleaning of the surface during high-temperature vacuum treatment after HIP.

X- ray spectral microanalysis (XSMA) of rotor blades in their original cast condition (before HIP, without heat treatment – Fig. 3), and those after HIP (without subsequent heat treatment – Fig. 4) showed that the oxygen, aluminum, titanium, and carbon content on the surfaces of the parts after HIP is approximately three times higher than the concentrations of these elements on the surfaces of the original blades (before HIP). The increase in the concentrations of these elements on the surface of blades that underwent HIP indicates oxidation due to the use of insufficiently pure argon during the HIP process.

Furthermore, the simultaneous application of high temperatures (1250 °C) and pressures (170 MPa) during isostatic pressing leads to intense diffusional mass transfer of aluminum and titanium atoms from the center to the surface, forming layers enriched with these elements on the alloy surface. This is also consistent with literature data on the diffusion of aluminum and titanium in nickel [4].

Luminescence testing using the LUM1-OV method in the axial section of the root and the cross-section of the airfoil of the incoming blades revealed that the blades before HIP exhibited a glow in the form of multiple small, brightly luminous dots (Fig. 5*a*, *b*). No phosphor glow was detected in similar sections of blades after HIP (Fig. 5*c*, *d*, *e*).

Metallographic examination revealed that the microstructure of the rotor blades submitted for examination is single-crystal. The main structural components are a γ-solid solution with the presence of intermetallic γ′-phase, a eutectic phase (γ-γ′), carbides, and carbonitrides (Figure 6).

Table 1 – Chemical composition of the rotor blades tested, made of ZhS26-VI alloy

Variant	Contents of elements, %										
	C	Cr	Co	W	Al	Ti	Mo	Fe	Nb	Si	V
0	0,15	4,68	8,95	12,00	6,10	0,89	1,04	<0,5	1,48	<0,2	1,04
1	0,14	4,77	9,03	11,72	6,10	0,90	0,91	<0,5	1,46	<0,2	0,91
2	0,14	4,76	9,07	11,59	5,94	0,90	0,99	<0,5	1,46	<0,2	0,99
Norms ТУ1-92-177-91	0,12-0,18	4,3-5,6	8,0-10,0	10,9-12,5	5,5-6,2	0,8-1,2	0,8-1,4	≤ 1,0	1,4-1,8	≤ 0,3	0,8-1,2

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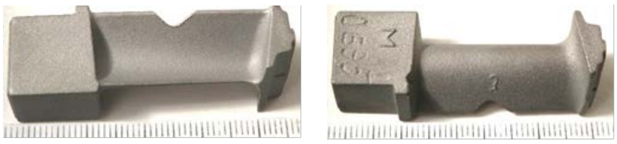
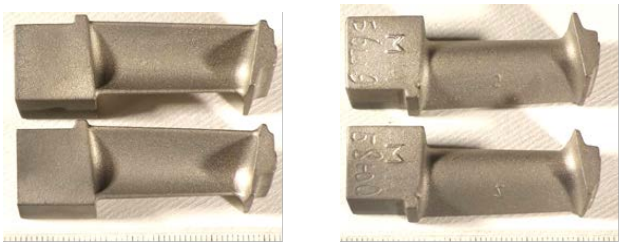


***a* – from the side of the trough** before HIP – variant “0” ***b* – from the back**

c – from the side of the trough **after HIP – variant “1”** *d* – from the back



e – from the side of the trough **after HIP + HT – variant “2”** *f* – from the back

Figure 1. External appearance of rotor blades before (*a*, *b*) and after (*c*, *d*) hot isostatic pressing (HIP), as well as after HIP and subsequent heat treatment at 1265 °C (vacuum) (*e*, *f*)

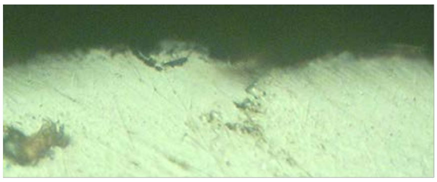
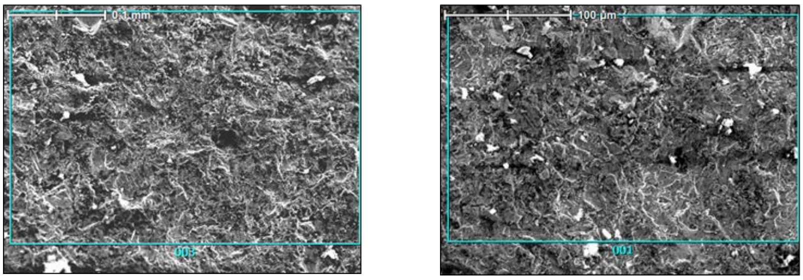


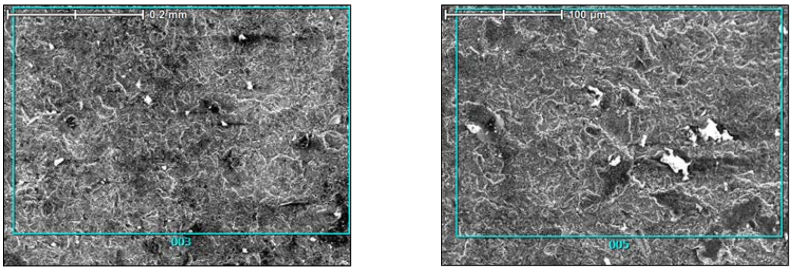
Figure 2. Microstructural condition of the rotor blade surface after HIP – variant “1”, ×650



a – ×350 *b* – ×450

№ points	C	O	Al	Ti	V	Cr	Co	Ni	Nb	Fe	Mo	W
001	5,09	5,56	13,89	1,71	0,90	4,54	8,05	54,06	0,83		1,15	4,23
003	5,31	6,92	14,64	1,88		5,75	7,76	48,89		2,19	1,09	5,57

Figure 3. Results of X- ray microanalysis of the surface of a working blade made of ZhS26-VI(HSDS) alloy before the HIP operation: *a* – blade root; *b* – blade airfoil



a – ×350 *b* – ×450

№ points	C	O	Al	Ti	V	Cr	Co	Ni	Nb	Mo	W
003	4,87	17,00	33,50	16,91	1,69	6,07		9,12	6,35	1,13	3,35
005	5,37	19,59	31,65	16,78	2,87	3,52	0,86	8,46	6,76	1,60	2,56

Figure 4. Results of X-ray microanalysis of the surface layer of a working blade made of ZhS26-VI(HSDS) alloy after the HIP operation: *a* – blade root; *b* – blade airfoil

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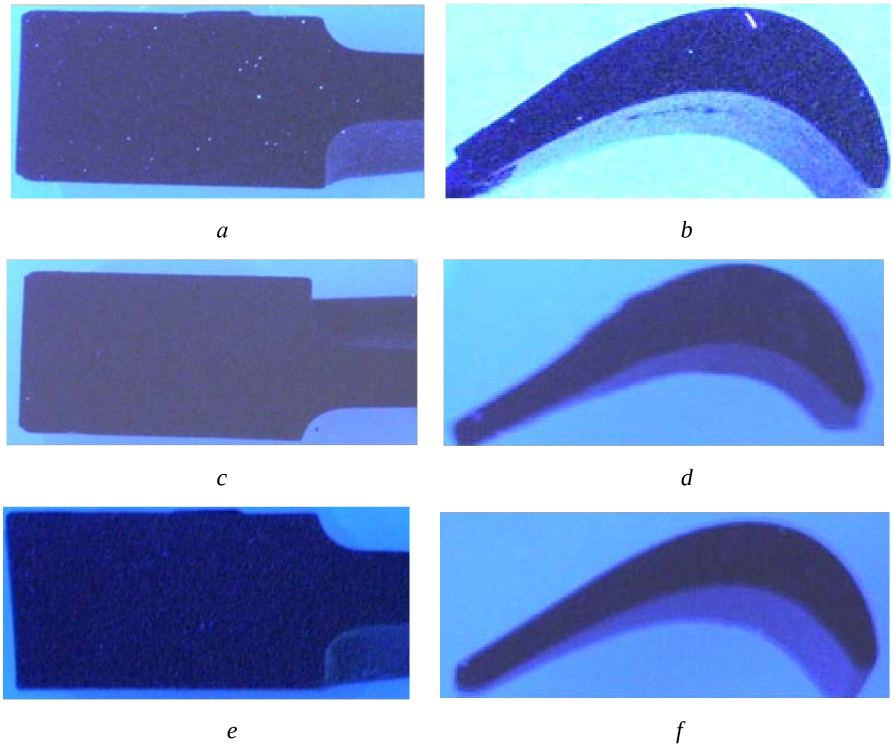

Figure 5. External appearance of rotor blades in the axial section of the root section (*a*, *c*, *e*) and in the cross-section of the airfoil (*b*, *d*, *f*) under a radiation source:
a, *b* – variant “0” – before HIP; *c*, *d* – variant “1” – after HIP; *e*, *f* – variant “2” – after HIP and heat treatment

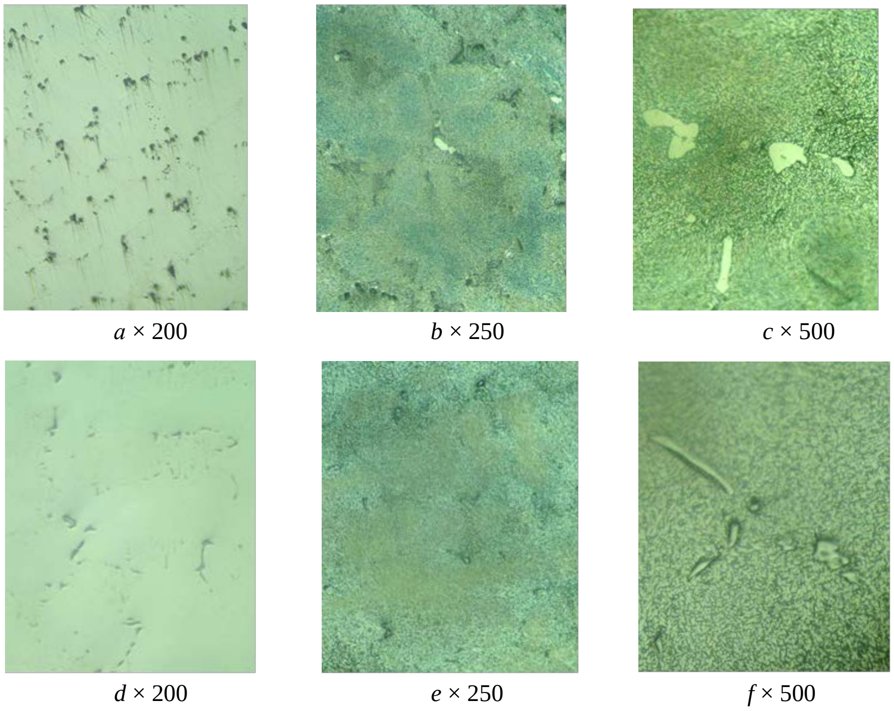
a × 200 *b* × 250 *c* × 500
d × 200 *e* × 250 *f* × 500

Figure 6. Microstructure of a rotor blade before the HIP operation – variant “0”: *a*, *b*, *c* – airfoil; *d*, *e*, *f* – root

The microstructure of rotor blades after HIP shows a reduction in the size of the structural components compared to the blades before the HIP operation. The size of the structural components, as well as the distance between the axes of the second-order dendrites in the blade airfoil, differs slightly from the microstructure parameters in the root section (Table 2).

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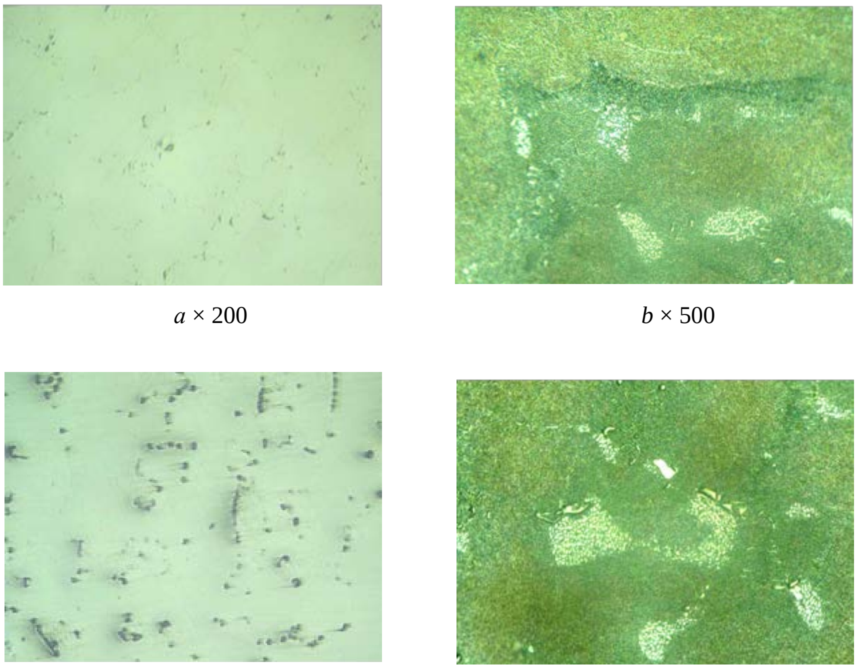
A microstructural study revealed that during hot isostatic pressing (HIP) at 1250 °C and 170 MPa (variant 1), significant dissolution and recrystallization of the eutectic phase (γ-γ′) occurred. Coagulated γ′- phase particles were observed in the interdendritic spaces. The microstructure of the rotor blade material after HIP is satisfactory, corresponding to the approved microstructure scale without overheating (Figure 7).

During a microstructural study using optical and scanning electron microscopy on etched microsections cut from rotor blades that had undergone the HIP operation (variant "1"), crater-shaped zones in the form of concentrically located elongated particles of the strengthening intermetallic γ´-phase, characteristic of a "raft" structure [10] (Figure 8), were identified in areas of complete or partial "healing" of micropores. Similar areas characterized by the formation of a "raft" structure were also found around some MC-type carbides (Figure 9). It was found that, as the center of these regions approaches, corresponding to the direction of the resulting stresses, an increase in the density and distortion of intermetallic particles, whose size ranges from 0.22 to 0.27 µm, is observed. Consequently, as a result of plastic deformation initiated by the hot isostatic pressing process, the concentration of distortions of structural components within the local volume of the material, in zones adjacent to micropores, carbides, etc., increases significantly.

Table 2 – Parameters of the structural components of rotor blades made of ZhS26-VI(HSDS) alloy

Material condition		Dimensions of structural components, µm			
		carbides		eutectic type (γ-γ′)	micropores
		globular type MS	eutectic type M$_6$C		
original (without HIP) before heat treatment	airfoil	2…6	8…15 (single up to 35)	8…14	6…43
	root	3…15	10…18 (single up to 40)	8…16	10…60
after HIP without heat treatment	airfoil	1,5…8	8…14 (single up to 28)	6…12	-
	root	2…12	8…16 (single up to 30)	8…15	-
after HIP without heat treatment heat treatment	airfoil	1,5…6	6…14 (single up to 20)	4…10	-
	root	2…12	8…16 (single up to 35)	5…14	-



a × 200 *b* × 500

c × 200 *d* × 500

Figure 7. Microstructure of the airfoil (*a*, *b*) and root (c, d) of a rotor blade after HIP – variant "1": *a*, *c* – before etching; *b*, *d* – after etching

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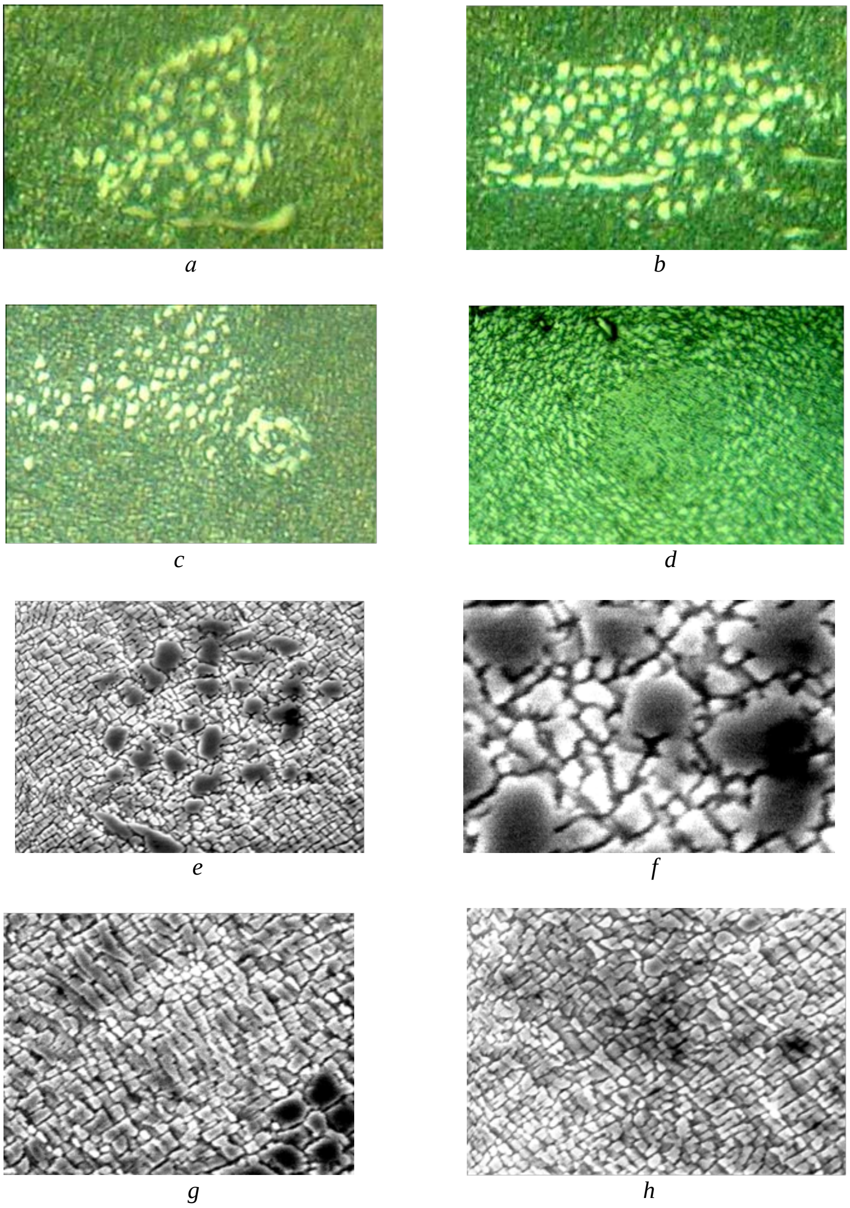
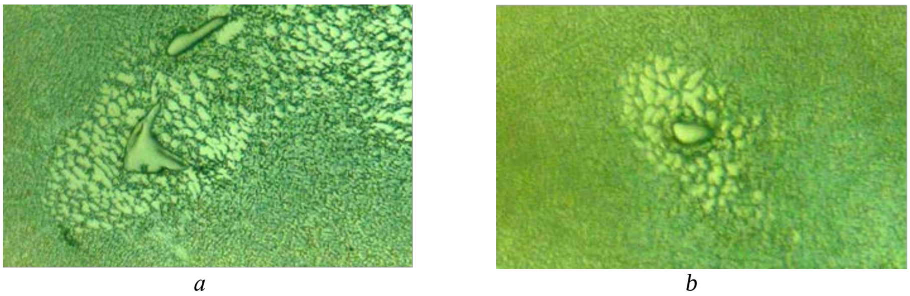


a *b* *c* *d* *e* *f* *g* *h*

Figure 8. “Raft” structure in the material of working blades after the HIP operation in the areas of “healing” of micropores: *a*, *b*, *c*, *d* – optical microscopy – × 700; *e*, *f*, *g*, *h* – scanning electron microscopy – × 7500



a *b*

Figure 9. “Raft” structure in rotor blade material after HIP around MC-type carbides, × 700

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In the “healed” zones of micropores, along with small intermetallic particles, a cluster of coagulated elongated γ΄-phase particles measuring 1.1–2.2 μm is also observed.

The size of individual micropores detected after HIP does not exceed ~ 0.2 μm, which is approximately 100–300 times smaller than the pores found in the blades before HIP. Heat treatment according to the standard mode after gas-static treatment (variant “2”) promotes almost complete recrystallization of the strengthening intermetallic γ′-phase, which consists of dissolution of the γ′- phase in the γ′- matrix and its repeated precipitation in the form of dispersed particles of cubic morphology with the presence of a small amount of coagulated intermetallic γ′- phase precipitated in the interdendritic spaces (Figure 10).

The study of the state of the strengthening intermetallic γ′- phase in the axes and interaxial spaces of the airfoil and root dendrites of rotor blades processed according to variants “0”, “1”, and “2” revealed that in the original material of cast blades (before HIP), the γ′- phase particles have a cubic morphology and form blocks consisting of four particles. The size of the γ- particles, measured along the side of a square equivalent in area, in the dendrite axes is mainly 0.38...0.57 μm (Fig. 11*a*; Table 3). In the interaxial spaces of the dendrites, along with γ′- particles measuring ~ 0.6 μm, there is a significant amount of coagulated phase up to 1.5 μm (Figure 11*b*).

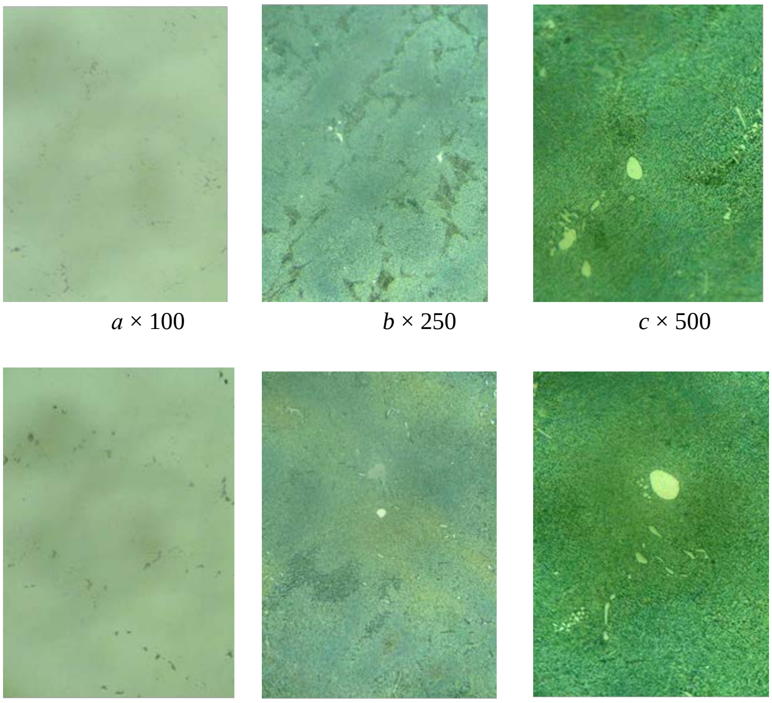
No significant differences in the morphology and size of the intermetallic phase precipitated in the blade's root compared to its airfoil are observed.

In the blade structure after isostatic pressing, a refinement of the intermetallic γ′- phase is observed (Fig. 11*c*, *d*). The size of the γ′- particles is approximately half that of the original alloy (see Table 3). In the blade material after isostatic pressing, the precipitation of a small amount of γ′-phase microparticles measuring 0.07–0.1 μm was detected, as well as zonal interdendritic precipitates of coagulated intermetallic particles reaching 2.57 μm in size.

During homogenization at 1265 °C for 1 hour 15 minutes, carried out after the isostatic pressing operation, the particle sizes of the γ′- intermetallic phase in the axes and interaxial spaces of the dendrites were equalized (Fig. 11*e*, *f*). It should be noted that the alloy structure retains zonal areas with the presence of coagulated γ′- particles measuring 1.1...2.86 μm, located between the axes (Fig. 12). The mechanical and heat-resistant properties were determined on unheat-treated samples (Ø15 mm; L=135 mm), cast using the directional solidification method, as well as after heat treatment according to the standard mode (homogenization at a temperature of 1265±10 °C for 1 hour 15 minutes). The results of mechanical tests and long-term strength tests are presented in Table 4.

Heat treatment according to the standard mode after HIP (variant “2”) promotes increased ductility of the alloy, while maintaining its strength and heat-resistant properties, which is due to an increase in the structural homogeneity of the alloy and the relaxation of stresses induced during hot isostatic pressing.

The most favorable combination of strength and ductility characteristics, as well as long-term strength, was achieved in samples processed using the second method (HIP + standard heat treatment).



a × 100 *b* × 250 *c* × 500

d × 100 *e* × 250 *f* × 500

Figure 10. Microstructure of rotor blades after HIP and heat treatment – variant “2”: *a*, *b*, *c* – airfoil; *d*, *e*, *f* – root

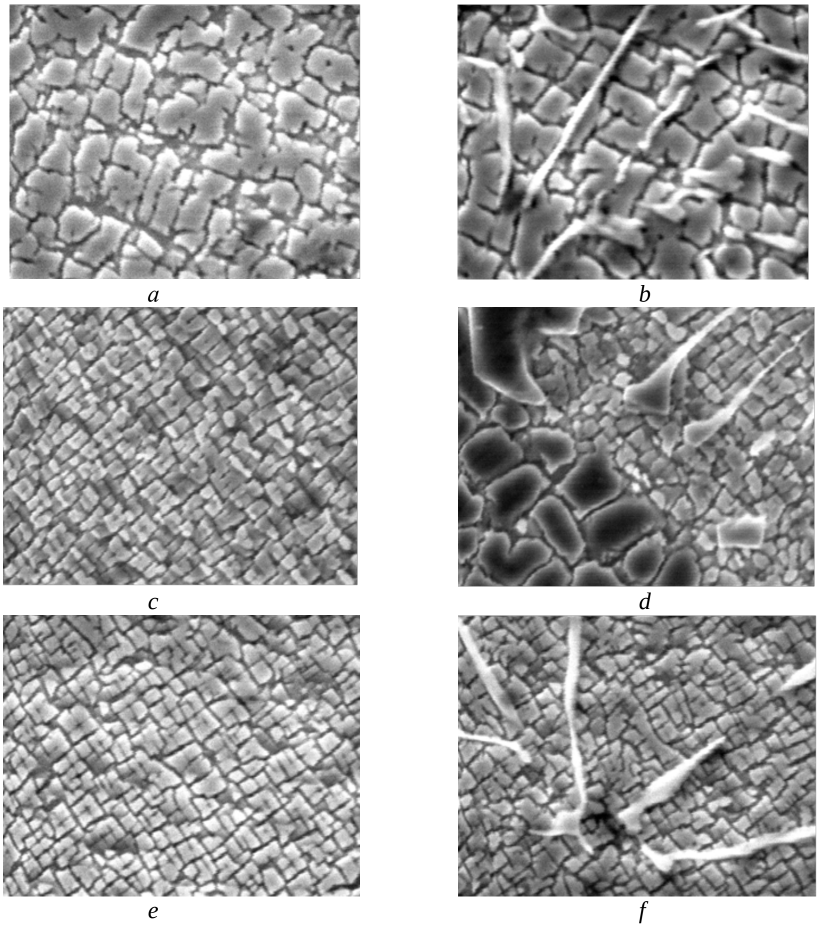


Figure 11. State of the intermetallic γ'- phase in the axes (a, c, e) and interaxial spaces of dendrites (*b*, *d*, *f*) of rotor blades cast from the ZhS26-VI (HSDS) alloy, × 10000:

a, *b* – before the HIP operation (without heat treatment) – variant “0”; *c*, *d* – after the HIP operation (without heat treatment) – variant “1”; *e*, *f* – after the HIP operation and heat treatment –variant “2”

Table 3 – Sizes of γ'-phase particles in the material of rotor blades made of the ZhS26-VI alloy, manufactured in accordance with variants “0”, “1”and “2”

Measurement area		Particle size of the particles γ'-phase, μm		
		before HIP	after HIP	after the HIP + HT
airfoil	axes	0,35…0,52	0,20…0,27 (microparticles – 0.07…0.09 μm)	0,20…0,25
	interaxle	0,058…0,93 (coagulated particles – up to 1.5 microns)	0,24…0,50 (microparticles – 0.08…0.1 μm)	0,22…0,38 (coagulated particles – 1.1…2.8 μm)
root	axes	0,38…0,57	0,21…0,29 (microparticles – 0.07…0.09 μm)	0,21…0,25
	interaxle	0,06…1,0 (coagulated particles – up to 1.5 microns)	0,24…0,57 (microparticles – 0.08…0.1 μm)	0,24…0,38 (coagulated particles – 1.1…2.86 μm)

Figure 13 shows the fractographic structure of fractures obtained during tensile testing of specimens cast from the ZhS26-VI(HSDS) alloy – before the HIP operation, after HIP, and after HIP and standard heat treatment. It was established that fracture of the specimens processed according to different options during testing occurred along the [001] crystallographic plane.

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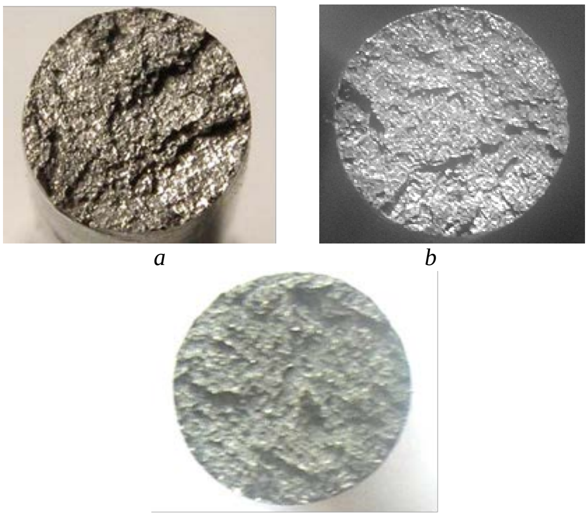
Table 4 – Mechanical and heat-resistant properties of the ZhS26-VI alloy before and after hot isostatic pressing

Material condition	Mechanical properties at t=20°C			Time to failure ($T_{исп.}$=975 °C, и σ= 260 MPa), τ_r, hours
	$\sigma_в$, MPa	δ, %	Ψ, %	
original (without HIP) without heat treatment	96,5	6,0	-	70^{20}
original (without HIP) after standard heat treatment	92,5 120,7	24,0 12,8	18,5 10,7	54^{30} 59^{30}
after HIP	103,2 104,3	6,4 6,2	8,99 9,36	57^{30} 57^{00}
after hot-pressing and standard heat treatment	102,8 102,9	8,0 11,2	11,2 11,6	56^{00} 63^{00}
Norms Н28ТУ-190	≥ 85,0	≥ 6,0	-	≥ 40,0



a *b*

c

Figure 13. Fracture structure of specimens cast from the ZhS26-VI (HSDS) alloy:

a – before the HIP operation (variant “0”); *b* – after the HIP operation (variant “1”); *c* – after the HIP operation and heat treatment (variant “2”)

Conclusions

1. Hot isostatic pressing (HIP) at 1250°C and 170 MPa (Variant 1) improves the quality of turbine blade castings made from ZhS26-VI (HSDS) alloy by stabilizing the structure and properties due to a reduction in microporosity during pore healing.

2. Heat treatment using the standard regime (homogenization at 1265 °C for 1 hour 15 minutes) after overpressure treatment (Variant 2) improves the structural homogeneity of the alloy and relaxes stresses induced during HIP, which has a positive effect on the ductility of the alloy while maintaining its strength and heat-resistant properties.

3. Processing according to the 2nd option (HIP + homogenization at a temperature of 1265 °C for 1 hour 15 minutes) ensures the most favorable combination of strength and plasticity characteristics, as well as long-term strength.

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ДОСЛІДЖЕННЯ СТРУКТУРИ ТА ВЛАСТИВОСТЕЙ РОБОЧИХ ЛОПАТОК АВІАЦІЙНИХ ГАЗОТУРБІННИХ ДВИГУНІВ ІЗ ЖАРОМІЦНОГО НІКЕЛЕВОГО СПЛАВУ ЖС26-ВІ

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 робочих лопаток газотурбінного двигуна ВК-2500 у вихідному стані та після різної технологічної обробки. Оцінити рівень механічних характеристик і тривалої міцності.*

Методи дослідження. *Досліджували якість матеріалу робочих лопаток 1-го ступеня ГТД із жароміцного нікелевого сплаву ЖС26-ВІ у вихідному стані та після гарячого ізостатичного пресування (ГІП), а також після ГІП і стандартної термічної обробки. Люмінесцентний контроль лопаток здійснювали методом ЛЮМ1-ОВ. Дослідження мікроструктури проводили методами оптичної (мікроскоп «Neophot-32») та растрової електронної мікроскопії (мікроскоп «JSM T-300»). Механічні властивості при кімнатній температурі визначали відповідно до ISO 6892-84 та СТ РЕВ 471-88, а показники жароміцності – відповідно до ДСТУ ISO 204:2019.*

Отримані результати. *Металографічними дослідженнями встановлено, що мікроструктура робочих лопаток є монокристалічною з основними структурними складовими: γ'- твердий розчин із наявністю інтерметалідної γ'- фази, евтектичної (γ-γ') фази, карбідів і карбонітридів. У мікроструктурі лопаток після ГІП спостерігається зменшення розмірів структурних складових.*

Наукова новизна. *Отримано нові дані про структуру та фазовий склад матеріалу робочих лопаток авіаційного ГТД. Термічна обробка за стандартним режимом після ГІП забезпечує практично повну перекристалізацію зміцнювальної інтерметалідної γ'- фази, що полягає у розчиненні γ'- фази в γ- матриці з повторним її виділенням у вигляді дисперсних частинок кубічної морфології.*

Практична цінність. *Показано, що гаряче ізостатичне пресування у комбінації зі стандартною термічною обробкою забезпечує отримання найбільш сприятливого поєднання міцнісних і пластичних характеристик, а також тривалої міцності лопаток.*

Ключові слова: *суперсплави, лопатки газової турбіни, гомогенізація, гаряче ізостатичне пресування, інтерметалідна γ'- фаза.*

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