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WEAR-RESISTANT ALLOY FOR PROTECTION OF CONTACT SURFACES OF AIRCRAFT ENGINE ROTOR BLADES FROM OXIDATION AT HIGH TEMPERATURES

Wear- and heat-resistant casting cobalt-based alloy for hardening the contact surfaces of rotor blades of aircraft gas turbine engines has been developed to replace commercial alloys HTN-61 and VZhL-2. High heat resistance was achieved by combined doping (modification) of the alloy. The optimum chemical and phase composition of alloy has been found based on the study of alloy heat resistance, wear resistance, structure, and melting point.

Key words: cobalt alloys, niobium carbide, alloying, heat resistance, melting point, and wear resistance.

The development of state-of-the-art technologies requires the creation of new multifunctional materials, including alloys, which should satisfy the whole set of various complex requirements that can arise out or in connection with their use. Particularly, it concerns the development of alloys for aviation and space industry, where the increase in operating temperature in engine combustion chamber, even by a few degrees, significantly enhances the engine power and performance thereby extending the aircraft capabilities.

The service life of aircraft gas turbine engine (GTE) is defined by reliability and durability of the most critical parts of its hot section, such as rotor and nozzle blades whose contacting surfaces operate in aggressive environment at high temperatures and variable loads for a long time and working capacity of which largely depends on their resistance to wear.

Reinforcement of the contacting surfaces by coating them with a material more durable than that of blade can extend service life of blades before repair; the repair will imply replacement of the worn coating instead of overhauling the blades. The existing materials, nickel alloys VZK and VZhL-2 developed by VIAM [1] (Russia) with melting points within the range from 1220 to 1260 °C, are wear-resistant only at temperature below 900 °C. This does not meet the requirements arising out of high engine operating temperatures reaching 1100 °C and those related to other technological processes of blade production, such as degassing and brazing at 1270 °C.

STATEMENT OF THE PROBLEM

The HTN-61 alloy developed at the Kurdiumov Institute of Metal Physics (IMP) of the NAS of Ukraine [2], which was successfully used within the range of operating temperature from 20 to 1000 °C, has proved itself to be not sufficiently heat-resistant at high operating temperature (up to 1100 °C). Given the need to raise the intensity and effectiveness of the GTE operation, which is associated with a further increase in operating temperature of blades up to 1100 °C, the IMP carried out research to find ways to improve the operating performance properties of HTN-61 alloy, including its heat resistance. As a result of the innovative project the promising compositions for the development of wear- and heat-resistant casting cobalt-based alloy have been defined, and the optimum alloy composition has been found to strengthen the contact surfaces of rotor blades of aircraft gas turbine engines to replace VZhL and HTN-2-61 serial alloys.

Operating conditions to be met by the materials are as follows:

- Specific contact load ≥20 MPa;
- Operating temperature range from 20 to 1100 °C;
- High uniform wear resistance within the range of operating temperature, at least, at the level of HTN-61 alloy;
- Weldability of material with ZhS-32 alloy of which blades are made should be, at least, as good as that of HTN-61 alloy;
- Melting point should be ≥1300 °C, which satisfies the conditions of the process (degassing and brazing at 1270 °C);
- Structural and phase stability during operation within the working temperature range;
- Affordable production technology: casting without heat treatment;
- Operating environment: gas environment of kerosene combustion products.

The key requirement for the development of new material is to achieve heat resistance which provides the blade service life of, at least, 12 000 hours at the following temperature conditions:

- At maximum temperature of 1110 °C, the service hours account for 2.5% of the service life;
- At a temperature of 950 °C the service hours account for 25% of the service life;
- All other temperature regimes should not be higher than 915 °C.

In addition, the alloys should have good casting properties, lend themselves to machining favorably, be heat-resistant and well-fused on the blade material.

Research to improve the heat resistance of HTN-61 alloy on the basis of Co-NbC eutectic was held at the IMP by developing an optimal doping selected upon the results of analysis of various industrial cobalt-based alloys [3—6] and experimental data of alloy sample tests on heat resistance, thermal stability, melting point, and wear resistance. Based on the data obtained the composition range has been identified for the promising alloys which have almost the same durability, but 10—20 times (depending on the composition and duration of the test) higher heat resistance as compared with HTN-61 alloy. Such alloys contain maximum 19.0 wt. % of niobium carbide (NbC) and include chromium, tungsten, aluminum, and iron as dopes. The limits of dope content (see Table 1) underlie the patent of Ukraine no. 39450 «Cobalt-Based Alloys» [7].

The approach is based on the study of phase equilibria in Co-NbC, Co-Al-W, and Co-Nb-C alloys and their melting diagrams with eutectic temperature, phase boundaries, and solubility range established.

The objective of this research was to optimize the alloy composition within the limits of content of niobium and carbon as the main carbide-forming elements and the content of doping elements: chromium, aluminum, iron, and tungsten for getting an alloy to be used as a wear- and heat-resistant material for coating the airfoil shroud platforms of aircraft gas turbine engines to protect them from high-temperature oxidation and wear during operation, i.e. to extension their service life between overhauls.

THE RESULTS

1. Determination of Carbide Component

The groundmass is two-phase eutectic alloy of Co-NbC system, which contains about 12 wt. % of NbC at the melting point of ~1400 °C. Doping

Table 1

Basic Element Content Limits

Nb	C	Cr	Al	W	Fe	Co
13.5—17	1.6—1.9	5—25	2—3.5	6—12	2—5	The rest

that is necessary to strengthen the cobalt basis of alloy lowers the melting point and the content of carbide component at the eutectic point. Therefore, the most important task was to get eutectic doped cobalt-based alloys with a melting point of at least 1300 °C, with an optimum content of niobium carbide which ensures minimum wear. At the same time, it is necessary to take into consideration the casting technique for manufacture of alloys, which implies that the alloys containing carbide phase much larger than that at the eutectic point of Co-NbC system melting diagram cannot be stirred and poured into molds without casting defects arising as a result of yield lost.

Some doping elements are partially dissolved in niobium carbide forming carbide (Nb, Me)C. Therefore, total carbon content in alloy was experimentally determined to prevent its unwanted excess. This excess causes partial melting of alloy at temperatures lower than 1300 °C due to the formation of non-equilibrium phases. The results of thermal analysis of cobalt alloys (see Table 2) show that for different shares of tungsten, aluminum, and iron a fixed range of carbon content should be established to ensure the formation of eutectic carbides.

Research and comparison of alloy melting points allow the researchers to exclude from consideration those elements that melt at temperature below 1300 °C. For example, increase in carbon content up to 2.1% in the alloy no. 3 leads to emergence of additional effect on its thermal analysis diagram (Fig. 1) as compared with the alloy no. 4 containing 1.8% of carbon on the thermal analysis diagram of which there is only an effect associated with its melting (Fig. 2). The melting point of the obtained alloys exceeds 1300 °C making further study of VZhL-2 alloy (which has a much lower melting point) unfeasible.

Given the requirements for the alloy manufacture and the fact that the formation of congruent melting niobium carbide $NbC_{0.9}$ it is necessary to meet a certain niobium-to-carbon ratio which is about 8.5 it has been experimentally established

Table 2

Carbon Effect on Alloy Melting

No.	Content of component, mass percentage				Temperature of thermal effects, °C	
	W	Al	Fe	C	1st secondary peak	2nd melting peak
1	4.5	4	–	1.8	–	1320
2	4.5	4	–	1.95	–	1330
3	4.5	4	–	2.1	1294	1316
4	6	4	–	1.8	–	1315
5	6	4		1.95	1290	1320
6	6	4	–	2.1	1280	1300
7	6	4	3	1.7	–	1310
8	9	4.25	–	1.8	–	1280
9	9	4.25	–	1.95	1270	1300
10	9	4.25	–	2.1	1270	1290
11	9	4.25	3	1.7	–	1310
12	7	4.25	3	1.9	1275	1310
13	7	4.25	3	1.8	–	1320
14	7	4.25	3	1.75	–	1315
VZhL-2						1220

Note. All samples contain 20 % of Cr, 15.5 % of Nb, the rest is Co.

that the optimal content of niobium carbide in the alloy is limited to 18 wt. %.

2. Heat Resistance Tests

The choice of temperature of alloy heat resistance test is based on the fact that the maximum operating temperature is 1100 °C (2.5 % of the service life). The samples were made of cast bars by spark cutting and lathed. Their surface area was measured with an accuracy of ±0.1 mm^2. The samples were weighed with an accuracy of ±0.001 g. Each sample was placed in a separate crucible made of aluminum.

Heating in electric resistance furnace to a temperature of 1100 °C in air was controlled by a thermocouple. The samples were kept at this temperature during 10 hours and cooled together with the furnace. The procedure was repeated five times. Totally, the samples were held at 1100 °C during 50 hours. The alloy heat resistance was calculated as increase in sample weight after every 10 hours of annealing divided by its surface area ($\Delta m/s$).

According to the measurement results showed in Table 3, almost all alloys have a much better heat resistance than commercial alloy HTN-61. The advantage of the investigated alloys increases significantly with increasing duration of exposure to high temperatures. For the samples annealed during 10 hours this advantage reaches 3—5 times, while for the samples annealed during 50 hours it ups to 20—25 times.

3. The Optimal Content of Doping Elements

The optimal content of doping elements in alloy to achieve the best properties is based on information about the limits of their solubility in Co-Cr, Co-W, Co-Al, and Fe-Co alloys. Chrome and aluminum more effectively improve resistance to high-temperature oxidation than other elements due to the formation of Al_2O_3 (internal) and Cr_2O_3 (external) films, but this positive effect is achieved only for a certain percentage ratio of chromium and aluminum in the alloy. Chromium significantly effects heat resistance of cobalt-based alloys provided its content is within the

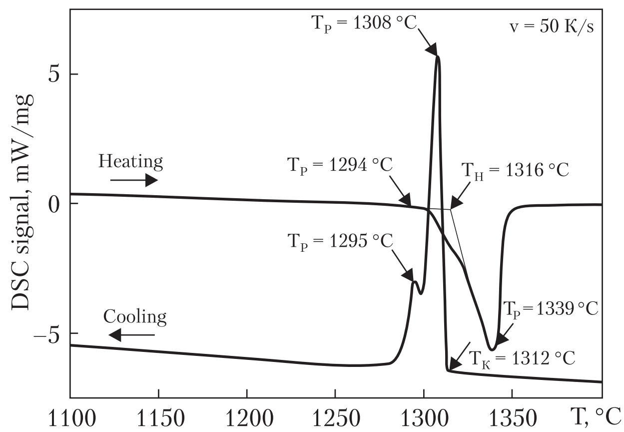


Fig. 1. Thermal analysis diagrams of alloy no. 3 (C = 2.1)

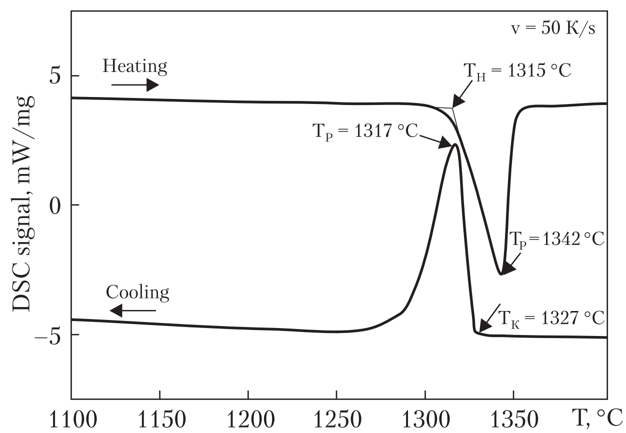


Fig. 2. Thermal analysis diagrams of alloy no. 4 (C = 1.8)

solid solution and cannot significantly increase due to the formation of brittle σ-phase. It enhances cobalt resistance to oxidation and strength at high temperatures. The cobalt binary alloys with 20, 25 or 30% chromium content have approximately the same oxidation, with the only difference being that the alloy with 25% chromium content is oxidized slowly. The same content of chromium ensures the largest increase in heat resistance [8]. In case of excessive carbon and a sufficient amount of chromium fusible eutectic Co-$Cr_{23}C_6$ with a melting point below 1270 °C appears in the alloy. The appearance of this eutectic should be prevented insofar as the rotor blades have to be treated at high temperatures (degassing and brazing at 1265—1270 °C). Thus, to achieve a high heat resistance the optimal chromium content is 20 wt. %.

Introduction of 3—4% aluminum to cobalt-based alloys reduces the rate of oxidation [9]. As its content increases over 6 wt. % exceeding the limit of solubility, the melting point decreases, but aluminum is a mandatory doping element in industrial cobalt alloys. Its function is to form an initial fine oxide layer on the friction surface. Further heating causes the oxidation of other elements for which Al_2O_3 microcrystals can act as crystallization centers. It provides the refinement of structure of oxide layers formed. In addition, in the presence of chromium aluminum provides its diffusion from the deeper layers to the surface. The chromium content of 20 wt. % and aluminum one of about 4 wt. % provide the highest heat resistance of alloys.

To achieve high wear resistance at temperature above 1000 °C or to maintain it at the level of HTN-61 alloy it is necessary to increase the hardness and strength at high temperature. For the eutectic Co-NbC-based alloy this is achieved by reinforcing solid solution with tungsten. The enhancement of heat resistance and wear resistance by doping with aluminum and tungsten, respectively, requires studying the limits of compatible solubility of these elements in cobalt-based solid solution. The information on these limits is given by the triple diagram of Co-Al-W system in the area of alloys rich in cobalt [10, 11]. The optimal tungsten content in alloy is 10 wt. % and the aluminum content should be less than 2 wt. %.

A small amount of iron (optimally, 3%) is added to the alloy to stabilize the phase transformation of cobalt (α ↔ ε). Such doping has a little effect on the properties of optimized alloy, inasmuch as such a small amount of iron is completely dissolved in solid solution.

4. Alloy Wear Tests

One of the requirements for the new material is to preserve durability at the level of HTN-61.

Table 3

Heat Resistance of Alloys

No.	Composition of sample, wt. %					Melting point, °C	Increase in sample mass, mg / mm²									
							1060 °C					1100 °C				
							Duration of annealing, hours									
	Cr	W	Al	Fe	C		10	20	30	40	50	10	20	30	40	50
15	20	7.5	3.5	—	1.9	1310	4.5	4.0	3.5	3.0	2.6	12.0	10.1	8.7	7.8	7.0
16	20	7.5	3.5	3.0	1.9	1310	1.7	1.63	1.37	1.4	1.31					
17	20	6.0	4.0	3.0	1.9	1280	2.3	2.13	2.2	2.5	2.03					
23	20	7.0	2.0	5.0	1.8	1320						8.54	8.25	5.19	4.94	3.71
26	20	9.0	3.5	3.0	1.7	1315						7.0	5.68	4.27	3.28	2.16
27	20	12	2.5	3.0	1.6	1300						4.82	4.12	3.93	3.69	2.1
28	20	4.5	4.0	3.0	1.9	1280	2.1	1.97	1.77	1.8	1.9					
29	20	10	3.0	3.0	1.9	1310	2.5	2.3	2.1	1.9	1.7					
30	25	9.0	2.0	3.0	1.8	1315						7.33	4.13	3.74	2.86	2.1
31	20	7.5	3.5	6.0	1.8	1315	6.5	5.6	5.1	4.8	4.5	13.9	12.6	11.5	10.4	9.1
32	20	10	3.0	1.5	1.8	1310	4.2	3.55	3.16	2.8	2.66	9.0	7.8	6.9	5.5	4.2
HTN-61						1320	13.3	14.0	14.6	156	16.7	25.8	29.1	33.5	47.9	50.5

Note. All the alloy samples contain 15.5 wt. % of Nb, the rest is Co.

Therefore, the alloys are subject to wear resistance tests. The high-temperature durability tests were conducted on the bench, where the conditions of operation of rotor blades of aircraft gas turbine engines were simulated with respect to heating rate, operating temperature, atmospheric composition, and nature of mechanical interaction of blade edge surfaces (load and amplitude of fluctuations). The samples were held by T-shaped holders; the test parameters were as follows: temperature: 20 °C and 1100 °C, load: 50 MPa, the amplitude of mutual displacement: 1.5 mm. Twelve samples were tested with respect to their high-temperature wear resistance. The best results of the tests are presented in Table 4. Wear resistance was determined by decrease in the sample volume during one cycle of oscillation.

Metallographic study of alloys after wear resistance tests included an external examination, a topographic study of contact wear zones and a metallographic analysis in the area of fretting wear. When considering the brazed plates under a binocular microscope, it was found that at high temperatures the plates were oxidized to dark gray color without significant traces of peeling and flaking of oxides (Fig. 3).

Such specific features of fretting wear as linear wear, traces of relative displacement of material across the contact planes (along the axis of the sample), setting, transfer of metal, beading with scratching, and formation of even glazed surface in the contact zone are more or less typical for all the samples.

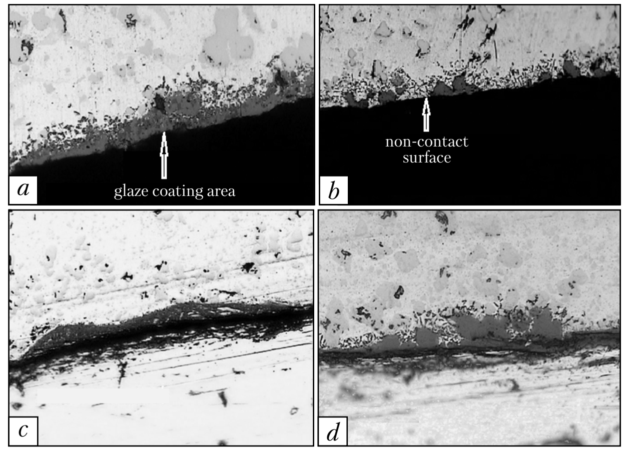


Fig. 3. Oxidation of HTN-62 alloy in wear test at 1050 °C ×400: *a*, *b* on the contact surface in the glazing area; *c*, *d* on the non-contact surface

The positive aspect is glaze coating of surface in the view of the fact that this surface has very high density, hardness, and wear-resistance. Metallographic analysis showed that in the area of glazing dense amorphous oxides were formed. All types of alloys studied showed a high wear resistance and, consequently, an acceptable condition of contact surfaces. The comparison of wear fac-

Table 4

Alloy Wear Resistance

Sample no.	W	Al	Fe	C	Melting point, °C	Alloy wear, $I_v \times 10^6$ mm^3/cycle	
						20 °C	1100 °C
20	9.0	5.0	3.0	1.7	1270	0.18	48.0
23	7.0	2.0	5.0	1.8	1320	0.25	15.1
24	4.5	5.0	3.0	1.8	1310	0.12	77.0
25	7.0	4.25	3.0	1.8	1310	0.30	65.0
26	9.0	3.5	3.0	1.7	1315	0.25	15.0
27	12.0	2.5	3.0	1.6	1300	0.24	14.9
HTN-61					1350	0.25	15.0

Note. All samples contain 20% of Cr, 15.5% of Nb, the rest is Co.

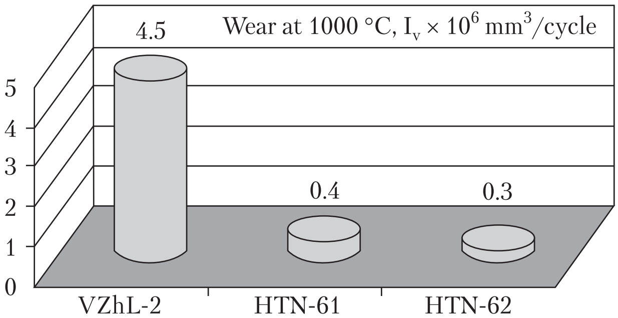
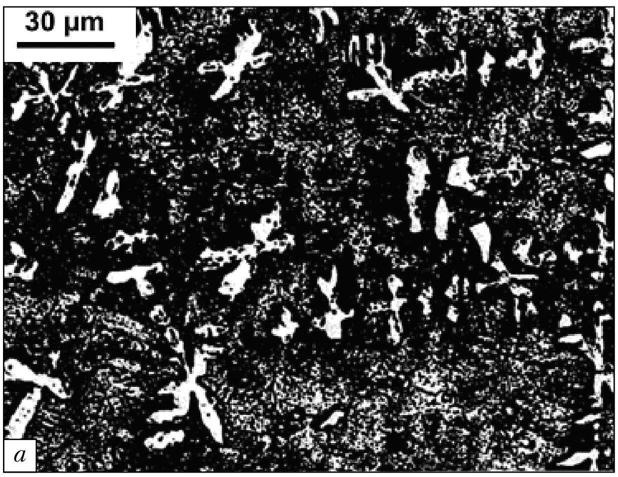


Fig. 4. Alloy wear factors at 1000 °C



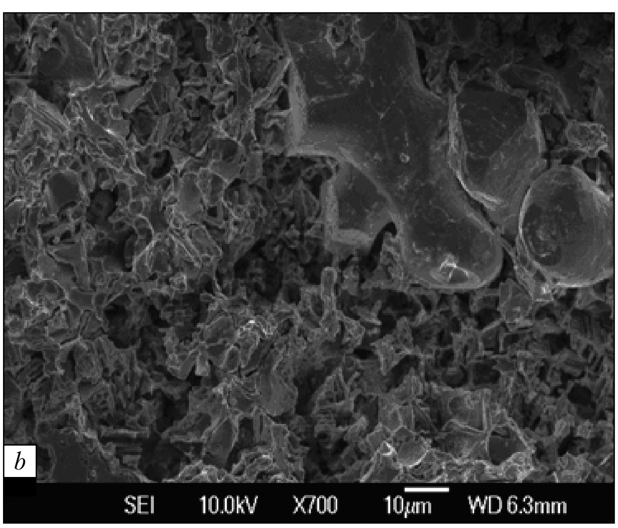


Fig. 5. The typical structure of HTN-62 alloy: a) NEOPHOT-2 light microscope ×300; b) JM7000F scanning electron microscope

tors for alloys VZhL-2, HTN-61, and HTN-62 at 1000 °C is illustrated in Fig. 4.

The wear resistance measurement for alloys studied as compared with VZhL-2 and HTN-61 alloys, at 1000 °C under the same conditions of the bench tests showed that for a certain content of chromium, niobium, tungsten, aluminum, carbon, and iron the former has as good durability as the latter. The alloys have high thermal stability in the test mode within the range from T_{min} = 200 °C and T_{max} = 1100 °C. After 1,000 cycles no cracks have been revealed.

Given the above analysis of data on the influence of doping on the melting point, thermal stability, heat- and wear resistance of cobalt-based alloys with niobium carbide the optimum alloy composition having better properties than the existing serial alloys VZhL-2 and HTN-61 has been identified. New composition is branded HTN-62.

5. Study of Microstructure

It is known that the alloy mechanical properties are sensitive to structural changes. The developed alloy due to a sufficient bulky part of carbide phase, its reinforcing effect, and regular thermally stable eutectic structure has a high wear resistance within a wide range temperature, specific load, and slip rate.

When developing the alloy it was established that a moderately hypereutectic structure is the most optimal one, since this alloy contains the largest allowable amount of carbide phase. Any larger content of niobium carbide makes smelting by induction melting technique in refractory crucibles impossible due to a sharp rise in end melting point (liquidus). In addition, this alloy becomes fragile due to excessive consolidation of primary crystals of carbide phase. In the case of lesser amount of carbide phase (e.g. pure eutectic alloy) the high-temperature wear resistance is significantly lower. The typical structure of HTN-62 alloy is showed in Fig. 5.

The most optimal structure of alloy is presented by primary (excessive) niobium carbide crystals and double eutectic containing two phases:

Fig. 6. HTN-62 alloy ingots

solid solution of doping elements in cobalt and lightly doped niobium carbide. The carbide crystals in the form of dendrites are surrounded with bladed-fibrous eutectic. The comparison of alloy microstructure before and after annealing at 1100 °C during 50 hours proves the structural stability of investigated alloys.

Thus, based on research of heat resistance, durability, structure, and melting point of alloys the optimal chemical and phase composition of cobalt-based casting alloy has been identified in terms of content of niobium, chromium, carbon, aluminum, tungsten, and iron.

The optimized alloy branded HTN-62 has the following advantages over the existing alloys:

- Uniform high wear resistance within the temperature range from 20 to 1100 °C under the conditions of aviation fuel combustion, which provides a significant increase in GTE service life between overhauls;
- Melting point of alloy (1320 ± 10 °C) satisfies the conditions of engine production;
- High heat resistance (10 times higher than that of HTN-61alloy; all other features being preserved, it gives a possibility to choose a material for specific conditions);
- High thermal stability;
- Structural and phase stability up to 0.8–0.9 T_m.

For the industrial alloy production the induction melting technique in vacuum or protective atmosphere without heat treatment has been optimized. It implies compliance with a given sequence of melting and with temperature and time parameters of the process, which ensures the alloy compliance with a given chemical composition and melting point. Due to compliance with the provisions of technical requirements the alloys have minimum amount of casting defects: pores, films, impurities. Using the proposed technique the project partner, *Melta* Ltd., has made 3 HTN-62 alloy ingots having a total weight of 20 kg (Fig. 6) of which *Progress* Design Office produced plates and applied them to the airfoil shroud platforms of turbine blades to test them on the engine. The alloy is under implementation and passed the control flight tests for 2000 hours. The trials are to be extended to 7000 hours.

CONCLUSIONS

1. The optimum composition of new heat- and wear-resistant cobalt-based casting alloy with carbide reinforcement has been developed having studied the phase equilibria in the Co-NbC, Co-Al-W, and Co-Nb-C. The alloy has no comparable counterparts in CIS countries. It is under implementation at the *Progress* Design Office.

2. The HTN-62 optimized alloy has the following advantages over the existing compounds:

- Uniform high wear resistance within the temperature range from 20 to 1100 °C under the conditions of aviation fuel combustion, which provides a significant increase in GTE service life between overhauls;
- Melting point of alloy (1320 ± 10 °C) satisfies the conditions of engine production;
- High heat resistance (10 times higher than that of HTN-61 alloy), with all other useful properties being preserved;
- Structural and phase stability up to 0.8–0.9 T_m.

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ИЗНОСОСТОЙКИЙ СПЛАВ ДЛЯ ЗАЩИТЫ КОНТАКТНЫХ ПОВЕРХНОСТЕЙ РАБОЧИХ ЛОПАТОК АВИАЦИОННЫХ ДВИГАТЕЛЕЙ ОТ ОКИСЛЕНИЯ ПРИ ВЫСОКИХ ТЕМПЕРАТУРАХ

Разработан износостойкий и жаростойкий литейный сплав на основе кобальта для упрочнения контактных поверхностей рабочих лопаток авиационных газотурбинных двигателей вместо серийных сплавов ХТН-61 и ВЖЛ-2. Высокие показатели жаростойкости достигнуты комплексным легированием (модификацией) сплава. На основе исследований жаростойкости, износостойкости, структуры и температуры плавления сплавов установлен оптимальный химический и фазовый состав разработанного сплава.

Ключевые слова: сплавы кобальта, карбид ниобия, легирование, жаростойкость, температура плавления, износостойкость.

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ЗНОСОСТІЙКИЙ СПЛАВ ДЛЯ ЗАХИСТУ КОНТАКТНИХ ПОВЕРХОНЬ РОБОЧИХ ЛОПАТОК АВІАЦІЙНИХ ДВИГУНІВ ВІД ОКИСЛЕННЯ ПРИ ВИСОКИХ ТЕМПЕРАТУРАХ

Розроблено зносостійкий та жаростійкий ливарний сплав на основі кобальту для зміцнення контактних поверхонь робочих лопаток авіаційних газотурбінних двигунів замість серійних сплавів ХТН-61 і ВЖЛ-2. Високі показники жаростійкості досягнуто комплексним легуванням (модифікацією) сплаву. На основі досліджень жаростійкості, зносостійкості, структури та температури плавлення сплавів встановлено оптимальний хімічний та фазовий склад розробленого сплаву.

Ключові слова: сплави кобальту, карбід ніобію, легування, жаростійкість, температура плавлення, зносостійкість.

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