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TRIBOLOGICAL CHARACTERISTICS OF EXPERIMENTAL HARD ALLOY GRADES WITH MODIFIED COBALT BINDER UNDER CONDITIONS OF DRY FRICTION ON TITANIUM-ALUMINUM ALLOY VT-3

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Abstract: *The paper is dedicated to investigations of tribological characteristics of experimental tool hard alloy (HA) grades based on tungsten carbide with modified cobalt binder under conditions of dry friction on disks made of titanium-aluminum alloy VT-3, as well as measures of their surface micro-hardness. All measured parameters were compared with similar characteristics of standard HA grade VK8, on the basis of which these experimental grades were developed. The research found that the surface micro-hardness of all experimental HA grades as pins were higher than that for the basic grade VK8; the highest value was fixed for the HA grade with symbol mark 2.22 (composition of the binder - 5.65% Co +1.8% Mo +0.6% Ti). The highest wear resistance was obtained for 2.23 (5.1%Co+2.7%Mo+0.61%Ti) and 2.21 (5.4%Co+1.43%Fe+0.82% Cu), the lowest – for grade 2.22. The analysis of friction processes peculiarities allows to explain the high wear resistance of grades 2.21 and 2.23 by features of surface structures ("the third body") formation during friction. Friction process for these HA grades include the periods of "the third body" intensive growth to the considerable thickness values, as well as the periods of its abrasion; due to this phenomena resulting wear rates for these two grades proved to be significantly lower than for the base grade VK8. The "third body" generated during friction protects surfaces from wear, at the same time it has its own significant shear resistance and increases actual contact area, due to this phenomena the friction forces for grades 2.21 and 2.23 are somewhat higher than for basic grade VK8. The grade 2.22 is characterized by the highest average friction force and its r.m.s. deviation value, which result in the greatest wear rates for both the HA pins and rotating disks. So according to the results of testing the best results among the investigated experimental HA grades were obtained for grade 2.23: the lowest average friction coefficient and the lowest track surface roughness on rotating disks, as well as the highest wear resistance values.*

Keywords: *tool materials, hard alloys, friction, wear resistance, surface micro-hardness, "the third body" formation.*

1. INTRODUCTION

Among the modern trends in improving performance and cutting properties of hard alloys (HA) used as inserts to equip the cutting tools (CT) the direction associated with improving carbide phase composition and the search for new materials for binding phases can be selected [1],[2],[3],[4].

The studies of thermodynamic processes in the friction zone based on entropy balance equations obtained analytical dependence indicating that wear rates are lower for HA grades with large values of the thermal entropy S [1],[5]. It has been established experimentally that HA grades with high values of S have smaller values of absolute or relative thermo electrical moving force (thermo-EMF), which leads to a decrease in the magnitude of thermo currents in the cutting (or friction) zone and reduce the oxidative wear rates [1],[6]. Thus, when designing new HA grades preference should be given to structures characterized by highest values of the thermal entropy and minimal values of the thermo-EMF.

In accordance with the above mentioned principles at the «Metal-cutting machines and tools» department of Don State Technical University experimental HA grades based on standard alloy VK8 were developed [7]. The compositions of these new grades of HA consist of WC carbide phase and modified binders of three types: Co-Mo, Co-Fe-Cu and Co-Mo-Ti. The values of relative thermo-EMF of these binders towards carbide phase are lower, and their entropy values are higher than for the base alloy VK8, obtaining their increased electrochemical stability. As a result of the tests, it was established that the best wear resistance when cutting stainless steel [1] and high resistance to gas corrosion [7] have alloys which chemical composition and properties are listed in table 1, 2.

Table 1. Composition of experimental hard alloys grades [1]

Grade	Chemical composition
2.21	5,4%Co+1,43%Fe+0,82%Cu+92,45WC
2.22	5,65%Co+1,8%Mo+0,6%Ti+91,95%WC
2.23	5,1% Co+2,7%Mo+0,61%Ti+91,59%WC
VK8 (basic)	7,5-8%Co; <0,3% Fe; 92,0%WC

Wear resistance of the material depends on its physical-mechanical properties including the modulus of elasticity and hardness [9],[10]. Rubbing bodies come into contact with each other on the picks of surface asperities; therefore the wear resistance of the material under conditions of friction without lubricant will primarily be determined by hardness of its surface sub contact layer on micro level. Micro hardness of the surface layer of material measured using the dynamic method of scratching is the best suited for simulation of friction conditions and is widely used for wear resistance evaluation of materials and coatings [11],[12],[13]. This parameter permits to evaluate the ability of the material to resist surface micro relief changes in dynamic interaction with picks on the surface of the second body or with solid wear particles having abrasive action. In places of metal contact of two rubbing bodies adhesive joints (or junctions) are formed, then, in addition to the destruction of surface layers as a result of plastic and elastic-plastic contact additional wear processes due to formation/destruction of adhesive joints will occur [10],[14],[15].

Table 2. Physical-mechanical properties of experimental hard alloys grades [1]

Grade	Entropy, J/mol·°K	Absolute thermo e.m.f. ε, mV	Density, kg/m^3
2.21	35,18	3,75	1476
2.22	35,26	3,32	1421
2.23	35,16	4,5	1410
VK8 (basic)	35,00	9,8	1460

The processes of formation of adhesive junctions and of their destruction should be separated according to their influence on the total wear rate. For example, for some combinations of rubbing materials the process of adhesive joints formation can be quite intense, but the junctions may have comparatively low shear resistance, hence friction force will not significantly increase [10]. During machining processes CT material and material of work-piece may have high propensity to adhesive joints formation [15], [16]. In these cases wear mechanism is specifically based on the incorporation of the machined material over two well-localized areas of the cutting tool: at the edge, giving rise to the Built-Up Edge (BUE); and at the rake face, giving rise to a Built-Up Layer (BUL). Both types of material incorporation may modify the initial cutting geometry, affecting the surface quality of the machined parts [17],[18],[19]. At the same time, a thin and stable BUE can protect the tool from wear by reducing the friction between the cutting tool and work piece and by its shielding effect [20].

Among materials processed using tools with cemented carbide inserts titanium-aluminum alloys can be selected, which due to their heat resistance, corrosion resistance and excellent physical and mechanical properties are widely used in various areas of engineering, including aerospace and medical equipment production [21],[22]. The alloy VT-3 refers to high-strength (α+β)-martensitic alloys of the Ti-Al-Mo-Cr-Fe-Si type and is widely used for various components in the aircraft industry. According to modern requirements to ecology and economy of production, machining work pieces made of VT-3 alloy occurs mainly under conditions of Minimum Quantity Lubrication (MQL) [23] or without lubricant at all. Taking into account above mentioned, the studies of peculiarities of the interaction between the new experimental HA grades and titanium-aluminum alloy under conditions of dry friction will be an important task.

The aim of this work is to study the tribological properties of the new experimental HA grades under conditions of dry friction on titanium-aluminum alloy VT-3, as well as the measurement of their surface micro-hardness as one of the most important factors determining wear resistance of the tool materials. All measured parameters will be compared with similar characteristics of standard HA grade VK8, on the basis of which these experimental grades were developed. This work is a part of complex researches of physical-mechanical, tribological and cutting properties of the new experimental HA grades with modified cobalt binder.

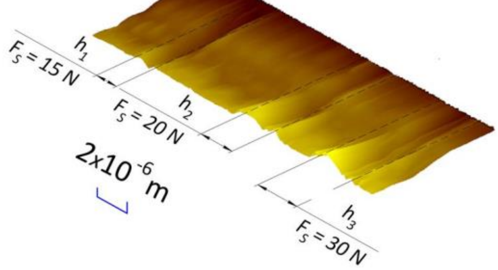
2. EXPERIMENTAL PART: MATERIALS AND METHODS

Surface micro-hardness measurements on contact surfaces of specimens (pins) made of experimental HA grades (contact surface roughness Ra = 0.1 - 0.12 µm) before and after friction on rotating titanium-aluminum alloy VT-3 counter bodies (disks, contact surface roughness Ra = 0.15 - 0.17 µm) were made using NanoSCAN-01 nano-hardnessmetre (Russia) by scratching the surfaces with different forces F_s. Tribological testing of square section samples (5x5 mm2) made of different grades of tool HA were performed on tribometre T-11 (Poland), which implemented a scheme of friction "pin on disk" widely used to simulate in the laboratory processes of friction when cutting metals [24],[25]. Measured and saved parameters were friction force *F*, the offset/inset of the indenter (pin) relative to the counter body (disk) Δ and the time of the experiment *T*. Studies were carried out at a constant speed of v=0.3 m/s (318 RPM, track radius 9 mm) and constant pressure P = 4.1 MPa, the sliding length was varied L = 100 - 1400 m. Measurements of the mass wear of the tested samples were carried out on the scales LV210-A (precision 0.0001 g) which are recommended for evaluation of mass wear of samples when tested according to the scheme "pin on disk" [26]. Roughness of rubbing surfaces after friction was measured using profilometre Abris-PM7 (Russia).

3. EXPERIMENTAL PART: RESULTS AND DISCUSSION

Comparison of surface micro-hardnesses for various materials was carried out by measuring the width of a scratch *h* left by diamond micro-indenter on the surface of the sample: the smaller was the width of the scratch under given value of the normal load F_s, the higher was the surface micro-hardness of the investigated material. The fragment of a scanned image of the surface of the specimen made of experimental HA grade 2.21 with scratches of different widths *h* from the various values of the normal load F_s as well as the curves of $h(F_s)$ dependences are presented in Figure 1.

Surface micro-hardness values of all experimental HA grades exceed the same parameter of basic standard grade VK8; the highest micro-hardness value is characteristic for 2-22 grade. It should be noted that surface micro-hardness measurements of materials 2-22 and 2-23 with a normal loads of less than 7.5 N left no significant changes of surface topography (scratches had not been observed) and, therefore, to evaluate surface micro-hardness by the width of the scratch left by ultrasonically oscillated indenter for these cases had not been possible.



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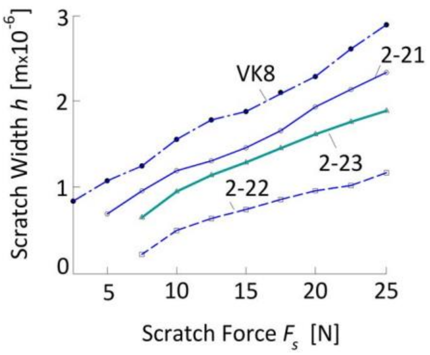
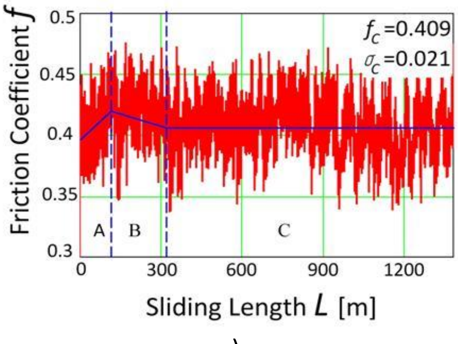


b)

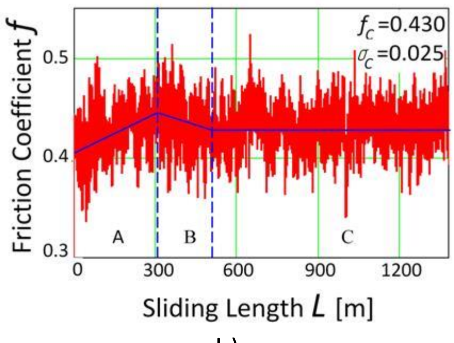
Figure 1. The indenter surface scan on the specimen of 2-21 alloy after scratching (a) and curves of scratch width h dependences on normal load F_s for different HA grades (b)

The evolution in time curves of the friction coefficient f for all tested samples were of the similar character which can be divided into three characteristic stages: A – stage of the friction coefficient increasing; B – stage of the friction coefficient reducing; C – steady-state friction stage (Figure 2).

The stages A and B represent, in fact, running-in period for steady-state friction stage C. The duration of these two phases differs depending on the HA grade: the shortest time to reach steady-state friction stage C was characteristic for indenters made from experimental grades 2.21 and 2.22, the largest - for the basic standard grade VK8. The average friction coefficients on stable stage f_C for indenters made from experimental grades do not differ significantly, however, these coefficients exceed the same characteristic for alloy VK8. The comparison of fluctuations intensities of friction coefficients can be produced by the average amplitude of oscillations [27] or by r.m.s. deviation values σ_C at a stage of steady-state friction (Figure 2). The lowest fluctuations intensities of friction coefficients according to the parameter σ_C were observed for the alloys VK8 and 2-23.



a)



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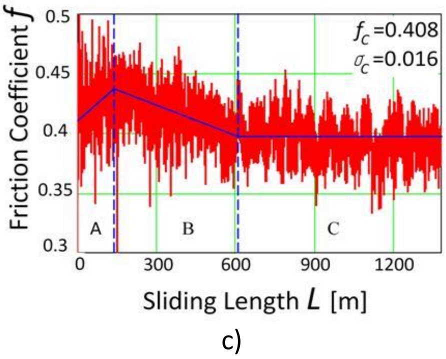

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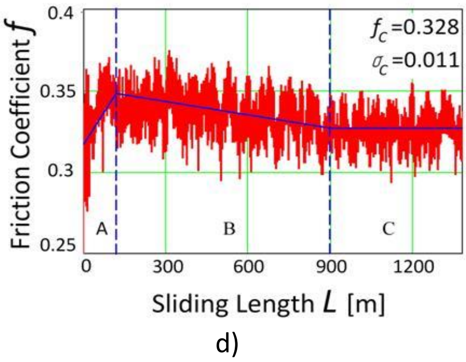


d)

Figure 2. Dependence of the friction coefficient f on the sliding length L: a – 2-21; b – 2-22; c – 2-23; d – VK8(basic)

The total friction force during friction without lubricant consists of adhesive and mechanical components [10],[14]. Therefore, higher friction coefficients and their considerable fluctuations observed in tests with experimental HA grades may have the following possible causes. Experimental alloys may have a higher propensity to adhesive junction formation with titanium-aluminum alloy and higher shear resistance of these junctions than basic alloy VK8. The second reason may be high shear resistance of the "third body" currently emerging in the contact areas during friction process and its rheological properties. Intensive processes of formation/destruction of adhesive junctions inevitably lead to high wear rates of rubbing bodies and change the geometry of contacting surfaces on micro level.

Analysis of the indenter offset/inset *Δ(L)* data allows to judge about the changing contacting surfaces geometry which occurs due to: *a)* comparatively soft counter body (disk) wear; *b)* hard indenter (pin) wear; *c)* the features of secondary surface structures self-organization and the formation of the "third body". Depending on the intensity of each of the above mentioned processes taking place in contact areas it can be observed removing (offset) of rubbing bodies or convergence (inset) of these bodies or near stable state [10]. It should be noted that in our previous studies dedicated to investigations of tribological characteristics of experimental HA grades based on tungsten carbide with modified cobalt binder under conditions of dry friction on disks made of structural steel the formation of the "third body" of a considerable thickness was fixed [28]. This phenomenon was conductive to decreasing of friction forces and contact temperature levels and obtained shielding effect reducing wear rates. The same phenomenon has been observed also while rubbing specimens made of some high speed steel grades [29]. Depending on the chemical composition of rubbing bodies and the level of thermal-mechanical activation the "third bodies" with different properties can be generated. The "third body" can perform either role of solid lubricant, or obtain shielding effect having its own significant shear resistance, or increase total wear rates due to additional abrasive wear. In all the experiments carried out in this study the convergence (inset) of indenter (pin) and counter body (disk) was observed, i.e. the processes of wear dominated over the processes of the "third bodies" formation. The Fig. 3 shows that the convergence (inset) of indenter (pin) and counter body (disk) for specimens made of experimental HA grades was going slower than for specimens made of basic grade VK8.

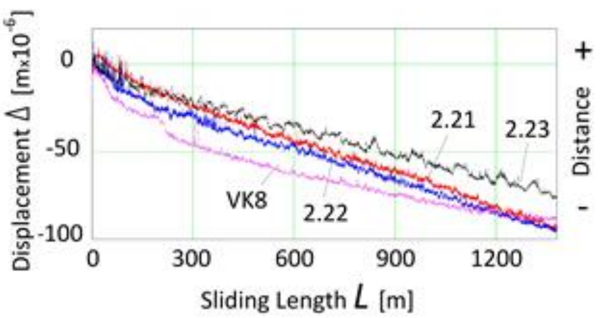


Figure 3. The dependencies *Δ(L)* for experimental and basic HA grades

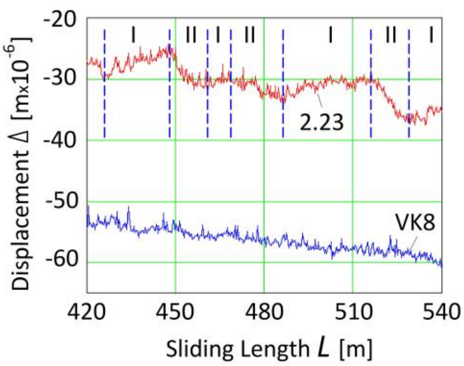


Figure 4. Comparative character of the curves *Δ(L)* for HA grades VK8 and 2.23

At the initial stage of the friction process (*L*<150 m) the curves *Δ(L)* are close enough to each other, and then diverge. Also at this stage the processes of friction for specimens made of experimental HA grades were accompanied by significant fluctuations of the displacement values; then the fluctuations were reduced. The maximum value of fluctuations was characteristic for specimens made of 2.23 experimental HA grade, for basic grade VK8 the fluctuations were of minimal value. It also should be noted that *Δ(L)* curves for specimens made of 2.23 experimental HA grade consist of two alternative phases: the first phase (I) of gradual rubbing bodies offset (fig. 4, plots I), the second phase (II) of gradual rubbing bodies inset (fig. 4, plots II). This process alternates over time, i.e. is quasi periodical in nature.

The plots of type I are a reflection of the thickness of the "third body" growth; during these periods the wear rates are of minimal value due to the removal of rubbing surfaces from direct contact. The friction force at these phases increases slightly due to significant shear resistance of the "third body" and actual contact area growth (fig. 5). Increase of the "third body" thickness is of non-linear character; kinetics of the growth may be best described by an exponential curve [28]. The plots of II type are indicative of the "third body" partial or total destruction and subsequent wear of rubbing bodies until the beginning of the next period of the "third body" growth; the friction force at these periods shows the downward trend (fig. 5). In the case of the most intense growth of the "third body" and high thickness of the intermediate "third body" layer observed for alloy 2.23, the resulting inset of indenter relative to counter body was of minimum value (fig. 3). Comparison of Δ*(L)* curves (fig. 3, 4) shows that friction processes for specimens made of experimental HA grades were accompanied by more intensive formation of the "third bodies" which were also thicker than for VK8. Stages of I and II types in Δ*(L)* curves for experimental HA grades 2.21 and 2.22 (not shown on fig. 4) were also observed, but they are less pronounced than for the alloy 2.23. Curves Δ*(L)* for basic alloy VK8 were comparatively smooth among all options to compare, indicating a clear predominance of destructive wear processes on the constructive processes of the "third body" formation and growth.

Let's try to quantify and compare the "third body" formation/destruction processes for various HA grades having different formulations. Intensive formation of the "third body" with shielding properties is a factor that reduces the wear rates of rubbing bodies. Ideally, the intensity of the "third body" growth process should be close in value to the intensity of its destruction process, and then the geometry of the tribo contact changes would be minimal. Thus, it can be considered desirable such a "script" of the friction process, in which the maximum possible increase of the "third body" thickness (offset value) δ_I would be achieved in less time T_I and its destruction time T_{II} preceding direct contact of rubbing bodies attributed with wear would be the longest possible and accompanied by a smaller inset value δ_{II} (fig. 5).

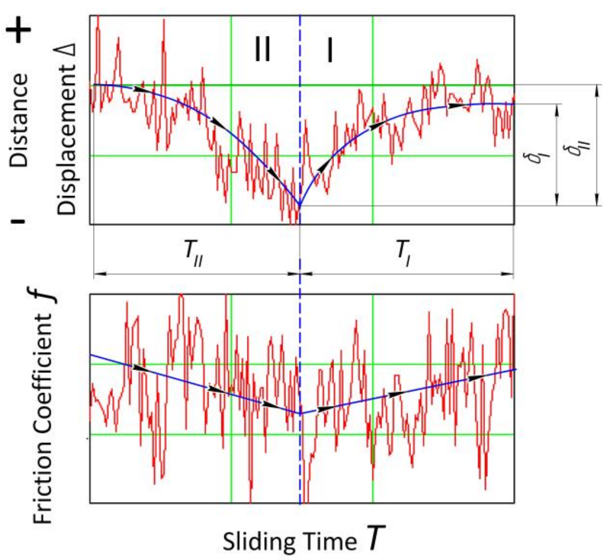


Figure 5. The characteristics of the "third body" formation/destruction processes

Then, to quantify and compare the efficiency of the "third body" formation/destruction processes to a first linear approximation, we introduce dimensionless parameter *Ψ*, specified as

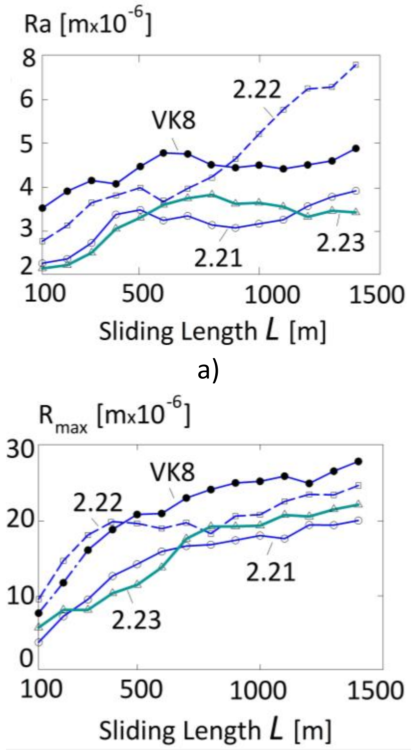
$$\Psi = \frac{\delta_I}{T_I} \cdot \frac{T_{II}}{\delta_{II}}, \qquad (1)$$

where δ_I, δ_{II} – the offset/inset values during formation/destruction of the "third body", [µm]; T_I, T_{II} – the periods of time during which these movements occurred, [min].

The higher is the value of the parameter *Ψ*, the stronger the formation processes of the "third body" compensate for destruction processes. The maximum values for the parameter *Ψ* were characteristic for alloys 2.23 (*Ψ* = 14.2) and 2.21 (*Ψ* = 6.3), the smallest value – for basic alloy VK8 (*Ψ* = 1.9).

Cutting tool materials with high values of entropy *S* have a strong propensity for the rapid formation of the "third bodies" having considerable thickness, secondary structures generated during friction (cutting) deposit on the contact surfaces of indenters (tools) made of HSSs, remaining on it after the termination of the experiment and forming a semblance of wear resistant shielding coatings [29]. For experimental HA grades the "third bodies" fully collapsed when friction process was stopped, and the worn surfaces of indenters maintained metallic luster [28].

Some considerations about the character of adhesive (cohesive) junctions formed during friction can be made on the base of counter bodies tracks roughnesses measured perpendicular to the direction of sliding velocity: in case of stronger adhesive (cohesive) junctions on the surfaces of contacting bodies the roughness will be higher [10]. Dependencies of R_a and R_{max} roughness parameters on sliding length *L* are shown in Figure 6 which shows that the lowest roughness parameters have counter bodies tracks after friction interaction with indenters made of 2.21 and 2.23 alloys.



b)

Figure 6. Dependencies of R_a and R_{max} roughness parameters on sliding length *L*

To evaluate the wear resistance of experimental HA grades under conditions of dry friction on titanium-aluminum alloy VT-3 mass loss measurements of indenters for each fixed value of sliding length *L* were made. Volumetric wear *ΔV* of samples was calculated by the formula:

$$\Delta V = \frac{m_1 - m_2}{\rho}, \quad (2)$$

where m_1, m_2 – sample masses before and after friction test; ρ – the density of the sample material.

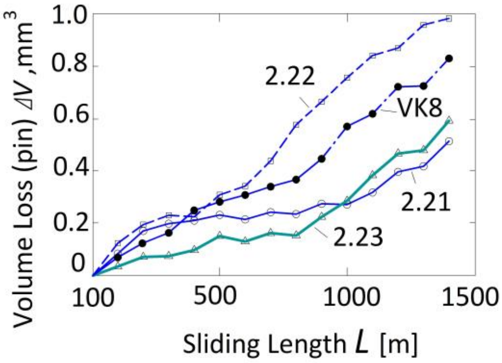


Figure 7. Wear curves for different HA grades.

The greatest volumetric wear *ΔV*, despite its high surface micro hardness (Fig. 1), was observed in samples made of alloy 2.22 (fig. 7). The process of friction for this HA grade was characterized by maximum values of average friction coefficient and its r.m.s. deviation (Fig. 2b), and also was accompanied by a significant changes of counter body and indenter contacting surfaces micro geometry (Fig. 3 and 4). These peculiarities indicate that the process of friction of indenters made of 2.22 HA grade on titanium-aluminum alloy VT-3 counter bodies was accompanied by strong adhesive junctions formation that led to the greatest wear rates among all tested HA grades. The lowest values of volumetric wear *ΔV* and minimal changes of the contacting surfaces micro geometry in comparison with basic standard grade VK8 were observed for 2.21 and 2.23 alloys. Higher values of friction coefficients for 2.21 and 2.23 HA grades can be explained by the features of the "third body" formation/destruction processes, as well as by the "third bodies" rheological properties: intermediate "third body" layers formed during friction have their own high shear resistance, but also have considerable shielding effect.

4. CONCLUSION

As a result of tribological tests of experimental tool hard alloy grades based on tungsten carbide with modified cobalt binder under conditions of dry friction on disks made of titanium-aluminum alloy VT-3 it was found that among the tested grades the best characteristics has alloy 2.23 which is characterized by the lowest average friction coefficient, the lowest surface roughness of counter body track after friction and the highest wear resistance. The friction couples of “hard alloy 2.23 *vs.* titanium-aluminum alloy VT3” type have significant propensity to the formation of secondary surface structures and specific features of self-organization in the friction areas leading to formation of the "third body" which protects contacting surfaces from wear due to considerable shielding effect and has its own significant shear resistance. Such properties of the "third body" can lead to reducing wear on the rake surface of the tool when cutting alloy VT-3 using cutting tools equipped with HA inserts made of 2.23 experimental grade, this consideration in the future to be verified experimentally.

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