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# КОНСТРУКЦІЙНІ І ФУНКЦІОНАЛЬНІ МАТЕРІАЛИ

# STRUCTURAL AND FUNCTIONAL MATERIALS

UDC 669.715:669.018.25:620.186

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# ASSESSMENT OF THE STRUCTURE AND PROPERTIES OF THE HEAT-RESISTANT NICKEL ALLOY ZHS32-VI AS A MATERIAL FOR THE MANUFACTURING OF GAS TURBINE ENGINE BLADES

***Purpose.*** *To study the macro- and microstructural state of pilot heat-resistant alloy ZhS32-VI casts for the production of critical gas turbine engine components and to evaluate their mechanical properties and heat resistance.*

***Research methods.*** *Structural stability parameters were assessed using the well-known PHACOMP and New PHACOMP calculation methods. Macro- and microstructural analysis and phase composition studies were performed using optical metallography. Mechanical properties at room temperature were determined in accordance with ISO 6892-84 and ST SEV 471-88, while creep-rupture strength tests were conducted in accordance with DSTU ISO 204:2019.*

***Results.*** *The structure and properties of ZhS32-VI alloy specimens produced in a ULMAC FM 1-2-100 vacuum furnace using equiaxed crystallization were studied. The microstructure of the specimens before heat treatment corresponded to the as-cast state of the alloy, and after heat treatment, it met the technical specifications and conformed to the approved microstructure scale. Mechanical properties and heat resistance meet the requirements of technical documentation for critical heat-resistant castings.*

***Scientific novelty.*** *New data on the structure and phase composition of the heat-resistant alloy ZhS32-VI alloy from pilot heats were obtained. Calculation and analytical evaluation method confirmed a high level of structural stability.*

***Practical value.*** *The obtained results provide an opportunity to expand the application of the ZhS32-VI heat-resistant nickel alloy for the production of critical castings.*

***Key words:*** *heat-resistant alloy, macro- and microstructure, mechanical properties, heat resistance, homogenization.*

## Introduction

Cast blades are the most critical components of a gas turbine engine, converting the kinetic energy of hot gases into propulsive power for the rotor shaft and power units [1].

Gas turbine engine blades operate under harsh conditions, subject to the simultaneous effects of centrifugal force from their own mass and transverse aerodynamic forces generated by the gas flow in the turbine in an aggressive environment at high temperatures reaching 0.8 $T_m$ [2].

As research results [3] indicate, during operation of rotor blades, there is a constant combined effect of tensile forces, dynamic and static vibration loads. The total (equivalent) loads in the first-stage blades are approximately 120 MPa. Furthermore, the load is also distributed unevenly across the rotor blade profile, with maximum equivalent values at the midsection. A temperature gradient also exists across the blade height and cross-section [4]. These operating conditions determine a set of requirements for materials used in the manufacture of gas turbine blades. High short-term and long-term strength, ductility, fatigue resistance, and structural and properties stability throughout the entire service life are essential. The requirement for the ability to repeatedly restore the structure and properties is economically justified [5].

Achieving the required performance indicators for gas turbine engines is ensured by the use of heat-resistant nickel alloys, or “superalloys” as defined by foreign authors [1, 6–8], for the manufacture of critical gas turbine engine components, primarily nozzle and rotor blades.

For modern gas turbine engines, high-strength nickel alloys are the optimal material for rotor and nozzle blades [2, 9, 10]. An example of such an alloy is the heat-resistant nickel alloy ZhS32-VI [11].

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## Material and Methodology

Experimental melts of the heat-resistant nickel alloy ZhS32-VI were conducted at Motor Sich JSC’s industrial production facilities using a modern FM-1-2-100 vacuum melting unit from ULVAC (Japan). Cast alloy blanks were produced by pouring liquid metal into 80mm-diameter metal molds. The initial melts' blanks had an equiaxed grain structure.

To test the alloy for compliance with the mechanical properties and long-term strength requirements of TU 1-92-177, specimens were produced using investment casting in UNVK-8P and UNVK-9A vacuum melting units. The cast specimens had a directional or single-crystal structure. Fresh charge materials (nickel, chromium, molybdenum, tungsten, rhenium, and tantalum) were used in the production of ZhS32-VI heat-resistant alloys using high-temperature melt processing.

The resulting cast samples were heat-treated by homogenization in a protective atmosphere (in a dynamic vacuum) at a temperature of 1270±10 °C, held for 1 hour and 15 minutes, and cooled at a rate equivalent to air cooling.

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

The macrostructure of the samples was revealed by chemical etching in a reagent containing 25 % $HNO_3$, 25 % HF, and 50 % water. The microstructure was evaluated on microsections before and after etching in Marble reagent (4 g $CuSO_4$, 20 mg HCl, 20 mg water) using a Carl Zeiss optical microscope at magnifications of ×20, ×500, and ×1000.

The short-term and long-term mechanical properties of the samples (tensile strength, high-temperature strength, relative elongation, and narrowing) were determined after heat treatment using the standard mode.

Mechanical properties at room temperature were determined in accordance with ISO 6892-84 and ST SEV 471-88, and long-term strength tests in accordance with DSTU ISO 204:2019 were performed on a DST-500 test rig at a temperature of 1000 °C and a load of 280 MPa until complete failure.

The parameters of structural stability were calculated using the well-known calculation methods PHACOMP [14, 16] and New PHACOMP [17, 18]. Using computer modeling of thermodynamic processes CALPHAD in the JMatPro program [13, 14, 16, 19] the ΔE method was used to evaluate the balance of the chemical composition. In accordance with the calculation and analytical model (CAM) developed at the Zaporizhzhia Polytechnic National University [12, 14, 16, 20, 21], important temperature parameters, the values of the short-term and long-term strength limits at different temperatures and different alloying levels were determined.

## Research Results and Discussion

All tested melts of the ZhS32-VI alloy meet the requirements of the technical documentation (Table 1).

The cross-sectional macrostructure of 80 mm diameter test melt blank fragments, produced in a ULVAC FM-1-2-100 vacuum furnace using equiaxed crystallization prior to heat treatment, is shown in Figure 1.

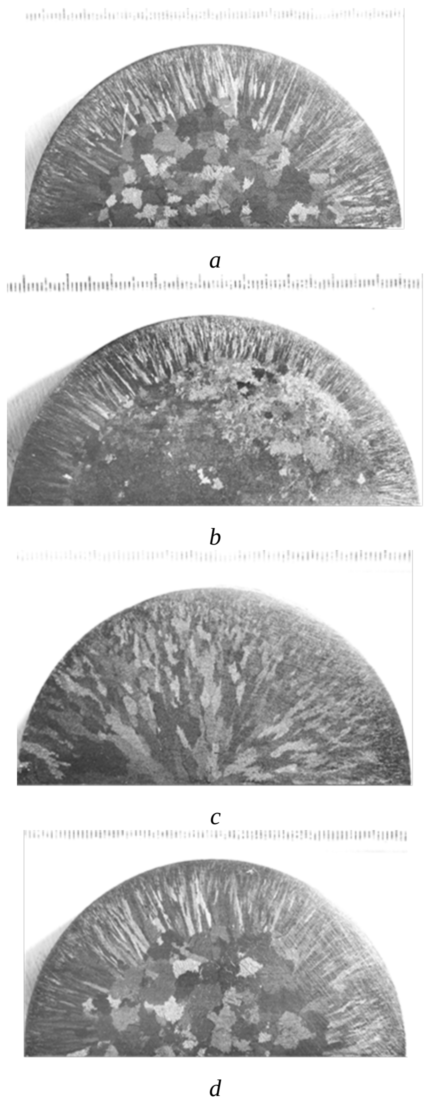

**Figure 1.** Macrostructure in the cross-section of the middle part of 80 mm diameter rod blanks made of ZhS32-VI alloy, produced on a ULVAC FM-1-2-100 unit before heat treatment:

*a* – Heat 1, *b* – Heat 2, *c* – Heat 3, *d* – Heat 4

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**Table 1 –** Chemical composition of the metal of experimental melts of heat-resistant nickel alloy ZhS32-VI

| Fuse | Content of elements, % by weight | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Cr | Co | W | Mo | Al | Nb | Ta | Re | Fe | Si | S | P | B | $O_2$ | $N_2$ | Ni |
| 1 | 0,127 | 4,90 | 9,00 | 8,78 | 1,13 | 5,82 | 1,59 | 3,96 | 3,82 | 0,06 | 0,12 | 0,005 | 0,005 | 0,020 | 0,00039 | 0,00052 | base |
| 2 | 0,143 | 4,92 | 9,03 | 8,65 | 1,12 | 5,93 | 1,69 | 4,07 | 3,80 | 0,06 | 0,11 | 0,005 | 0,005 | 0,015 | 0,00045 | 0,00060 | base |
| 3 | 0,140 | 5,00 | 9,26 | 8,80 | 1,17 | 6,03 | 1,74 | 4,05 | 3,93 | 0,06 | 0,11 | 0,005 | 0,005 | 0,014 | 0,00040 | 0,00060 | base |
| 4 | 0,130 | 4,64 | 9,11 | 8,87 | 1,17 | 5,80 | 1,60 | 3,83 | 3,65 | 0,06 | 0,02 | 0,005 | 0,005 | 0,015 | 0,00043 | 0,00053 | base |
| Norms ТУ 1-92-177-91 | 0,12-0,17 | 4,5-5,3 | 9,0-9,5 | 8,1-8,9 | 0,9-1,3 | 5,7-6,2 | 1,4-1,8 | 3,7-4,4 | 3,6-4,3 | ≤ 0,5 | ≤ 0,2 | ≤ 0,005 | ≤ 0,010 | ≤ 0,02 | ≤ 0,002 | ≤ 0,002 | base |

The following crystallization zones are observed in the structure of the blanks:

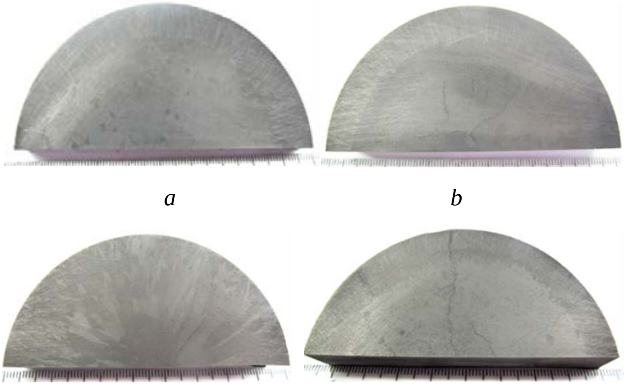
- zone of fine subcortical crystals;
- zone of columnar crystals;
- zone of equiaxed crystals.

The results of the macrostructure parameter measurements are presented in Table 2.

**Table 2** – Macrostructure parameters of 80 mm diameter blanks made of ZhS32-VI alloy

| Melt number | Size of crystallization zones, mm | | | Macrograin size in the equiaxed crystal zone, mm |
|---|---|---|---|---|
| | Zone of fine subcortical crystals | Columnar crystal zone | Zone of equiaxed crystals | |
| 1 | 1…2 | 18…20 | 40…44 | 2…6 |
| 2 | 1…2 | 8…13 | 54…64 | 0.75…2 |
| 3 | 1…2 | ~ 40 | - | - |
| 4 | 1…2 | 16…18 | 44…48 | 2…7 |

Figure 2 shows the macrostructure of fragments of blanks Ø 80 mm (melts 1–4), obtained in a vacuum furnace FM-1-2-100 from ULVAC using the equiaxed crystallization method after standard heat treatment (homogenization at a temperature of 1270±100 °C – 1 hour 15 minutes).



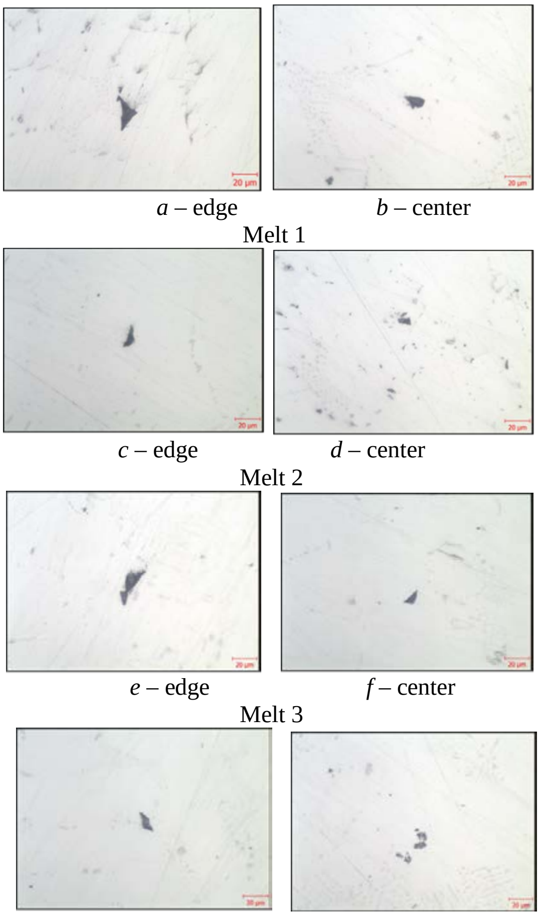
*a* *b*

*c* *d*

**Figure 2.** Macrostructure in the cross-section of the middle part of 80 mm diameter rod blanks made of ZhS32-VI alloy, produced on a ULVAC FM-1-2-100 unit after heat treatment:
*a* – Melt 1, *b* – Melt 2, *c* – Melt 3, *d* – Melt 4

## Microstructure of a rod blank before heat treatment

Inspection of unetched microsections cut from the peripheral and central zones of the middle portion of blank fragments from melts 1–4 revealed no metal contamination in the form of coarse slag inclusions or clusters. The size of oxide inclusions does not exceed 0.023 mm (Figure 3).



*a* – edge *b* – center
Melt 1

*c* – edge *d* – center
Melt 2

*e* – edge *f* – center
Melt 3

*g* – edge *h* – center
Melt 4

**Figure 3.** Oxide inclusions in the material of blanks made of ZhS32-VI alloy, obtained on the FM-1-2-100 installation from ULVAC, ×500

Globular carbides range in size from 1 to 12 μm, while lamellar carbides range from 5 to 27 μm (see Table 3). Shrinkage microporosity is present in the central

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zone of the fragments of the analyzed blanks (the maximum micropore size is ~0.06 mm) (Figure 4, see Table 3).

The blank from heat 1 contains isolated, rare films (Figure 5). No films were detected in the remaining fragments of the received blanks.

Figure 6 shows the carbide distribution in the central zone of the blanks received for analysis.

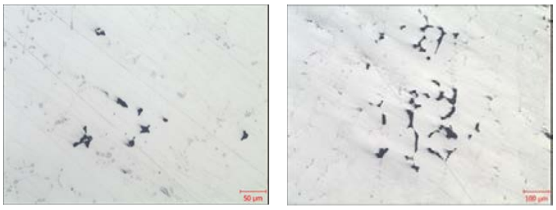
The microstructure of the studied blanks is identical and, prior to heat treatment, consists of a γ-solid solution with the presence of an intermetallic γ´ phase, a eutectic (γ-γ´) phase, carbides, and carbonitrides (Fig. 7–10).

The parameters of the structural components in the blanks of melts 1–4 made of the ZhS32-VI alloy (before heat treatment) are presented in Table 3.

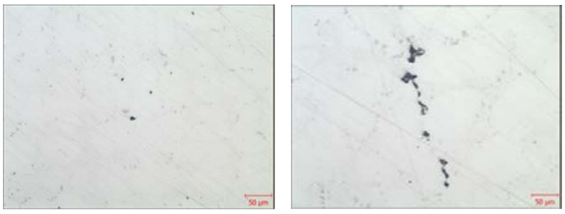
Furthermore, it should be noted that skeletal precipitates of carboboride eutectic, located near particles of the eutectic (γ-γ´) phase (Figure 11), were detected in the structure of all the studied melts.

**Table 3 –** Parameters of structural components in a blank ∅ 80 mm made of ZhS32-VI alloy before heat treatment

| Melt number | Place of measurement | Dimensions of structural components, μm | | | | |
|---|---|---|---|---|---|---|
| | | carbides | | eutectic type(γ-γ′) | Micro-pores | Distance between the axes of 2nd order dendrites |
| | | globular type MC | plate type $M_6C$ | | | |
| 1 | edge | 2…7 | 5…12 | 5…15 | up to 20 | 15…25 |
| | center | 2…7 | 5…27 | 5…60 | up to 45 | 35…50 |
| 2 | edge | 2…12 | 5…25 | 5…15 | up to 20 | 12…25 |
| | center | 2…12 | 5…27 | 5…50 | up to 60 | 30…50 |
| 3 | edge | 2…10 | 5…10 | 5…27 | up to 10 | 10…25 |
| | center | 2…12 | 5…20 | 5…50 | up to 10 | 30…50 |
| 4 | edge | 1…5 | 5…10 | 5…15 | up to 15 | 12…25 |
| | center | 1…8 | 5…17 | 5…50 | up to 25 | 30…50 |

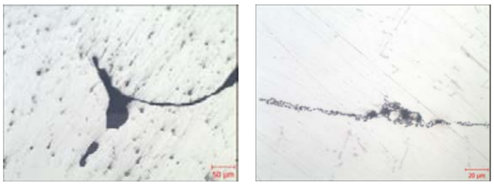


*a* – melt 1, × 200 *b* – melt 2, × 200



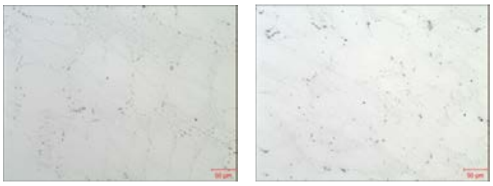
*c* – melt 3, × 200 *d* – melt 4, × 200

**Figure 4.** Microporosity in the material of blanks made of the alloy ZhS32-VI, obtained on the FM-1-2-100 installation of the company “ULVAC”

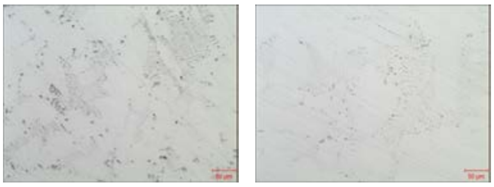


*a* – edge, ×200 melt 1 *b* – center, ×500

**Figure 5.** Films in the material of the workpiece made of the alloy ZhS32-VI, obtained on the FM-1-2-100 installation of the company “ULVAC”



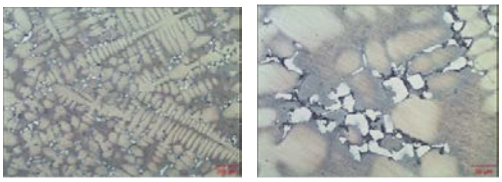
*a* – melt 1 *b* – melt 2



*c* – melt 3 *d* – melt 4

**Figure 6**. Distribution of carbides in the material of blanks made of the alloy ZhS32-VI, obtained on the FM-1-2-100 installation from ULVAC, × 200

*a* – ×50 edge *b* – ×200



*c* – ×50 center *d* – ×200

**Figure 7.** Microstructure of the middle part of the ∅ 80 mm billet made of ZhS32-VI alloy (heat 1) – before heat treatment: *a*, *b* – peripheral zone; *c*, *d* – central zone

To determine the mechanical and heat-resistant properties of ZHS32-VI alloy bar blanks produced from fresh components in a ULVAC FM-1-2-100 vacuum furnace, samples (∅15 mm; L = 135 mm) were cast using high-speed directional solidification (HSDS).

The microstructure of the HSDS samples before heat treatment is identical and consists of a γ-solid solution with the presence of an intermetallic γ´ phase, a eutectic (γ-γ´) phase, carbides, and carbonitrides. Skeletal carboboride

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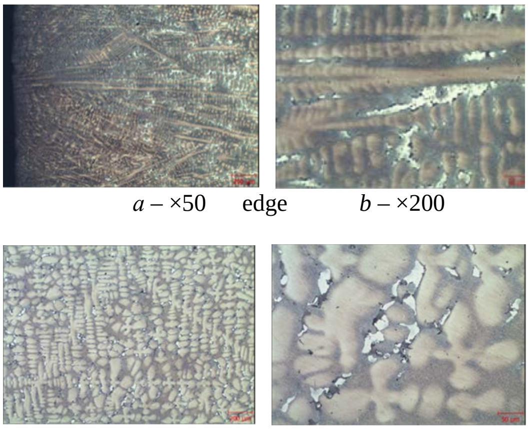
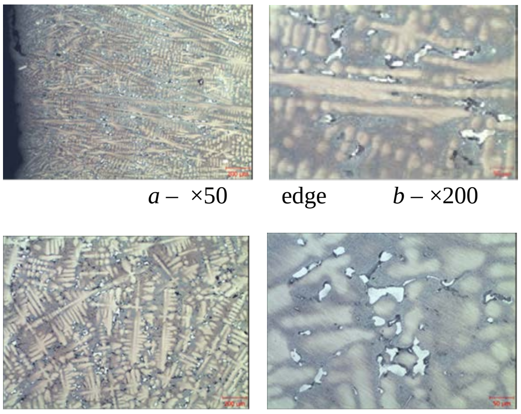
eutectic precipitates were detected near the eutectic (γ-γ´) phase in the structure of all studied samples (as well as in the material of the studied blanks).


*a* – ×50 edge *b* – ×200

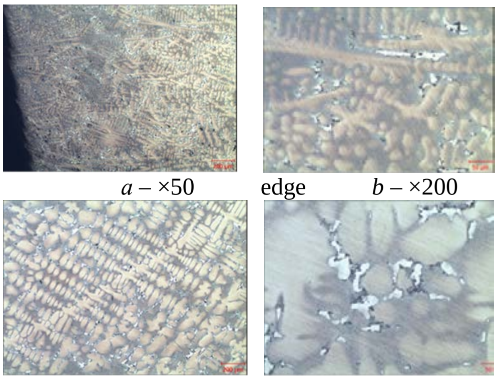
*c* – ×50 center *d* – ×200

**Figure 8.** Microstructure of the middle part of the ∅ 80 mm blank made of the ZhS32-VI alloy (heat 2) – before heat treatment: *a*, *b* – peripheral zone; *c*, *d* – central zone


*a* – ×50 edge *b* – ×200

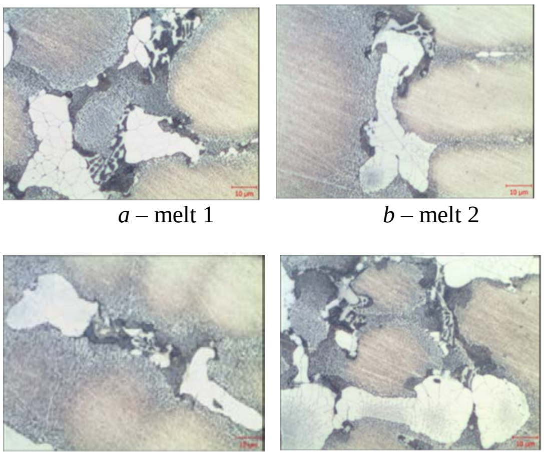
*c* – ×50 center *d* – ×200

**Figure 9.** Microstructure of the middle part of the 80 mm diameter blank made of ZhS32-VI alloy (heat 3) – before heat treatment: *a*, *b* – peripheral zone; *c*, *d* – central zone


*a* – ×50 edge *b* – ×200

*c* – ×50 center *d* – ×200

**Figure 10.** Microstructure of the middle part of a Ø80 mm billet made of ZhS32-VI alloy (heat 4) – before heat treatment: *a*, *b* – peripheral zone; *c*, *d* – central zone


*a* – melt 1 *b* – melt 2

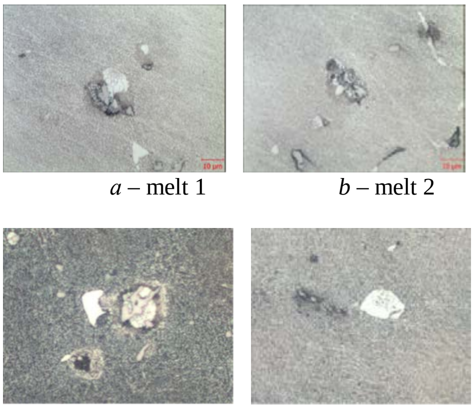
*c* – melt 3 *d* – melt 4

**Figure 11.** Carboboride eutectic in the material of ZhS32-VI alloy blanks produced on a ULVAC FM-1-2-100 unit, × 1000

The microstructure of blanks from heats 1, 2, and 3, heat-treated using the standard mode, revealed structures characteristic of the overheated state of ZhS32-VI alloy (Figure 12*a*, *b*, *c*).

The microstructure of the blank from heat 4 after heat treatment is satisfactory for a normally heat-treated ZhS32-VI alloy and corresponds to the approved microstructure scale; there is no overheating (Figure 12d).

No topologically close-packed phase (TCP) was detected in the studied fragments of the rod blanks (either before or after heat treatment using the standard mode).


*a* – melt 1 *b* – melt 2

*c* – melt 3 *d* – melt 4

**Figure 12.** Microstructure of ZHS32-VI alloy blanks heat-treated using a standard process, produced in a ULVAC FM-1-2-100 furnace, × 1000

The microstructure of samples cast from melts 1–3, heat-treated using the standard mode, revealed structures characteristic of the overheated state of the ZhS32-VI alloy (Figure 13*a*, *b*, *c*).

The microstructure of samples cast from melt 4, after standard heat treatment, is satisfactory for the normally heat-treated state of the ZhS32-VI alloy and corresponds to the approved microstructure scale; there is no overheating (Figure 13*d*).

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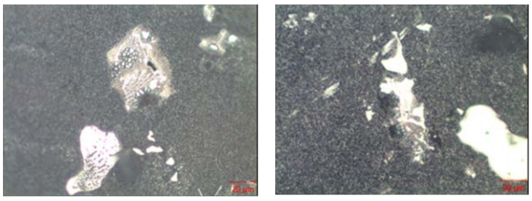
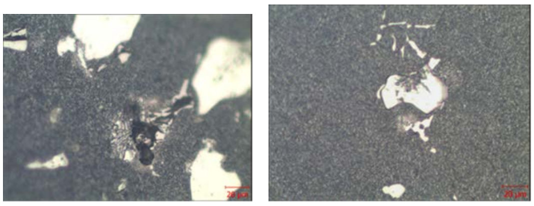
The mechanical and heat-resistant properties were determined according to TU1-92-177-91, 18T-TU-158, and 18T-TU-187 on non-heat-treated samples. Additionally, samples heat-treated using the standard regime (homogenization at 1270±10 °C for 1 hour and 15 minutes) were tested.

The results of the mechanical and high temperature strength tests are presented in Table 4. The crystallographic orientation (CGO) on the studied single-crystal samples did not exceed 0.9 angular degrees.



*a* – melt 1 *b* – melt 2



*c* – melt 3 *d* – melt 4

**Figure 13.** Microstructure of samples of alloy ZhS32-VI heat-treated in a standard mode, ×500

**Table 4 –** Mechanical and heat-resistant properties of alloy ZhS32-VI

| Condition of the material | Melt | Mechanical properties at t = 20 °C | | Time to failure (at Tst. 1000 °C σ= 280MPa),τr, hours |
|---|---|---|---|---|
| | | σв, МПа | δ, % | |
| Without heat treatment | 1 | 1167 | 8,4 | $52^{20}$ |
| | 2 | 1093 | 6,4 | $42^{10}$ |
| | 3 | 1089 | 10,0 | $65^{30}$ |
| | 4 | 1125 | 10,0 | $64^{00}$ |
| After heat treatment | 1 | 1178 | 6,8 | $89^{30}$ |
| | 2 | 1155 | 6,4 | $88^{30}$ |
| | 3 | 1174 | 11,2 | $88^{35}$ |
| | 4 | 1158 | 8,0 | $88^{00}$ |
| Standards TU1-92-177-91; 18T-TU-158 and 18T-TU-187 | | ≥ 850,0 | ≥ 6,0 | ≥ 40,0 |

The calculation and analytical assessment of the structural and phase stability of the alloy ZhS32-VI carried out using the integrated CAM method [11, 12, 14, 16, 20, 21] confirmed the high level of structural stability in terms of the alloy's tendency to form TPC ($П_{TPC}$≈0.3373…0.3489<$П_{CRIT}$=0.5), as well as in terms of the alloying system imbalance parameter ($\Delta E$≈-0.0047…-0.2401<$\Delta E_{erit}$=±0.4), which allows us to consider the alloy ZhS32-VI as sufficiently balanced at the lower level of alloying element content.

The calculated value of short-term strength $б_B$ at room temperature, determined according to the method [14, 16], yielded a value in the range of 1053.59...1125.08 MPa, which corresponds to the values, obtained on test samples (1089...1167 MPa, Table 4).

## Conclusions

A study of the macro- and microstructure of a series of experimental heat-resistant nickel alloy ZhS32-VI melts revealed the satisfactory condition of all samples and their compliance with technical documentation requirements. The microstructure of the studied samples is identical and, prior to heat treatment, consists of a γ-solid solution with the presence of an intermetallic γ´ phase, a eutectic (γ-γ´) phase, carbides, and carbonitrides. Skeletal precipitates of carboboride eutectic located near particles of the eutectic (γ-γ´) phase were detected in the structure of all the melts.

The mechanical and heat-resistant properties of the metal in all melts exceeded the standard values, and the calculation and analytical evaluation method confirmed a high level of structural stability and a sufficient balance in the content of alloying elements, as evidenced by the absence of TPC phases in the structure.

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# ОЦІНКА СТРУКТУРИ ТА ВЛАСТИВОСТЕЙ ЖАРОМІЦНОГО НІКЕЛЕВОГО СПЛАВУ ЖС32-ВІ ЯК МАТЕРІАЛУ ДЛЯ ВИГОТОВЛЕННЯ ЛОПАТОК ГАЗОТУРБІННИХ ДВИГУНІВ

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***Мета роботи.*** *Вивчити макро- та мікроструктурний стан дослідних плавок жароміцного сплаву ЖС32-ВІ для виробництва відповідальних деталей газотурбінного двигуна, оцінити механічні властивості та жароміцність.*

***Методи дослідження.*** *Параметри структурної стабільності оцінювали за відомими розрахунковими методиками PHACOMP та New PHACOMP. Макро- та мікроструктурний аналіз і дослідження фазового складу проводили методом оптичної металографії. Механічні властивості при кімнатній температурі визначали відповідно до вимог ISO 6892-84, СТ СЕВ 471-88, а випробування на тривалу міцність – відповідно до вимог ДСТУ ISO 204:2019.*

***Отримані результати.*** *Проведено дослідження структури та властивостей зразків сплаву ЖС32-ВІ, отриманих у вакуумній печі FM 1-2-100 фірми “ULMAC” методом рівноосної кристалізації. Мікроструктура*

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*зразків до термічної обробки відповідає литому стану сплаву, а після термообробки – задовольняє технічним умовам та відповідає затвердженій шкалі мікроструктур. Механічні властивості та жароміцність відповідають вимогам технічної документації до відповідального жароміцного лиття.*

***Наукова новизна.*** *Отримано нові дані про структуру та фазовий склад жароміцного сплаву ЖС32-ВІ дослідних плавок. Метод розрахунку та аналітичної оцінки підтвердив високий рівень структурної стійкості.*

***Практична цінність.*** *Отримані результати дають можливість розширити застосування жароміцного нікелевого сплаву ЖС32-ВІ для виготовлення виливків відповідального призначення.*

***Ключові слова:*** *жароміцний сплав, макро- та мікроструктура, механічні властивості, жароміцність, гомогенізація.*

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