MULTIDIMENSIONAL DESIGN OF TECHNOLOGY FOR OBTAINING SOLID LUBRICANT COATING ON TOOL HARD ALLOY

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This article deals with the new method for producing solid lubricant coatings on hard alloy tools by thermo-hydrochemical treatment (THCT). The results of investigation of the tribotechnical properties of solid lubricant coatings obtained on hard alloy ВК6 grade (94 % WC + 6 % Co) using THCT method are presented. The composition of the medium and the temperature and the time parameters of THCT process were optimized by the friction coefficient of solid lubricant coatings. The diagrams of "parameters of process–property" were constructed using mathematical models. Processing by optimal THCT regime of ВК6 hard alloy in hydrosol medium based on TiO_2 - MoO_3 makes it possible under the condition of lubrication absence to decrease the friction coefficient of hard-alloy surface by 3,8–4,2 times as compared with untreated.

KEYWORDS:
Thermo-hydrochemical treatment, solid lubricant coating, tool, hard alloy

1 INTRODUCTION

Cutting and other forming tools made of hard alloys are intended for the high-performance mechanical processing of complex alloyed hard-to-process steels and alloys with special properties. But, hard-alloy tools still have insufficient service durability. There are different ways of increasing it. The main trend of present foreign technologies is the development and application of wear-resistant coating from refractory compounds obtained by the methods of PVD (physical vapor deposition), CVD (chemical vapor deposition), spraying, and TCT (thermochemical treatment) in vacuum, activated by nonconventional heating sources (plasma, laser, electron beam, etc.). However, these techniques of strengthening have a series of disadvantages, the main ones of which are as follows: high process temperatures resulting in the deformation of products and weakening of the initial matrix, low productivity and complexity of the processes, high labor intensiveness and energy consumption of the processes, environmental degradation and harmful energy effect on human health, high cost of the applied equipment and components, etc. [Hocking 1989], [Cavaleiro 2006], [Shmatov 2018]. So the process of thermo-hydrochemical treatment (THCT) is of the greatest scientific and practical interest, because it is distinguished by simplicity and high efficiency and productivity; it makes it possible to obtain coatings based on any ceramic materials; it is applicable to operation-ready products made of various alloys, and it slightly changes their initial sizes, shape, and structure [Shmatov 1998], [Shmatov 2014], [Shmatov 2016], [Shmatov 2017], [Shmatov 2019].

THCT is intended for the chemical deposition of various materials antifriction solid lubricant coatings, which possess spare capacities under severe and catastrophic conditions of operation of tools and parts made of various steels, alloys and materials [Shmatov 2014]. The coatings acquire solid lubricant properties in the following cases: (1) they are created from materials with layered polycrystalline structure (graphite, sulfides, etc.); (2) they are formed on the basis of nanostructured refractory and superhard materials; (3) the Bernal theory is fulfilled, according to which any solid body acquires the properties of a liquid if the crystal lattice contains more than 10 % of vacancies; (4) the Rebinder effect is fulfilled, which leads to the plasticization of surface layer and creation of a positive gradient of mechanical properties in the friction zone; (5) the Kirkendall effect is fulfilled, which leads to selective dissolution of alloying elements from alloy owing to the differences in their electrochemical potentials, resulting in a quasi-liquid film being formed, which decreases the friction coefficient and frictional heating [Polzer 1983].

THCT is the simplest and most universal method for obtaining solid lubricant coatings. Using the method, one can create nanostructured coatings based on oxides, sulfides, carbides, diamond, carbon, and other antifriction materials [Shmatov 2014]. Upon the formation of such coatings, the Rebinder effect is fulfilled owing to introduction surface-active substances (SASs) into an aqueous-dispersion medium. The obtained nanostructured coatings have superplasticity, and they facilitate the gap of adhesive joints in the friction zone; at the same time, the hardness of nanomaterials made of metals and refractory compounds increases by 2–3 times [Cavaleiro 2006]. According to vacancy-diffusion and adhesion deformation mechanisms of friction, increasing the wear resistance of solids is achieved by a combination of the above-mentioned effects: high hardness of its surface and low strength of adhesive bond [Polzer 1983].

Since in most cases as a result of THCT, the initial structure is retained (is not softened), and final dimensions and shape of products hardly change, these coatings can be applied onto ready-made tools. On the other hand, under the conditions of intense operation of tools when there is no lubricant in the friction zone or its supply is limited, the best way to reduce the friction of the cutting edge is depositing solid lubricant coatings on it [Vityaz' 2007], [Shmatov 2014], [Shmatov 2017].

From the above presented analysis, it follows that the THCT process has great prospects for its development, first of all, for high-performance tools experiencing significant mechanical and temperature loads. In this regard, special attention should be paid to the tools made of hard alloys (of the VK, TK, TTK, and other brands) which owing to their high hardness, wear and heat resistance are widely used to fabricate various types of cutting and punching tools.

The mathematical methods of planning experiments which make it possible to acquire maximum information at a minimum cost, can provide a researcher with great support in the labor-intensive selection of the optimum option of executing the process of THCT of alloys. In materials science, direct problems are traditionally solved, when the properties of a material are determined on the basis of a minimum number of experiments performed according to the predefined temperature–time modes (according to the experimental design); then mathematical models are created which describe the influence of the factors, and optimum process parameters are selected using graphical interpretation [Novik 1971]. However, such an approach can not solve the entire set of problems emerging upon designing a technology because the functioning of any process system (in this case, the technology for THCT of the ВК6 hard alloy in hydrosol medium based on TiO_2 - MoO_3) occurs under the conditions of constant random variation of the values of the parameters of the system under the action of various external and internal destabilizing factors. Process systems themselves as the design objects possess a series of specific features: multiparametricity multicriteriality, stochasticity (spread of parameters), presence of nonlinear intrasystem connections, etc. When studying, designing, and exploring such objects, it is necessary to solve not only direct but also inverse problems, when the researcher predefines a set of the required properties of the material and finds the optimum temperature–time process parameters using computer modeling. This methodological approach, named a multidimensional design synthesis of technological system, is successfully applied in development of new technologies and materials [Vityaz' 1971], [Shmatov 2014], [Shmatov 2019].

In view of the above, the aim of this work was the optimization and computer-aided design of THCT technology in hydrosol medium based on TiO_2 - MoO_3 for the preparation of a solid lubricant coating on ВК6 hard alloy using the method of multidimensional design synthesis of technical objects, technologies, and materials.

2 OBJECTS AND METHODS

ВК6 hard alloy (94 % WC + 6 % Co), which is widely used in practice for cutting, milling, boring, and hole enlarging of cast iron, refractory and nonferrous alloys, and nonmetallic materials, has been subjected to thermo-hydrochemical treatment. The THCT process itself was carried out by conducting two of operations: (a) hydrochemical treatment (HCT) of hard alloy surface at 95–100 °C for 10–30 min in a specially prepared aqueous medium based on dispersed oxides TiO_2 and MoO_3; (b) further thermal treatment (TT) upon heating in a protective (nonoxidizing) atmosphere to 100–1050 °C, holding for 10–15 min, and cooling. The aqueous suspension was preliminarily prepared by special technology upon mixing nano- and ultradimensional (0.1–1 μm) grains of oxides with 4–8 % of sulfanol (a SASs) in water. The working composition with acidity pH 6–9 was considered ready. The desired acidity was set and maintained by dosed introduction of NH_4OH. When performing the HCT, the specimens were placed and stored in a bath with the ready-made work composition, heated to the process temperature. The surface of specimens was preliminarily degreased and pickled in a 5–10 % sulfuric acid solution for 1–2 min. After each HCT operation, the samples were washed in water. Isothermal exposition of hard alloy at temperatures up to 200 °C was performed in an air, and above 200 °C, it was performed in a protective atmosphere.

The tribotechnical properties of solid lubricating thermo-hydrochemical coatings were determined on a microtribometer (Fig. 1) [Shmatov 2014]. The relative wear resistance index of the strengthened hard-alloy tool was determined according to the formula: $K_w = t_2/t_1$, where t_1 is the operating time (working length) of the initial tool and t_2 is the operating time of the strengthened tool.

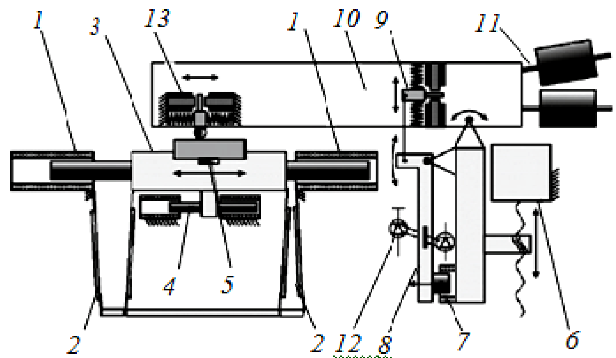

Figure 1. Reciprocating microtribometer with the maximum applied load of 1 N (manufactured by MPRI, Gomel, Belarus):
(1) driving electromagnets; (2) bending guides; (3) sample holder table; (4) position sensor; (5) triboacoustic emission sensor; (6) stepping motor drive; (7) loading system electromagnet; (8) lever; (9) load sensor; (10) head; (11) balance weights; (12) optoelectronic coupler; (13) friction force sensor.

When designing the technological process of THCT of ВК6 hard alloy, the method of multidimensional design synthesis of technological objects, technologies, and materials was applied in the form of the SINTEZ MK software [Vityaz' 2004]. The algorithm of multidimensional computer-based design of this process consists of the solution of two major problems, namely, a direct problem of optimization and an inverse problem of 100 % reproducibility of the optimum process parameters in the permitted tolerances of the applied process equipment. To implement the procedures of multidimensional design synthesis of the technological system upon conducting the THCT of ВК6 hard alloy, a set of new methods was used, the most significant of which were the following: the method of solving the inverse multicriterial problem; the method of computer-based selection of the technically optimal variant; the method of allocation of stability regions of the studied technological system in the multidimensional space of process parameters; and the method of constructing a graphical representation of states of the technological system.

The method of multidimensional design synthesis of the technological system, unlike the traditional optimization method [Novik 1971], makes it possible to do the following:

(1) to select the technically optimal variant possessing the highest resistance to the action of destabilizing production factors; (2) simultaneously to solve the inverse multicriterial problems: to allocate in a space of the system the stable regions and select the technically optimal variant of the technological system in one of the stable regions when ensuring the desired level of the reproducibility of material properties; (3) to select the region of the stable state of the system in the space of process parameters in which the

predetermined properties of the material are simultaneously achieved and consistently reproduced.

3 RESEARCH RESULTS

To design a new THCT process, ВК6 hard alloy was subjected to hydrochemical treatment (HCT) in hydrosol containing TiO_2 - MoO_3 when heating to a temperature close to the boiling point for 10–30 min, and thermal treatment (TT) was performed at a temperature of 1000–1050 °C. Under such conditions at THCT of ВК6 hard alloy, solid lubricant coatings based on TiO_2 - MoO_3 with the best antifriction properties are formed (Fig. 2).

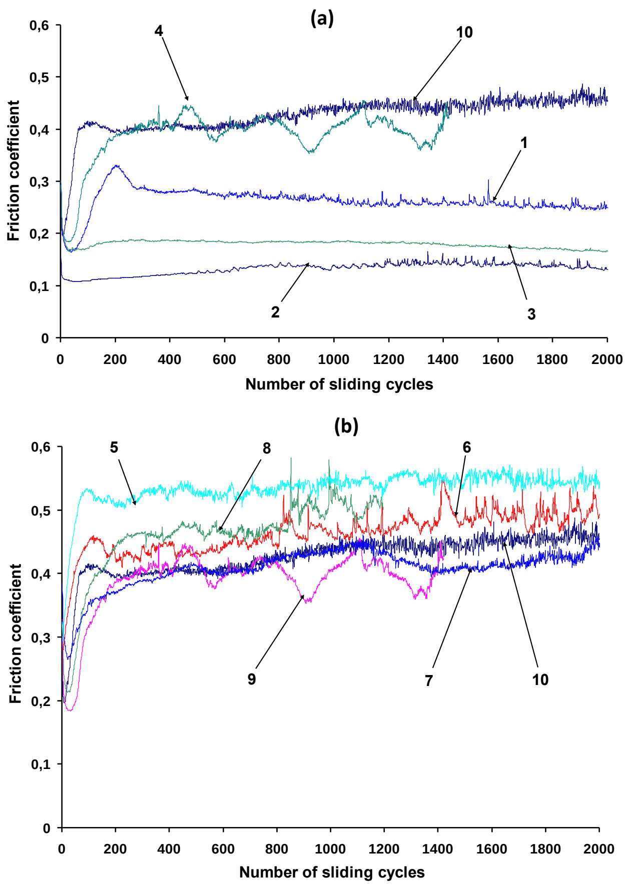

Figure 2. Influence of parameters of THCT on the friction coefficient of ВК6 hard alloy. THCT conditions are hydrosol for HCT based on TiO_2 - MoO_3: (a) HCT at T = 100 °C with TT at T = 1000°C, τ = 10 min ;
(b) TT at τ = 15 min after HCT at T = 100 °C, τ = 1 h.
Test conditions are dry sliding friction (without lubrication); friction pair is hardened ВК6 hard alloy (plane) — ШХ15 steel (sphere 4 mm in diameter); load is 1 N; stroke length (track) is 3 mm, speed is 4 mm/s.
HCT conditions: 1 — 10 min; 2 — 15 min; 3 — 30 min; 4 — 60 min;
TT conditions: 5 — 100 °C; 6 — 250 °C; 7 — 550 °C; 8 — 870 °C;
9 — 1000 °C; 10 — ВК6 hard alloy (before treatment).

In optimization of the process, only the temperature and time of hydrochemical treatment, the fractional content of the basic component of the chemically active medium, and the thermal treatment temperature were varied. In this work, the volume fraction and the morphology of initial particles of TiO_2 and MoO_3 were not taken into account since they very weakly affect the tribotechnical properties of the obtained coatings, which is related to the change in all structural parameters of the particles during hydrochemical nanodispersion up to hydrosol formation. The results of tribotechnical tests of the thermo-hydrochemically strengthened ВК6 hard alloy obtained upon implementation of 8 experiments of the test plan are presented in Tab. 1.

Experiment number	Factors				Parameter of optimization
	Hydrochemical treatment			Thermal treatment	
	Tempe-rature T, °C	Time, τ, min	MoO_3 in oxides mixture, %	Tempe-rature T, °C	Friction coef-ficient for 2000 cycles, f
Designation	X_1	X_2	X_3	X_4	Y_1
Basic level (0)	95	20	50	1025	
Variation interval	5	10	25	25	
Upper level (+1)	100	30	75	1050	
Lower level (–1)	90	10	25	1000	
1	+	+	+	+	0,105
2	-	+	+	-	0,121
3	+	-	+	-	0,107
4	-	-	+	+	0,110
5	+	+	-	+	0,108
6	-	+	-	-	0,135
7	+	-	-	-	0,114
8	-	-	-	+	0,113

Table 1. The results of investigation of the friction coefficient of coatings obtained on ВК6 hard alloy by means of THCT in hydrosol based on TiO_2 - MoO_3

On the basis of these data, the linear and nonlinear mathematical models describing the influence of temperature and time parameters and composition of active mixtures on the friction coefficient of obtained solid lubricant coatings based on TiO_2 - MoO_3 were calculated. However only the nonlinear multicriterial mathematical model of following form (1) were recognized to be adequate:

$$\begin{aligned} Y_1 = &-0{,}223 - 12{,}14 \cdot 10^{-4} X_1 - 20{,}84 \cdot 10^{-4} X_2 - 18{,}34 \cdot 10^{-4} X_3 + \\ &+ 9{,}59 \cdot 10^{-4} X_4 - 9{,}62 \cdot 10^{-7} X_1^2 + 6{,}93 \cdot 10^{-5} X_2^2 - 4{,}86 \cdot 10^{-7} X_4^2 + \\ &+ 2{,}08 \cdot 10^{-5} X_1 X_3 - 1{,}04 \cdot 10^{-5} X_2 X_3 \,, \end{aligned} \tag{1}$$

where Y_1 is the friction coefficient, X_1 is the temperature of hydrochemical treatment, X_2 is the time of hydrochemical treatment, X_3 is the MoO_3 percentage in oxides TiO_2 - MoO_3 mixture of hydrosol, and X_4 is the thermal treatment temperature.

Owing to multicriteriality, stochasticity, and nonlinearity of “the THCT process of ВК6 hard alloy” technological system, the prediction of its behavior is complicated. The values of parameters of each actual object differ from the designed ones and are randomly distributed in a scatter band. As a consequence, there is no guarantee that all points of optimization of the actual system will be placed in the stable domain, i.e., it is not always possible to improve the material properties up to the desired its level. So that this does not happen, when designing the technological process, a certain system stability margin is provided, which makes it possible to avoid a degradation of the quality of system functioning by the criterion of reproducibility of material properties.

Under the traditional methodology of optimization of system parameters, the solutions of the problems of technological designing of the system are not entirely correct, as the processes are considered as deterministic ones, i.e., passing under adherence of precise values of technological system parameters. In fact, deterministic systems do not exist, as the values of parameters of actual technology systems always are random and the systems themselves are stochastic. The selection of optimal variant of THCT of ВК6 hard alloy in hydrosol of TiO_2 - MoO_3 was carried out with the method of multidimensional design of technology systems with the help of the specially developed SINTEZ MK software program, which is intended to solving nonlinear and stochastic tasks for providing for whole working capacity of technological systems.

The multidimensional design of THCT technology of the ВК6 hard alloy using SINTEZ MK software was executed in several steps. The results of the selection of the optimum variant of the studied technological systems are summarized in Tab. 2 and 3. When solving the inverse multicriterial problem, the desired limit values of properties of solid lubricant coatings fabricated with THCT of ВК6 hard alloy were set (Tab. 4). The results of the virtual tests of the working capacity of the system are presented in Tab. 5. For graphical interpretation of the results obtained when solving the tasks of the research and multidimensional computer-aided design of THCT technology of the ВК6 hard alloy in hydrosol based on TiO_2 - MoO_3, discrete portraits were constructed (Fig. 3).

Name of process parameter	Rated value	Permissible scatter bands
Temperature of hydrochemical treatment, °C	100	9
Time of hydrochemical treatment, min	19	10
MoO_3 percentage in oxides mixture , %	59	28
Tempering temperature, °C	1035	28

Table 2. Optimal parameters of the THCT process of the ВК6 hard alloy in hydrosol based TiO_2 - MoO_3 and their scatter bands

Name of optimal index of properties	Rated value	Scatter band
Friction coefficient, *f*	0,106	0,006

Table 3. Optimal indices of properties of solid lubricant coatings fabricated with THCT of ВК6 hard alloy in hydrosol based on TiO_2 - MoO_3 and their scatter bands

Name of desired index of properties	Minimum value	Maximum value
Friction coefficient, *f*	0,10	0,11

Table 4. Set limits of properties of solid lubricant coatings fabricated with THCT of ВК6 hard alloy in hydrosol based on TiO_2 - MoO_3

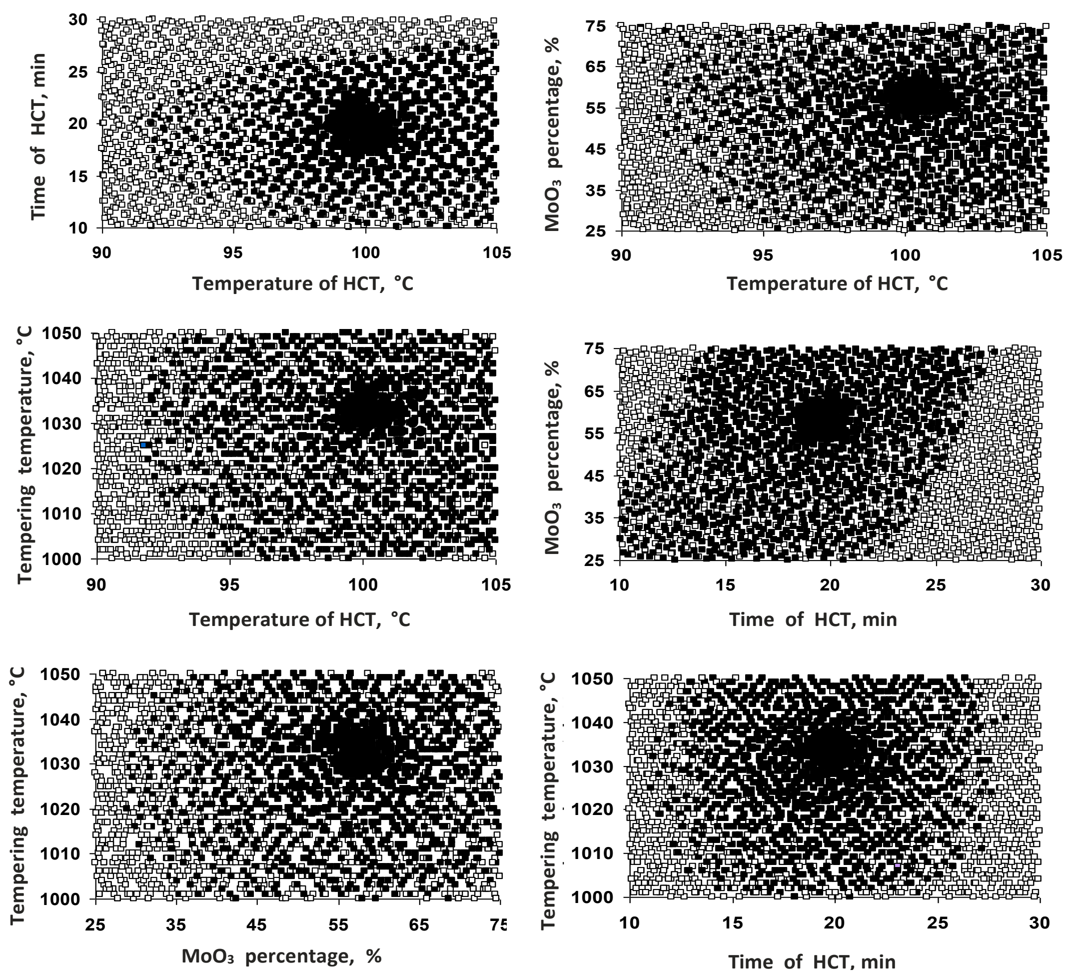

Figure 3. Discrete portraits of virtual space of technological system of THCT process of the ВК6 hard alloy in hydrosol based on TiO_2 - MoO_3:
♦ – variant of the system providing the set properties of ВК6 hard alloy; ◊ – variant of the system not providing the set properties of ВК6 hard alloy.

Name of process parameter	Parameter value	Manufacturing tolerance value	Manufacturing tolerance margin	Coefficient of working capacity
Temperature of hydrochemical treatment, °C	100	±1	2	4,5
Time of hydrochemical treatment, min	19	±1	2	5,0
MoO_3 percentage in hydrosol oxides mixture, %	59	±1	2	14,0
Tempering temperature, °C	1035	±5	10	2,8

Table 5. Determination of the reserve working capacity of the process system with respect to the input parameters

The allocation of stable domains in a multidimensional space of states is an important stage in the selection of a technically optimal variant of the system. The friction coefficient with desired level of 0.10–0.11 is used as the optimization criterion (see Tab. 4). It is seen from Fig. 3 that the THCT technology of the BK6 hard alloy is implemented with high properties only when the system gets into the stable domain marked with dark dots. Overrunning of one or more parameters of the process beyond the stable domains into the domains marked with light dots is evidence that the material of the coating with the set properties in this case will not be obtained.

As a result of solving of the problem of designing of THCT technology of the BK6 hard alloy in the hydrosol based on TiO_2 - MoO_3, the actual indices of its main tribotechnical property (Tab. 6), 100 % reproducibility of which is achieved upon exact compliance of the process parameters within manufacturing tolerances (see Tab. 5), were stated. This was also confirmed by the test results (Fig. 4).

Name of index of properties	Rated value	Scatter limits of index of properties	
		lower	upper
Friction coefficient, *f*	0,1063	0,1058	0,1067

Table 6. Actual indices of BK6 hard alloy properties after THCT and their scatter limits by the results of virtual tests of technological system

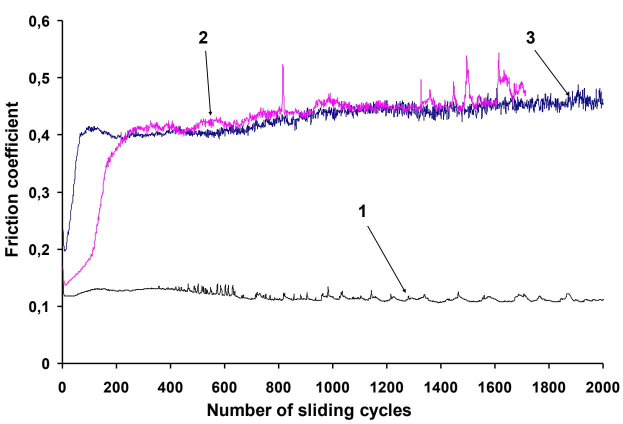

Figure 4. Comparative diagram of changes in friction coefficient vs. wear duration (without lubrication) of the surface of BK6 hard alloy before and after THCT. Testing conditions: dry sliding friction; friction pair is strengthened of BK6 hard alloy (plane) — ШХ15 steel (sphere 4 mm in diameter); load is 1 N; stroke length (track) is 3 mm; speed is 4 mm/s: 1 — BK6 hard alloy after THCT in hydrosol of TiO_2 - MoO_3 in optimal regime; 2 — BK6 hard alloy with diamond-like Ti - Mo - V diffusion carbide coating after TCT; 3 —BK6 hard alloy (before treatment).

For any tool of which the place of contact with a machinable workpiece changes over time [Bel'skii 1984], it is important to have minimum and unchanged values of the friction coefficient during the whole operating period. The thermo-hydrochemical coatings correspond to these demands; and this is their advantages against diamond-like Ti - Mo - V diffusion carbide coating (see Fig. 4) and well-known solid lubricant coatings [Vityaz' 2007].

4 APPLICATION OF RESEARCH RESULTS

The manufacturing testing results revealed that the THCT using aqueous-dispersion oxide and carbon-containing compositions makes it possible to increase the service life of various types of hard-alloy tools by the factor of 1.3–4 in comparison with untreated tools (Tab. 7).

Type of tool	Grade of hard alloy	Test place	Increase in tool service life, K_W
Finish turning inserts	T15K6	BELAZ, KZTSh, AGU (Belarus)	1.8–3
	MP4	BMZ (Belarus)	1.3
	«Sandvik» CT35, «Orion» HC6620,	Veza (Russia)	1.6–1.7
	«Karloy» PC9030	Iskra (Russia)	2.2
Rough turning inserts	T15K6	Motovelo (Belarus)	3–4
	PT40	BMZ (Belarus)	2.6–3.3
	«Kennametal»KCU10 «Walter»WSM20	Novomet-Perm (Russia)	1.8–3.6
Corner-rounding cutters	T15K6	MPZ (Belarus)	2
wire-drawing dies	Different hard alloys	BMZ (Belarus)	1.4–1.8
Prefabricated end mills	T15K6	MPZ (Belarus)	2.1
	MK8	BMZ (Belarus)	1.6–2

Table 7. Test results of hard-alloy tools subjected to THCT

Considering Tab. 7, one should note that the highest indices of wear resistance of the cutting hard-alloy tools were achieved in the case of rough turning and milling treatment, especially of high-alloy structural and stainless steels and alloys. The technology of thermo-hydrochemical treatment was applied in Belarus at the BELAZ, Motovelo, AGU plants, and other countries.

5 CONCLUSIONS

(1) The mathematical simulation and the computer design of the THCT process of the BK6 hard alloy in a hydrosol medium of TiO_2 - MoO_3 using computer technologies of the method of multidimensional design synthesis of technical objects, technologies, and materials were implemented. The technically

optimal regimes for implementing the process in manufacture with guaranteed achievement of the set properties of hard alloy products subjected to THCT were determined.

(2) The treatment of ВК6 hard alloy according to the optimal THCT regime makes it possible to substantially (by 3,8–4,2 times) reduce the friction coefficient of the hard alloy surface under sliding conditions without lubrication.

(3) The simple electrolysis-free and economical method of thermo-hydrochemical treatment of tool hard alloys has been developed, the use of which makes it possible to increase the service life of different types of hard-alloy tools by the factor of 1.3–4 in comparison with standard tools.

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