doi.org/10.15407/tpwj2017.01.12

ADHESION-ACTIVE HIGH-TEMPERATURE WEAR-RESISTANT SURFACING CONSUMABLES KMKh AND KMKhS

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Adhesion-active high-temperature wear-resistant composite surfacing consumables KMKh and KMKhS were developed. They provide for significant increase of wear resistance of contact surfaces of parts of hot gas path in gas turbine engines. It is determined that additional introduction of chromium carbide in alloy based on solid solution of cobalt, alloyed by molybdenum, chromium, boron and silicon, promotes for stabilization of its structure and properties with simultaneous decrease of melting temperature of composition. Boron and silicon provide for increase of adhesion alloy activity in deposition on contact surfaces and form uniformly distributed thermodynamically stable high-dispersion complex silicides and borides. Wear resistance tests show that average value of wear intensity of working surfaces, deposited with new KMKh and KMKhS consumables, are 3–4 times lower under conditions of operation in oxidizing medium at critical temperatures, than the surfaces deposited with known commercial alloys. High characteristics of wear resistance and possibility of work under critical temperatures allowed recommending developed composite consumables and technology of their surfacing to commercial application. 10 Ref., 3 Tables, 1 Figure.

Keywords: *surfacing, adhesion-active wear-resistant composite consumables, high-temperature alloys, structure, phase composition, wear intensity*

One of the main problems of ship machine building is rise of efficiency, safety and life of gas turbine engines (GTE). First of all, these parameters are determined by wear of the contact surfaces of working blades, which are operated under extreme conditions at high operating loads and temperatures.

Currently there is a wide range of wear-resistant consumables for surfacing on the contact surfaces with base metal melting or without it.

The main criteria of their serviceability are melting temperature and possible methods of deposition of high-temperature alloys on the contact surfaces. On practice, mentioned criteria can have mutually exclusive effect that significantly complicates or makes impossible simultaneous choice of optimum composition of surfacing alloy and method of formation of wear-resistant layer, which could satisfy specific requirements of particular manufacturer [1].

Aim of present work is a development of new adhesion-active high-temperature wear-resistant composite consumables, providing significant rise of life of the contact surfaces of parts of GTE hot gas path.

It is known fact that ship gas turbine building uses high-temperature nickel alloys of ChS88U-VI, ChS70U-VI and other types for construction of turbine working blades. These alloys are strengthened with disperse precipitations of γ'-phase $Ni_3(Al, Ti)$, having tendency to coagulation in process of contact interaction at high-temperatures, that results in formation of favorable conditions for wear increase, including due to intensification of oxidation processes in a depleted surface layer by alloying elements. These alloys refer to the materials with unsatisfactory process weldability, therefore temperature of their heating during deposition of wear-resistant layer on the contact surface should not exceed 1220±10 °C. Otherwise, it is impossible to eliminate rapid decrease of base metal strength as a result of γ'-phase degradation and formation of cracks in deposition zone [2]. In this connection, alloys used for strengthening of the contact surfaces, should have melting temperature not more than 1220±10 °C at deposition in form of melt. With higher temperature of melting of wear-resistant consumable its deposition is carried out by brazing, but turbine blade design does not always allow application of this effective method.

Thus, wear-resistant alloys can be comfortably divided on two groups by melting temperature before and after 1220±10°C.

It is extremely difficult problem to develop the alloys, relating to the first group and having necessary level of wear resistance at operating temperatures (to

900 °C) and capable to withstand short-term heating to 1150 °C which is close to solution temperature of strengthening γ′-phase in the base metal.

Alloys of the first group include KBNKhL-2 composition having nickel-cobalt matrix with content, wt.% of nickel 35.5–36.5; cobalt 20.5–21.5; chromium 24.5–25.5; chromium carbide 11.5–12.5; chromium boride 2.5–3.5 and boron 2.9–3.1 [3]. High relative wear resistance of alloy is provided by strengthening of nickel-cobalt matrix with chromium carbides and borides. A disadvantage of alloy is its low melting temperature (~1070–1090 °C) that does not provide alloy with possibility to withstand short-term thermal loads at temperatures up to 1150 °C.

All other known alloys can be referred to the second group that significantly complicates their application in surfacing on the contact surface. For example, there is cobalt-based V3K-r alloy, having in its composition, wt.%: 28.0–32.0 of chromium; 7.0–11.0 of tungsten and 1.6–2.0 of carbon as main alloying elements and additionally alloyed in small amount by Si, Mn, Ni, B, Fe. Alloy strengthening is provided by formation of tungsten and chromium carbides [4]. Temperature of stable operation of this alloy does not exceed 600 °C.

Cobalt-based alloy Stellite 12 has similar composition, it includes as main alloying elements, wt.%: chromium 28.0–31.0; tungsten 7.2–9.2, carbon 1.55–1.75 and additionally Ni, Si, Fe and Mo. Alloy strengthening takes place as a result of formation of tungsten and chromium carbides [5]. Operating temperature of this alloy also doesn't exceed 600 °C.

There is nickel-based alloy Kh0N50Yu5T2, having, wt.%: 32.0–36.0 of chromium; 5.0–6.0 of aluminum; 1.4–2.1 of titanium; 1.2–1.6 of carbon as the main alloying elements and additionally boron and iron in small amount. High relative wear resistance of this alloy is provided by formation of $Ni_3(Al, Ti)$ intermetallics and chromium and titanium complex carbides. Such a strengthening mechanism is of low efficiency due to instability of γ′-phase under conditions of effect of significant contact loads at increased temperatures in oxidizing medium. This promotes for rise of intensity of alloy wear that is its significant disadvantage.

Aviation engineering successfully applies cobalt-based alloy KhTN-61, containing, wt.%: 19.0–21.0 of chromium, 15.0–16.0 of niobium; 2.7–3.3 of tungsten; 1.8–2.2 of molybdenum; 0.8–1.2 of aluminum and 1.95–2.30 of carbon, strengthened by disperse precipitations of niobium monocarbides and having high wear resistance exceeding that of nickel-based alloys due to resistance of strengthening phase [6]. Significant disadvantage of this alloy is its low high-temperature resistance and loss of properties in melting (melting temperature 1340±10 °C). Deposition of this alloy on the contact surfaces is possible only by brazing.

Similar composition has cobalt-based alloy KhTN-62, containing, wt.%: 5.0–25.0 of chromium; 13.5–17.0 of niobium; 6.0–12.0 of tungsten; 2.0–3.5 of aluminum; 2.0–5.0 of iron; 1.6–1.9 of carbon. Alloy has increased high-temperature resistance, however relatively low content of carbide phase (NbC) results in significant decrease of alloy wear resistance that is substantial disadvantage and does not provide in full all necessary complex of properties.

A basis of development of new adhesion-active high-temperature wear resistant composite consumables is a problem of providing a necessary level of their wear resistance at operating temperatures (to 900 °C), capability to withstand temporary thermal loads in oxidizing medium at temperatures to 1150 °C and possibility of deposition in form of melt on the contact surfaces at temperatures of their heating not more than 1220±10°C.

New high-temperature wear-resistant consumables KMKh and KMKhS, which correspond to the requirements given in works [7, 8], were developed together with SE GTSPC «Zorya-Mashproekt».

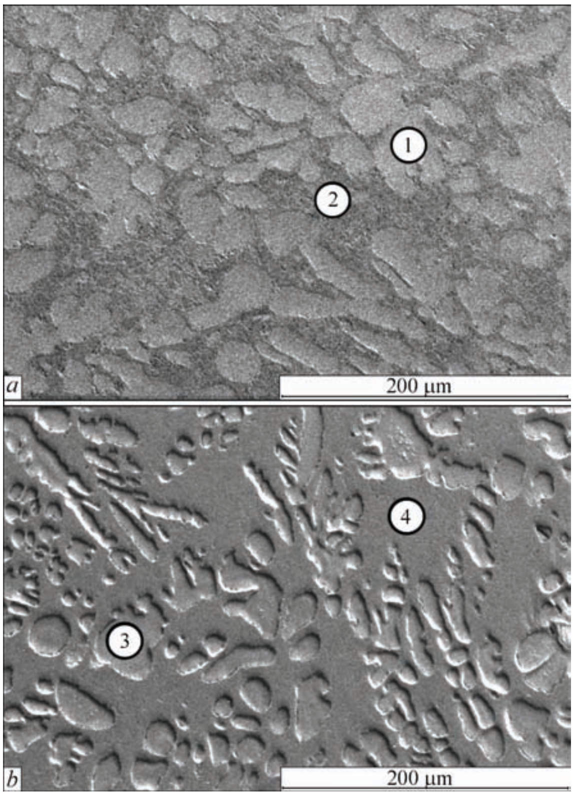
Table 1 gives composition and melting temperature of KMKh and KMKhS alloys.

Philosophy of the new materials design is based on application of cobalt-based solid solution alloyed by molybdenum and chromium as a matrix. It can withstand contact and thermal loads to 1000 °C temperature with additional implementation of boron and silicon, which reduce melting temperature and increase adhesion activity of the alloys to necessary level during deposition on the contact surfaces in liquid state. Besides, after solidification boron and silicon actively form uniformly distributed, thermodynamically stable, high-disperse strengthening phase, consisting of complex silicides and borides. This pro-

Table 1. Properties of KMKh and KMKhS alloys

Alloy grade	Composition, wt.%							Melting temperature*, ºC
	Co	Cr	Mo	Si	B	Ni	Cr_3C_2	
KMKh	Base	17–18	27–28	2.8–3.2	0.8–1.2	–	–	1185^{+5}
KMKhS	Same	17–18	27–28	2.8–3.2	0.8–1.2	2.8–3.2	1.9–2.1	1165^{+5}

*Melting temperature was determined by means of high-temperature differential thermal analysis.



Microstructure of KMKh (*a*) and KMKhs (*b*) alloys

vides for necessary high level of alloys wear resistance. Dosed additives of chromium carbides in KMKhS alloy somewhat reduce melting temperature in comparison with KMKh alloy and stabilize its structure and properties.

Table 2. Phase composition of KMKh and KMKhs alloys

Alloy grade	Interplanar spacing (experimental data), d_{hkl}	Interplanar spacing (reference data), d_{hkl}	Phase [9]
KMKh	2.046 1.775	2.040 1.770	Co
	0.219 0.185	0.219 0.183	CoB
	0.237 0.220	0.237 0.219	Mo_2B
	0.237 0.219	0.237 0.220	MoSi
	0.198 0.181	0.197 0.183	CoSi
KMKhS	2.047 1.776	2.040 1.770	Co
	0.219 0.185	0.219 0.183	CoB
	0.237 0.220	0.237 0.219	Mo_2B
	0.237 0.219	0.237 0.220	MoSi
	0.198 0.181	0.197 0.183	CoSi
	0.238 0.218	0.237 0.219	Cr_2C_6

Figure shows microstructure of the alloys, produced by vacuum-induction melting in vacuum of around 10^{-2} Pa with further annealing during 1 h at 1100 °C temperature. The alloys have regular double-phase structure, density and homogeneity of which rise at transfer from KMKh to KMKhS alloy. Hardness of KMKh alloy makes around 710–715 units (*HV*10) and that of alloy KMKhS is 735–740 units. Average microhardness (Hμ50) of constituent phases for KMKh alloy corresponds to 4771 MPa (zone 1, Figure) and 2365 MPa (zone 2) and that for alloy KMKhS is 6661 MPa (zone 3) and 3213 MPa (zone 4), respectively.

X-ray structure analysis of the alloy samples indicate that basis of both alloys is a solid solution of alloyed stable cubic cobalt (β-modification), which is uniformly reinforced with disperse precipitations of strengthening phases: CoB, Mo_2B, MoSi and CoSi. Alloy KMKhS, besides, contains chromium carbides Cr_2C_6 (Table 2). All identified phases have alternating stoichiometric composition and contain in different relationship alloys' element-components.

Comparative wear resistance tests of commercial alloys and new composite consumables KMKh and KMKhS were carried out using known procedure [10] under conditions of high-temperature fretting on gas-dynamic bench allowing complete reconstruction of operating conditions of the contact surfaces of turbine blades in the engine on loads, acceleration levels, heating and cooling rates, vibration frequency as well as gas medium. Aircraft kerosene TS-1 was used as a fuel.

Wear intensity was determined in wear resistance testing of studied samples: $J_V = V/N$, where J_V is the volumetric intensity of wear-out, mm^3/cycle; V is the volume of worn material, mm^3; N is the number of loading cycles (derivative of samples' oscillations). Other parameters corresponded the following conditions, namely static contact load 50 MPa; amplitude of relative movement of samples — 0.169 mm; oscillation frequency — 2500 min^{-1}; test time —2 h; temperature in area of contact of studied samples ~ 1150 °C.

Studied samples of high-temperature nickel alloy ChS88U-VI with 22×12×2 mm platform size were deposited by a layer of wear-resistant consumable of 2 mm thickness with further annealing at 1100 °C temperature in 10^{-2} Pa vacuum during one hour for stress relief. All surfacing consumables were used in form of rods of 2×2 mm section. Commercial surfacing consumables Kh30N50Yu5T2 and V3K-r were deposited by tungsten argon-arc welding (welding code 141), at that microcracks in a base to deposit-

Table 3. Results of testing of wear resistance of deposited samples

Tested material	Kh30N50Yu5T2	V3K-r	KBNKhL-2	KMKh	KMKhS
min–max average	7.718–14.408 10.126	Fractured		1.817–3.750 2.761	1.548–2.894 2.372
Wear intensity, J_v, mm^3/cycle	Based on testing 40 min			Based on testing 2 h	

ed metal transition zone conditionally were considered as inacceptable defects. Surfacing by stellite KBNKhL-2 and new adhesion-active surfacing consumables KMKh and KMKhS was carried out using oxyacetylene flame of normal regulation with GS-2 torch, nozzle No.2 (welding code 311). Surface for deposition and surfacing rods were fluxed by spirit solution of PV200 flux (relationship 1:7). After surfacing the samples were cleaned from flux remains using galvanic method, mechanically treated and tested by non-destructive fluorescence method. Wear tests were carried out on pairs of identic samples with area of mutual contact of around 50 % (12–14 mm^2). The results of tests are given in Table 3.

Analysis of test results showed that the commercial high-temperature wear-resistant alloys V3K-r and KBNKhL-2 did not withstand contact loads and completely fracture under heating to ~1150 °C. The samples deposited by commercial alloy Kh30N50Yu5T2 can work under such conditions only for limited time due to intensive wear. Developed new adhesion-active materials KMKh and KMKhS demonstrate significantly higher wear resistance at that average value of intensity of their wear based on two hours testing is 3–4 times lower than that in the surfaces deposited by commercial alloy Kh30N50Yu5T2 based on 40 minutes testing. Dosed additives of chromium carbides (in around 2 wt.% amount) in KMKhS alloy simultaneously with decrease of alloy melting temperature (by ~20 °C) result in rise of its wear resistance in comparison with KMKh alloy by 15–20 %. High wear resistance characteristics and possibility of operation under effect of critical temperatures allowed recommending developed composite consumables and technology of their surfacing on platforms of blades of ship gas turbine engines to commercial application at SE GTSPC «Zorya-Mashproekt».

Conclusions

1. Commercial high-temperature wear-resistant alloys, used in ship machine building, such as V3K-r, KBNKhL-2, Kh30N50Yu5T2 do not withstand contact loads and fracture under conditions of heating to critical temperatures.

2. Proposed new adhesion-active composite consumables KMKh and KMKhS can withstand critical temperatures up to 1150°C as well as demonstrate at that high wear resistance, satisfying the operation and repair requirements of current ship GDE.

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Received 09.12.2016