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Tribology Characteristics of Heatproof Alloys at a Dynamic Pin Ladening in the Variable Temperature Field

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ABSTRACT

An analysis of the operating conditions of gas turbine engines, their components, and the destruction causes was carried out. The designer problems of tribo-joints operating under difficult conditions of force and temperature loads are singled out. The study aimed at obtaining the comparable quantitative dependences of blade material wear, taking into account the role of both cyclical changes in the temperature of the gas flow under the conditions close to real ones, and their frictional characteristics. Deformable heat-resistant nickel alloys and foundry heat-resistant nickel alloys from which T-shaped samples were made, were chosen for the research. The tests were carried out on the developed gas dynamic stand, which simulates the working conditions of the bandage joints of the bladed turbomachines of gas turbine installations. The intensity of wear was determined as the ratio of the worn material volume to the number of load cycles under different temperature conditions. The wear resistance of three-way connections operating under the conditions of non-stationary thermal loads and fluctuations in the contact was considered. It was shown that thermal cycling leads to a decrease in the wear resistance of heat-resistant nickel alloys by 2–3 times and depends on the average temperature of the cycle. It wasfound that resistance to the wear, and also the character of change of coefficient of friction is mainly determined by the terms of education and destruction of the protective superficial layer. Basic factors managing tribology processes in the zone of contact were determined.

Keywords: heatproof alloys, thermocycling, tribocoupling, superficial layer, wear, wearproofness, hardfacing, coating.

INTRODUCTION

Gas turbine engines are used in various spheres of activity: air, sea and pipeline transport, energy, several critically important industries, etc. [1, 2]. In particular, gas turbine installations are an important part of the energy system of many countries. They are especially useful in the situations where a quick start-up or shutdown of the power system is required, as well as during peak loads. Gas turbines can work on different types of fuel, which makes them very flexible in use, and they can also be adapted for the production of electricity for a city or a region [3–5]. Gas turbine plants are successfully used in the chemical, oil and gas, and metallurgical industries, as they are characterized by high fuel efficiency compared to other types of power plants. Most commercial aircraft use turbojet or turbofan engines that provide the necessary power for flight and can operate stably at high altitudes. Gas turbine engines are used on large sea vessels (tankers, cargo and military ships, passenger liners, etc.) [6, 7]. The gas turbine drive is also used for modern tanks. Therefore, improving the operational characteristics of elements of turbojet installations is an urgent task.

During the gas turbine performance, operators face several problems: at low loads, their efficiency can significantly decrease; slight deviations in the operation of cooling systems can lead to overheating of engine parts and damage or loss of efficiency; leaks of liquid fuel or flammable gases can create a fire hazard. At the same time, as a result of high temperatures and mechanical loads, the blades of the turbines as well as their bandage and lock connections can undergo significant wear and damage [8]. Detection of failures of gas turbine parts with possible causes and methods of elimination are discussed in papers [9, 10].

The study [11] investigated the parameters of interatomic interaction in alloys containing nickel, which can serve as a theoretical basis for the development of new compositions of heat-resistant alloys. Researchers [12] developed the concept of software for the rational selection of materials. To improve the quality of products, optimization of the technological processes of manufacturing parts is also used [13].

The works [14, 15] provide an overview of the main methods of applying thermal barrier coatings and evaluating the efficiency of blade cooling systems for gas turbines. Particulate erosion is a common phenomenon observed in gas turbine engines. Composites with a ceramic matrix are the main candidates for protecting components of hot sections of gas turbine engines [16, 17]. Calculation of the thickness of protective coatings is usually a complex multi-criteria optimization problem due to the contradictions that arise between the goals of the task: achieving high thermal insulation characteristics, ensuring long-term operation, manufacturability and low manufacturing cost [18–20].

The studies [21–23] introduced the models for studying the effect of abrasive on covered parts. The impact and abrasive wear resistance of protective coatings were studied in papers [24–26]. Researchers [27–29], based on the model of contact along the line, considered the issue of the mechanics of the destruction of plate parts, taking into account the partial closure of crack-like defects during bending. Similar problems about the behaviour of contact cracks in plates under the action of simultaneous stretching and bending were studied in publications [30–32].

Some authors studied contact phenomena in lock joints [33, 34], including taking into account energy dissipation during mutual sliding on contact surfaces [35]. Analytical-numerical [36, 37], experimental [38, 39] and technological [40, 41] approaches to the study of stresses in composite structures also deserve attention. The temperature distribution in layered elements was also studied [42, 43]. However, such studies are usually performed for bodies of simple forms. It should be noted that the qualitative properties of analytical solutions of a much more general system were studied in [44, 45].

When creating tribojoints (e.g., bandage joints and interlocking bladed turbomachines) that operate in rough conditions, i.e. high power loads and high temperatures, the designer has a number of challenges and difficulties. Among the design problems, two are most important:

- limited number of given data regarding influence load on properties not only particular joints, but also parts materials included in joint;
- the results obtained in laboratory terms by different researchers are incomparable [46, 47], as conducted on different methodologies, at the different modes of ladening.

In the article an attempted has been made to complete this subject (solve the problems). The ultimate goal of the research is a receipt of comparable quantitative dependences of wear paddles materials, taking into account the role of both cyclic changing temperature of the gas stream under the conditions of near to the real and their friction descriptions. However, as a mechanism of wear in these terms is very complicated and determining terms of his modification is difficult, then limitations were laid on in studies, foremost on the high bound of thermocycle in relation to the temperature of exploitation knot, in order to eliminate possible irreversible structural changes in material [48, 49].

MATERIALS AND METHODS

Table 1 shows the chemical composition of the tested deformable heat-resistant nickel alloys, i.e. KHN62MVKYU and KHN77TYR (GOST 5632–72 Standard. High-alloy steel and corrosion-proof, heat-resisting and heat treated alloys. Grades) and foundry heat-resistant nickel alloys: ZhS6U, ZhS6K

Table 1. Chemical composition of heat-resistant nickel alloys

Element, wt. %	Alloys grade				
	KHN62MVKYU	KHN77TYR	ZhS6U	ZhS6K	VZhL2
C	0.1	0.07	0.13–0.20	0.13–0.20	0.11–0.17
Si	0.6	0.6	0.4	0.4	1.0–2.0
Mn	0.3	0.4	0.4	0.4	–
Cr	8.5–10.5	19.0–22.0	8.0–9.5	9.5–12.0	12.0–15.0
Ti	–	2.4–2.8	2.0–2.9	2.5–3.2	2.0–3.2
Al	4.2–4.9	0.6–1.0	5.1–6.0	5.0–6.0	1.5–3.0
W	4.3–6.0	–	9.5–11.0	4.5–5.5	8.0–10.0
Mo	9.0 – 11.5	–	1.2–2.4	3.5–4.5	12.0–15.0
Nb	–	–	0.8–1.2	–	–
Fe	4.0	1.0	1.0	2.0	2.0–3.5
S	0.011	0.07	0.011	0.015	0.02
P	0.015	0.015	0.015	0.015	0.02
Co	4.0–6.0	–	9.0–10.5	4.0–5.5	–
B	0.02	0.01	0.035	0.02	0.065
Ce	0.02	0.02	0.02	0.025	–
Pb	–	0.001	0.001	0.001	–
Zr	–	–	0.04	0.04	–
Bi	–	–	0.0005	0.0005	–
Y	–	–	0.01	–	–
Ni	Basis	Basis	Basis	Basis	Basis

and VZhL2 (OST 1 90126–85 Industry standard. Heat-resistant alloys foundry of vacuum smelting).

To carry out wear tests, alloys were used (Table 1), from which T-shaped samples were made (Figure 1).

During hard engine starting modes, the temperature rises rapidly from ambient to maximum. Material of details tribojoints in these condition is in the difficult enough tense state arising up from an action cyclic mechanical and thermal loads causes thermo fatigued destruction. The cyclic changes of temperature causes craks formation and propagation. Moreover, KHN77TYR alloy duration of work decrease almost 2–3 times with comparison to stationary tests in increase temperature. At warm-up engine both protracted and brief durability decreases, i.e. there is more intensive cracks propagation from the appearance of thermal strain. Therefore, it is expedient to define the influence of thermocycle parameters (t_c – temperature change range, °C; τ_h – heating rate, s; τ_{cool} – cooling rate, s) on the wearproofness of heatproof materials.

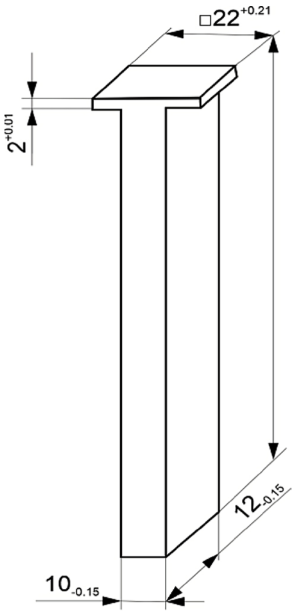

Fig. 1. Specimen for wear testing

The samples made of heat-resistant nickel alloys were tested on a specially developed gas-dynamic bench National University “Zaporizhzhia Polytechnic”, Ukraine [50, 51], which allows the simulation of the working conditions of bandage connections of bladed turbomachines of a gas turbine installation. The intensity of wear, in relation to the volume of threadbare material, was determined by the amount of cycles of loads. The volume of the worn alloy was determined by the size of the friction zone and the amount of linear wear. The amount of linear wear was measured using a dial indicator with a division scale of 1 μm (1MIG GOST 9696–82 Standard) and a profilogram of the sample surface with the original and worn area was constructed. Wear zone 2x12 mm is shown in Figure 1. The result was taken as the arithmetic mean of three wear tests. The standard deviation of the measurements did not exceed 5% of the mean value. Comparison obtained at the different loads, amplitudes, and temperatures of results conducted on the coefficient of wear K_W

$$K_W = I_V/pAF_n\, t \tag{1}$$

where: I_V – the intensity of wear, mm^3/cycle;
p – the specific loading in a contact, kg/mm^2;
A – amplitude of the mutual moving of standards, mm;
F_n – a nominal area of contact, mm^2;
t – a temperature of tests.

Mechanical loads realized at the next modes:

- the amplitude of the mutual moving of patterns – 0.1 mm;
- specific pressure is in contact – 27 MPa;
- frequency of vibrations patterns – 33 Hertzs;
- a base of tests – $0.5 \cdot 10^6$ cycles.

The comparative tests of wear heatproof nickel-alloys at a thermocycling were conducted at the hardest ladening on when the temperature drops and speed of heating and cooling, near to the thermo shock (at $t_c = 20 \leftrightarrow 700$ °C, $\tau_h = 7$ s, $\tau_{cool} = 11$ s; $t_c = 20 \leftrightarrow 900$ °C, $\tau_h = 12$ s, $\tau_{cool} = 18$ s).

RESULTS AND DISCUSSION

In tests conditions the absolute value of wear of the investigated alloys (see Figure 2) exceeds the wear at a ambient temperature almost tenfold, at equal maximal temperature of the cycle (terms of mechanical loads are the same). Therefore, considerable wear at a thermocycling is the result of two basic processes in the flow of one thermocycle:

- fatigued – at temperatures below transition temperatures from high wear to stable at tests in isothermal conditions ;
- oxidizing – at temperatures higher than transition temperatures.

These two processes are accompanied by the phenomena, inherent to thermal fatigue, assisting the destruction of local volumes of material.

Comparison of coefficients wear conducted under various conditions shows that at a ambient stationary temperature at a thermocycling pattern of behavior curves are practically the same (see Figure 2) and well enough described by dependences of a kind:

- for the alloy KHN77TYR

$$K_W = \exp(\alpha\, t^2 + \beta \ln t + \gamma/t) \tag{2}$$

- for the alloyZhS6K

$$K_W = 1/(\alpha/exp\, t + \beta\, t^2 + \gamma_1/t) \tag{3}$$

where: K_W – the coefficient of wear;
t – a temperature of tests;
$\alpha, \alpha_1, \beta, \beta_1, \gamma, \gamma_1$ – are the coefficients determined by the contact load, speed and amplitude of the mutual moving working surfaces.

Empirical dependences (2) and (3) are obtained based on the mathematical processing of experimental results.

The absolute value of coefficient wear at thermocycling is higher (approximately 4.7 times for the KHN77TYR alloy and 6.6 times for the ZhS6K alloy) than in the case of the test at t = *const.* It is significant to decline of speed reduction of

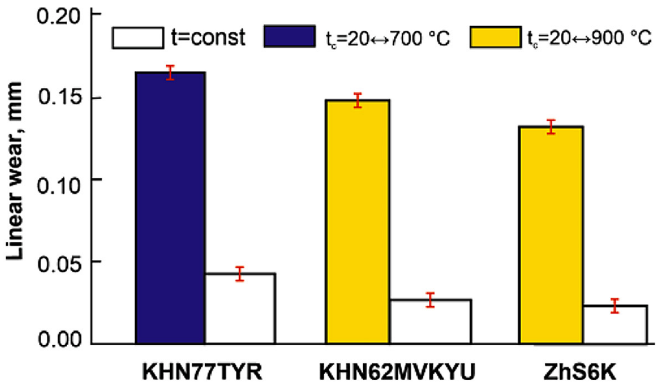

Fig. 2. Wear of heatproof alloys at a thermocycling and stationary temperature

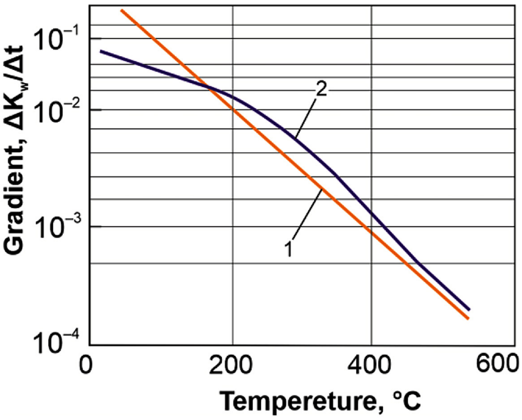

Fig. 3. Speed of reduction coefficient wear of the KHN77TYR alloy depending on a temperature: 1 – t = *const*; 2 – t_c = 20 ↔ 700 °C

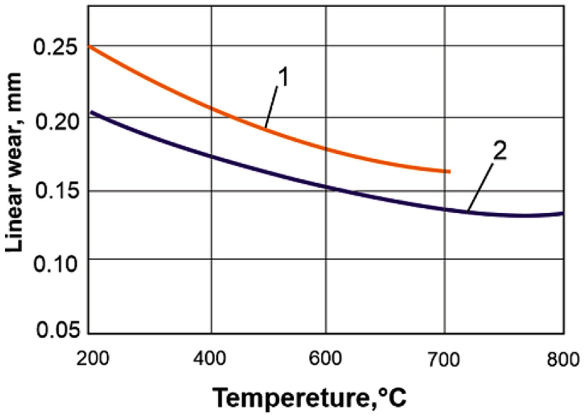

Fig. 5. Influence of temperatures in thermocycle on the wear of alloys KHN77TYR (1) and ZhS6K (2)

K_w with the height of temperature (see Figure 3). However K_w factor is in an area of more low temperatures than at high.

The same changes of speed decline K_w damage of material (higher intensity of wear) is explained at a thermocycling. The identity of the behavior of curves of $K_c = f(t)$ (see Figure 4) testifies to the regular processes that happen in contact.In the case of t = *const* at room temperatures, wear is a result of fatigue processes (on the type of pin fatigue) [52], and may overlap with oxidation, which is the predominant factor in this case.

From the analysis of wear materials in the range of temperatures from a room, it is necessary value to maximal (see Figure 4), that the basic state of general wear is the wear at temperatures below transition temperatures, as half time pin co-operation is caused at these temperatures.In this case, oxides appear in very negligible quantities.It is insufficient for the formation of protective layer. Therefore contact is mainly on new surfaces. As in the case of wear at ambient temperatures, adhesion processes are possible. In this temperature range, as at thermocycling there is a transfer of material from one surface to another.

The impact of some parameters thermocycle of on wearproofness heatproof alloys of ZhS6K, KHN77TYR is shown in Figure 5 an Figure 6.

With an increase in both the maximal and middle temperature of the cycle (see Figure 6) the

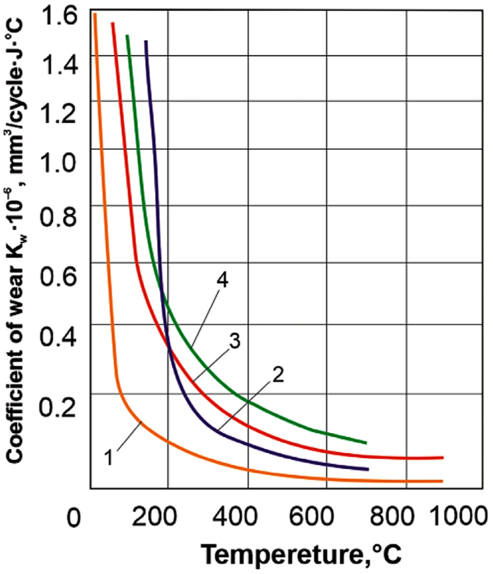

Fig. 4. Temperature dependences of coefficient wear of the ZhS6K (1, 3), KHN77TYR (2, 4) alloys at a thermocycling (3, 4) and at t = *const* (1, 2)

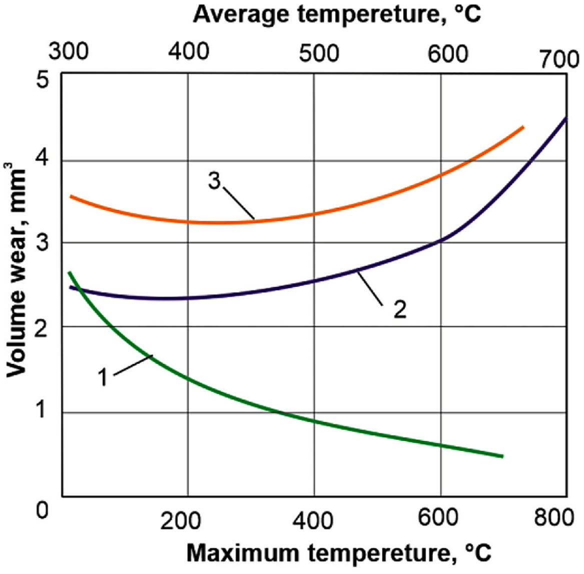

Fig. 6. Wear of alloys KHN77TYR (1, 3) and ZhS6K (2) depending on the maximal (3) and middle (1, 2) temperature of the cycle in different environments: 1 – in the air; 2, 3 – in an argon

wear of all investigational alloys tends to decline/decrease. This decline is conditioned by properties of the protective oxide layer that appears at a thermocycling, though less intensively, what at t = const. The rate of wear decline alloy of ZhS6K some less in area of range temperatures 20↔700 °C and even changes the trend at 20↔900 °C. Such character of change is conditioned by a propensity to the embrittlement of this alloy in an area of temperatures 700–800 °C. During the dynamic pin loads , due to the completely use the plasticity reserve, assist fatigued destruction.

In the conditions of thermocycling, as with isothermal tests, oxidizing processes play a substantial role in the decrease of durability The proof is experiment of the wearproofness alloy of KHN77TYR and ZhS6K in the conditions of thermocycling to added in the zone of friction argon. In reference to charts in Figure 6 in an air environment with the increase of average temperature of cycle wear alloy of KHN77TYR drop (curve 1) because of intensification oxidizing processes with the increase of temperature. In this case, different cycles were used by changes the values of the initial and final temperatures, which made it possible to expand the possibilities of analyzing the influence of a large number of different values of the average cycle temperature on the wear resistance of the alloys under study.

However, entering the friction zone argon changes the characters of curve wear depending on temperature (curves 2 and 3). With an increase a t_{max} wear does not drop, but increases because oxidizing processes are suppressed in this case, the protective function of oxides is lack and thermal fatigue processes begin initialize. It should be noted that in a neutral environment, the wear of alloy ZhS6K with the increase of t_{max} increases quicker, than KHN77TYR as keeps a less (almost 5 times) reserve of plasticity.

The impact of parameters thermocycle on wearproofness of materials shows up mainly through tensions appearing both as a result of the heat of changing and through tensions formed during oxidation. Variable thermal effect because of different speeds of heating and cooling causes heating tensions of compression, that on an absolute value considerably exceed tensions of stretching. Consequently, superficial layers practically fully are in the conditions of the asymmetric cycle of the compression equated by a condition:

$$-1 < \sigma_{cool} / \sigma_h < 0 \tag{4}$$

where: σ_{cool} – are tensions arising up at cooling;
σ_h – are tensions arising up at heating.

Thermal cyclic tensions are determined by the difference in temperature in the cycle (t_{max} and t_{min}).

Increasing temperatures in the process of thermocycling cause the oxidization of superficial layers, attended with penetration on the depth of layer metal oxide mixture of type spinels, because oxidization is not only on a surface but also on the borders of grains, and also in pores and nearby areas. The metal oxide mixture in a superficial layer has lower values of coefficient thermal expansion characterizes as basic metal (see Table 2). Also because of that the volume of oxides exceeds the volume of metal an oxide formed of that several times, there are tensions at a thermocycling. These tensions are compression, if the temperature of the pattern below than temperature of the formation oxide layer and stretchings, if the temperature of the pattern exceeds the temperature oxides appear at that. Remaining tensions arising up at oxidization, in the interval of temperatures 20↔800 °C (at cooling) arrive at considerable sizes, order of 26 MPa [53]. Variable cyclic tensions formed and as a result of the heat changing and as a result of oxidization cannot coincide on a phase with tensions arising up at the appendix of the dynamic pin loads. However in any case there is cumulation of damages, which accelerates the process of microcracking in the damaged superficial layer and the process of cracking and removing layer by layer of oxides considerably.

During thermocycling, there are changes in decrease of hardness carbides mainly at borders grains and precipitate of alloying elements, which change the parameter of the crystalline grate of alloy. The increase amount of heat change a carbidic phase appears as point inclusions. They located from borders deep into grains that then can be locked in carbidic layers. Development of such

Table 2. Coefficients of thermal expansion of some oxides and alloys [53]

Materials	Interval of temperatures,°C	$\alpha \cdot 10^{-6}$, 1/°C
ZhS6K	20–600	13.3
KHN77TYR	20–700	15.1
NiO	400–800	12.8
Cr_2O_4	400–800	7.5
Al_2O_3	400–800	9.0
TiO_2	400–800	8.15

carbidic excretions causes the embrittlement of alloy, which is contributed to decline of the duration cycle "strengthening – unstrengthening" and subsequent separation of particle wear. Similar to the case of tests in isothermal conditions the growth of sizes γ' – phase. Therefore, coagulation takes place at a thermocycling, that results in a general coarse of structure for an alloy ZhS6K. The growth of sizes γ' – phase is observed both at the growth of the number of thermocycles and at the increase of the interval cycle. In both cases is the increase of tension γ' – phase and reduction of the degree of her putting in order. An increase in the size of the intermetalline phase at heat of changing assists dislocation mobility, which affects, in the final analysis, on friction tiredness.

In the thermocycling process the wear on poorly etch surface appears zone of small depth impoverished by alloying elements. This zone has high hardness (17–19 GPa) and in the process of pin interaction, there is its permanent crushing and displacement. On some alloys, there is sheared formation, Carlsbad twin of in subsuperficial zones. Presumably, the change of heat at a high t_{max} cycle cause rapid material ageing.

At thermocycling structural and phase changes in the superficial layers of metal are practically the same, as in the case of wearproofness tests in isothermal conditions. However, these changes are quicker.

Along with wearproofness other important tribology characteristics of construction materials is a coefficient of friction, which at a dynamic pin loads will allow to precisely select a wearproof material. For constructors it will be helpful to make dicision regardin material for example for the bandage shelves of working shoulder-blades turbine turbo-engines. Experimental research selected heatproof alloys was performed on methodology [50]. Based on the tests of alloys ZhS6U and VZhL2, it is concluded that in dynamic character conditions of application loads in the contact layouts the coefficient of friction alloys decrease, according to formula:

- for the alloy ZhS6U

$$f_f = 29.346\ n^{-0.30939} \tag{5}$$

- for the alloy VZhL2

$$f_f = 0.95889\ n^{7.72127} \tag{6}$$

where: n – a number of loads.

In an initial period the change of coefficient friction is uneven, and these vibrations, for example, for the alloy of ZhS6U make 20–25% from nominal. The instability of coefficient of friction in a primary period is a result of character interaction contacting surfaces, affecting a lot on final size of wear. Probably, maximum values correspond to the period of the mechanical interaction roughs, accompanied with adhesion processes in the zone of contact. The minimum values of coefficient friction are in the period of destruction of separate ledges on pin surfaces, including appearing in initial period products of transfer metal.

The uneven change of coefficient friction is conditioned yet and by that for every cycle of contact speed of slipping becomes equal to zero, at that the moment beginning of the movement is consequently the biggest and a coefficient of friction will be maximal. In addition, the uneven changes of coefficient friction cause the additional vibrations (to take place at a dynamic pin loads) of the normal load, frequency will be determined by the stiff of the tribology system. In the case of the dynamic of the normal loading, these vibrations can increase (at resonance) or decrease (at asynphases vibrations). Duration of period uneven change of coefficient friction (expressed in this case by the number of cycles loads Ncr) is determined, in the final analysis, by the temperature dependence of wear contacting materials (see Figure 7) The alloy of ZhS6U has this smooth enough change, while at VZhL2 there is a maximum value N_{cr} at a temperature of about 400 °C. Similar in the case of dependence wear on a temperature [52] duration of this period defines time, during that a protective layer consisting mainly of products oxidization of material appears on a surface.

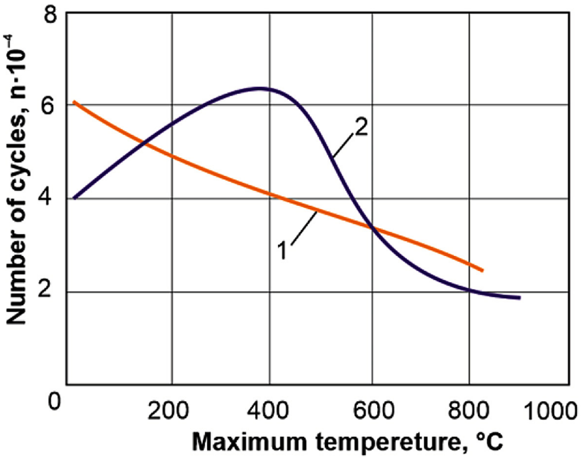

Fig. 7. Change of duration passing to the set value of force friction depending on a temperature: 1 – ZhS6U; 2 – VZhL2

Higher the temperature in the zone of contact, the less duration of this period. The necessary condition of passing to the set period of friction is stopping contact with new surfaces due to the formation of a sufficient amount of oxides and conglomerates, making a protective layer. On the surfaces of friction the separate shiny, almost mirror spots of contact, perceiving on itself loads, appear at the end of this period. With the increase of temperature over 600 °C separate spots in general complication occupy more than 50% of contour area contact. It should be noted that, unlike the reversible or unidirectional friction of skidding in the conditions of dynamic pin ladening at temperatures below transition temperatures such spots of contact on a surface appear even if, the speed of their appearance is considerably less speed of destruction. Formation and subsequent destruction of such spots contact, presumably, will be determined by the speed of formation protective layer, which has influenced the ability for oxidization of alloys, property of oxides, their propensity to dispergating and deformation under the action of external mechanical (amplitude, effort, frequency) and thermal parameters of loads. It should be noted that micro- and nanoparticles of metal oxides have different functional properties [54], therefore, their different effects and mechanism of wear of parts can be expected. In addition, the durability (in particular, fatigued) of separate ledges, their cyclic viscidity and dependence on adhesion processes from a temperature, affect on longevity of such layers. All indicated factors are in permanent interaction and must be examined complexly consider the external terms of loads.

Despite the significant progress achieved in tribology, many problems related to the improvement of wear resistance and reduction of friction losses are still not fully understood. This is due to the wide range of mechanical and physicochemical phenomena that occur in the contact zone. Simultaneous analysis of all such phenomena is nearly impossible . It is advisable to consider a limited set of informative parameters which may be sufficient to comprehensively characterize a tribosystem.

Moreover, in testing on a friction machine, the tribocontact loads conditions should correspond as close as possible to the real conditions of tribojoint operation. It is a matter of general experience that a variety of wear mechanisms exist. Variation in any given factor, or the appearance of a new one, can result in changes in the wear mechanism. Numerous studies into many load factors have been conducted and friction and wear regularities have been determined under specified conditions. The solution to the problem of the surface strength of friction pairs under normal vibrations is only possible after finding the main mechanisms and features of the contact destruction of two solids that are nominally stationary relative to each other and subjected to simultaneous vibration as well as variable temperature.

According to the obtained results (Figure 2), the cyclic temperature change contributes to a decrease in the wear resistance of heat-resistant nickel alloys by 2–3 times compared to tests at a constant elevated temperature during the tribo-joints operation of nodes of various machines and mechanisms under conditions of complex dynamic load and non-stationary temperatures. This is important, since most tribo-junctions, in particular, aircraft gas turbine engines, are operated under conditions of complex dynamic loads. At the same time, there is a combined effect of high temperatures, the properties of an aggressive gas environment, and the mutual movement of parts with the presence of vibrations acting in different directions, including the presence of shock loads. Without consider the entire complex of load factors, the research results are distorted and a picture of the wear process is created, which does not match the real one.

The complex non-stationary nature of the load leads to a specific stress state of the surface layers of tri-joint materials, which significantly affects its wear resistance. This is accompanied by a change in the coefficients of friction and wear, as can be seen from the analysis of the obtained results (Figure 3, 4), which is determined by the conditions of formation and destruction of the protective surface layer. Moreover, as follows from the obtained results (Figure 5, 6), the wear resistance of heat-resistant nickel alloys also depends on the temperature in the thermocycle. With an increase in both the maximum temperature and the average temperature of the cycle (Figure 6), the wear of all studied alloys tends to decrease. The appropriate mechanism of wear of heat-resistant nickel alloys in the considered contact conditions is described.

This explains the limited possibilities of using the general provisions of friction theories, as well as most of the results of experimental studies. In addition, traditional research methods are based on the separate study of the influence of one or an extremely limited number of factors without consider their interaction, as well as without consider the dynamics of the tribosystem as a whole. It is known that the wear of heat-resistant alloys can occur by several different mechanisms. A different nature of wear depending on temperature occurs both for heat-resistant alloys based on Ni and Co and for mild steels based on Fe. A change in one or another load factor and the appearance of a new factor lead to a change in the wear mechanism and its physical picture.

Previous studies [48, 50, 51, 52, 55] established the need for a comprehensive study of the wear resistance of tri-joints, taking into account the contact conditions, especially temperature and its changes during operation. At the same time, the plastic-destructive attributes of the metal during friction should be considered a physicochemical process, that is, a process accompanied by a complex of structural, physical, and physicochemical changes in the state of the surface layer of the deformed alloy. However, the influence of non-stationary temperature on the wear resistance of tribo-joints under conditions of complex dynamic load is practically not covered in publications.

Of course, the results of the first stage of research are given. In further research, it is necessary to more deeply consider and analyze the actual state of the surface layer of alloys after tribological tests, the corresponding traces of wear on the friction surface, determine the influence of the chemical composition and physical and mechanical properties of alloys on wear resistance under the considered friction conditions. The given materials present the results of the study of the attributes of heat-resistant nickel alloys under the conditions of testing tribojunctions maximally close to the operating conditions of aircraft gas turbine engine assemblies. But it is necessary to consider the wear resistance of other alloyed steels that are used for the manufacture of tri-joint parts that are operated at non-stationary lower temperatures, including at cyclic negative temperatures.

In world practice, the trend of development of functionally oriented research methods and their correlation with data obtained during field tests can be observed. This is quite natural since the design of tribonodes based on traditional design solutions without taking into account the specificity of their operating conditions (first of all, changes in load parameters over time) often leads to the fact that such designs of triboconnections turn out to be insufficiently reliable. It is appropriate to note that the reliability of the results obtained during full-scale tests is very low due to a large spread of the controlled values, which are a consequence of the nature of the contact interaction, which changes over time. This character of each machine is its own and depends both on the structural features of the part and components, their manufacturing technology, and on the operating conditions. Therefore, there is an urgent need to determine the nature of the load of tribonodes, the ranges of load parameters, and their evolution during operation, determined based on statistical data of a typical set of load modes and their changes over a set period.

After studying the influence of each of the load parameters separately or in combination on the tribo characteristics of the unit and its parts, it is possible to determine the equivalent state of the contacting surfaces and then simulate these states in laboratory conditions. Such simulation makes it possible to increase the reliability of the obtained results and significantly reduce the duration of tests. On the other hand, the study of the mechanism of damage to materials, and the creation of wear models of the contact surfaces of parts that work in extreme conditions, allow to purposefully create (or choose from among existing) wear-resistant materials, to develop constructive and technological measures aimed at increasing the durability of parts that wear out. The considered regularities of changes in the wear resistance of tribo-joints depending on the operating conditions can be useful to specialists during the construction of gas turbine engine assemblies.

Research results [55] show that by optimizing the structural state of the surface layer, an increase in the wear resistance of alloys is achieved.The obtained results of tests of nickel-based alloys at different temperature requirements are consistent with the results of research [10], where the influence of the stress-strain state of metal parts on the operational characteristics of gas turbine engines was studied.

Research results [56] showed that to extend the life cycle of gas turbine engines, it is advisable to use surfacing to restore worn parts from heat-resistant nickel alloys. Rationally selecting heat-resistant alloys for the manufacture of parts and operating modes, it is possible to increase the resource of gas turbine engines [57] and their environmental friendliness [58].

Further studies, it is planned to investigate the wear of heat-resistant alloys during an asymmetric loading cycle, examination of images of wear marks, as well as analysis of materials after testing.

CONCLUSIONS

The article research the effect of thermal cycling on the tribological characteristics of heat-resistant nickel alloys. Based on the conducted experiment, it was established that:

- The wear resistance and tribological characteristics of heat-resistant alloys depend significantly on the conditions of dynamic and temperature contact of the tribojoint.
- Cyclic temperature changes contribute to a decrease in the wear resistance of heat-resistant nickel alloys from 2 to 3 times compared to studies at a constantly elevated temperature.
- The absolute value of the wear coefficient during thermocycling in the range 5 to 7 times higher than during tests with a constant temperature, which is determined by the conditions of formation and destruction of the protective surface layer.
- The factor of friction is characterized by a step change and depends on the oscillations of sliding in the contact zone and the temperature of thermocycling.

The analysis of results researches of tribology characteristics of heatproof alloys shows impact of different combinations of factors dynamic pin loads and cyclic thermal. The most contribution to damage of materials have the processes of grasping and phenomenons of the pin thermo fatigued.

In conclusion, researches allow to find the principal reasons for the decline wearproofness heatproof alloys. In addition, investigations let to define impact degree of factors on the pin surface. That allow to set process wear parameters necessary for the proper constructing of tribocouplings in the final analysis.

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