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Adhesive built-up edge on tool steels due to friction and wear

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Abstract

When processing metals by cutting, there are a number of materials prone to growth. This phenomenon leads to a change in the geometry of the cutter, cutting forces and surface quality, final dimensions of the part. In friction nodes: shaft-sleeve, piston-sleeve, etc. this phenomenon causes jamming. In this work, experimental studies of the processes of dry friction of tool steels with coatings were carried out to evaluate the effectiveness of reducing the growth process. As a result, it was established that the nature of formation, destruction and size of growth of materials prone to growth depends on the chemical composition of the material and modes of friction. High-strength chromium-manganese steels are most prone to growth and microseizures. It is shown that the well-known recommendation of increasing speed cannot always be used to prevent build-up, but it can be achieved by using single-layer and multi-layer coatings with a defect-free structure and moderate friction modes. It was found that electrolytic single-layer nickel and chromium coatings contribute to the formation of growth on the studied materials and this phenomenon does not depend on the modes of friction, while the same chemical coatings, which have an almost defect-free structure, are almost not prone to growth formation.

Key words: adhesion, build-up, friction, wear, contact pressure, tool steels, chemical and electrolytic coatings.

Introduction

Under certain conditions of friction in air, in a vacuum and in environments that do not contain enough oxygen for the formation of secondary structures with its participation, wear of the contact surfaces is observed, which is associated with their direct destruction due to the development of the adhesion process.

From the practice of cutting metals, it is known that there are a number of materials prone to growth. This phenomenon is undesirable, because in the process of metal cutting, it leads to a change in the geometry of the cutter, cutting forces and surface quality, and the final dimensions of the part. In closed systems (shaft-sleeve, piston-sleeve, etc.), this phenomenon causes jamming. In the practice of metal cutting, this phenomenon is overcome by changing the cutting modes, and in mechanical engineering, as a rule, they try not to use such materials. But such an approach is irrational, since materials that are likely to be prone to growth can exhibit quite attractive mechanical, physical, and tribological properties.

In addition, the data provided in the literature about materials prone to build-up formation do not contain information about the behavior of the build-up in the friction process, and if the behavior of the material under certain operating conditions (modes) is unknown, the possibility of their use becomes problematic.

Therefore, in order to study the nature of this phenomenon, it became necessary to conduct a series of studies to identify materials that are prone to growth, study the nature of this phenomenon, and recommend prevention of growth. To identify the propensity of materials to build up, it is necessary to conduct a series of complex experimental studies.

Review of known studies

Buildup can affect tool wear and surface integrity when machining ductile metals. The main purpose of the work [1] is to study the close relationship between the formation of growth and the tribological behavior at the interface between the tool and the working material during the processing of plastic metals. Machining of AA2024-T351 aluminum alloy with WC–Co carbide tool is considered as a practical example. A new method is proposed, based on the introduction of a time-dependent friction coefficient at the interface between the tool and the working material. Two cases were considered, which correspond, respectively, to a sharp change and a gradual development of friction at the tool-work material interface.

When turning SAE 1045 carbon steel with uncoated carbide cutting tools at a cutting speed of 50 m/min–150 m/min , the wear is characterized by crater wear [2]. In the mode of low cutting speed, the formation of a built-up edge (BUE) is visible. BUE structures are unstable in the cutting process and lead to deterioration of the surface of the workpiece. Laser surface texturing was applied to texturize the front surface of the cutting tool with different textures to change the adhesion tendency of the growth to the cutting tool. The process is accompanied by better wear behavior compared to a non-textured cutting tool with respect to corner radius wear. It is shown that the adhesion of the workpiece material on the front surface can be changed in relation to the non-textured cutting tool made of hard alloy in the process of dry metal cutting by applying laser textures.

The work [3] presents a study of the formation of a raised edge during the machining of S32750 stainless steel. The BUE structures obtained at different cutting speeds were studied. The growth geometries were determined using a scanning electron microscope and white light interferometry. Analysis of the growth structure revealed a high level of grain refinement and elongation for both ferritic and austenitic structures. The effect of growth on the machining process from the point of view of chip formation and surface integrity was studied. It is shown that it is possible to significantly improve the friction conditions and the integrity of the workpiece surface at low cutting speeds.

When processing titanium alloys, the task remained to find an effective technology to increase tool life during machining using surface treatment tools. It was found that in the case of turning, this can be achieved by applying a self-lubricating TiB2 PVD coating. TiB2 coating has been shown to increase tool life by more than 60% compared to an uncoated tool. An analysis [4] of the wear resistance of the coated and uncoated cutting tool was carried out using the methods of optical 3D imaging. The coating also showed less impact on the substrate, as it did not indicate better protection of the coated tool surface. The TiB2 coating is shown to combine beneficial micromechanical characteristics and self-lubricating properties due to the formation of tribofilms on the tool surface during operation.

A feature when cutting many alloys is that workpiece material adheres to the cutting tool at the sliding contact surfaces, between the work material and the tool [6]. This built-up material formed during cutting is of fundamental importance in machining operations, because it may significantly affect the surface roughness, tool wear, workpiece dimensions and tolerances, tool forces, and chip form. The agglomeration of the work material to the tool appears to be analogous to cold welding, metal transfer in tribology and dead zone in extrusion. In machining terminology this phenomenon is often called "built-up edge" (BUE). Several important factors affect the built-up material formation, e.g. cutting temperature, cutting speed, strain hardening, adhesion between the work material and the tool, micro-crack formation, plastic flow of the work material in the vicinity of the cutting edge, etc.

Tool wear is one of the main parameters employed for evaluating tool life, due to its influence in the loss of quality of the manufactured parts [7]. Different mechanisms can cause the tool wear in a specific machining process. Adhesion wear is one of the tool wear mechanisms that can be present in a wider range of cutting temperatures. This type of tool wear can be produced by the direct adhesion wear is caused by the incorporation of tool particles to the chips. Tool geometry changes by the material incorporation. In a second place, when these fragments are removed, they can drag out tool particles causing tool wear. This study has been developed using aerospace aluminium alloys. Results is formed by mechanical adhesion mechanism. On the other hand, BUL is initially formed by thermo-mechanical causes. Obtained results have confirmed that BUE changes the tool position angle giving rise to a reduction of Ra.

Built-up edge has been noted as a major cause for surface finish deterioration in micromachining processes—even a trace formation of hardened and brittle structure on the tool edge alters the chip load, creates ad hoc and irregular material flow patterns, and results in deposits and smeared regions on the machined surface. To date, few investigations have addressed the formation and effects of BUE in micromachining. The paper [8] is one of the first experimental investigations of the BUE effects on surface quality and its prediction in micromachining. The experiments consisted of micromilling 12mm long thin channels on 316L stainless steel plates (30mm×40mm×0.5mm) using uncoated tungsten carbide micromills at 16 different settings of carefully selected combination of cutting speed and chip load with minimum quantity lubrication (MQL). These metrics capture, respectively, the extent and dispersion of BUE on the surface. We also conducted empirical studies to assess the extent to which these quantifiers can determine the variation in surface finish (Sa). Results suggest that the BUE is the major determinant of surface finish besides the chip load effect in micromachining.

Titanium alloys are widely used in aerospace industries due to their excellent physical and mechanical performances, however, their poor machinability always induce fast tool wear. In [9] design of experiments was used towards analyzing pertinent effects involved in machining Ti6Al4V. Uncoated carbide inserts were artificially treated with different initial flank wear (VB) in order to decouple the effects involved in progressive wear condition from rake and flank faces. Dry cutting, flood cutting with emulsion and cryogenic cutting with liquid nitrogen (LN2) were used as different cooling strategies. The results show that initial VB presents significant contributions to BUEs formation, diffusion wear and cutting forces fluctuation, especially under aggressive cutting conditions.

Research methodology

The research was carried out on a modernized universal friction machine UMT 2168 with data fixation and recording (linear wear, average temperature in the friction zone and friction moment) in automatic mode without stopping the friction process [10]. The samples were used with a spherical friction surface, the counterbody is made of AISI G51320 HRC 55 steel. Experiments were performed with a constant force of pressing the sample to the counterbody (from 20 to 60 N) in the range of speeds from 0.6 to 1.5 m/s. Since the shape of the surface of the sample is hemispherical with a radius of R=2.5 mm, according to Hertz's formula, high (1300-2000 MPa) contact stresses occur in the contact zone at the initial stage of friction.

The dependence of the size of the contact area on the stress is shown in Fig. 1.

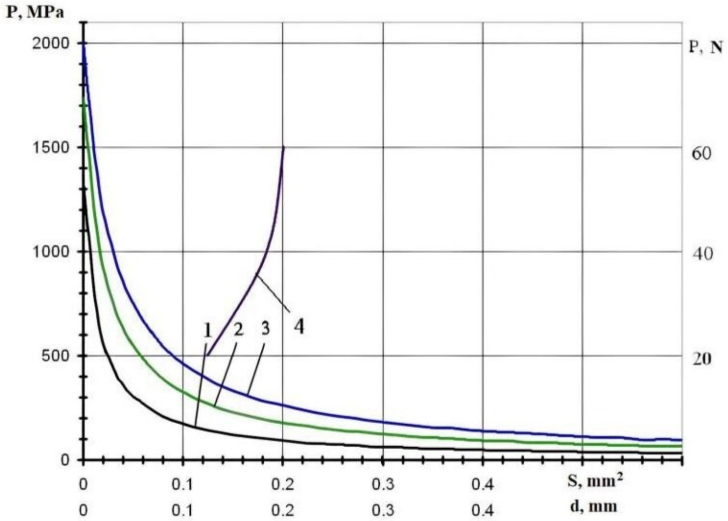

Fig. 1. Dependence of the diameter of the contact spot on stress at different pressing forces (P) (1 – 20 N, 2 – 40 N, 3 – 60 N) of contacting bodies. Dependence of the size of the initial area of the contact spot (4) on the pressing force

Friction modes are given in table. 1, which were chosen from conditions close to the parameters that occur when cutting metals (in particular, stress) and from the requirements of mathematical planning.

Table 1

Modes of friction

Mode No	Friction parameters		
	Pressing force, N	Initial stress, MPa	Cutting speed, m/min
1	60	2000	80
2	20	1300	40
3	60	2000	80
4	20	1300	40

Tool alloy steels (AISI 9262, AISI T31507) and high-speed AISI M3 in the heat-hardened state were used as the object of the study, the mechanical characteristics of which are given in the table. 2.

Table 2

Mechanical characteristics of tool steels

Material	HRC	Endurance limit σB, MPa
AISI 9262	55	1760
AISI T31507	52	1850
AISI M3	60	1300

To increase the tribological parameters and prevent the formation of growth, chromium and nickel coatings were used, as well as composite coatings based on Ni and dispersed particles of Cu, Al_2O_3 (the thickness of the coating was 10...15 microns). At the same time, the coating technology was used [11].

Research results and their discussion

After conducting a number of test experiments on different steels AISI M3, AISI 9262, AISI T31507 and under different test conditions, it was found that the tendency of AISI T31507 and AISI 9262 steels to form growth, which manifested itself in an increase in the initial linear dimensions of the sample at the first stages of the experiment. Moreover, this phenomenon was observed only at the initial stages, and therefore our calculations will reflect the characteristics of friction and wear of the studied materials at the initial stage, that is, during a fairly short period of time of the study (for 200...300 m of the tested path). We will not provide data on changes in tribological parameters (moment of friction, temperature in the contact zone, intensity of wear) in this message.

As shown by the results (Fig. 2), at the first stage of research on AISI T31507 steel, at friction modes 2, 3, 4, the first wear zone is distinguished, where an increase in the linear size of the sample by 0.02-0.05 mm is observed when passing 25 m of the friction path and its gradual reduction to the initial dimensions at 150 m of the traveled friction section, intensive wear of the sample occurs in mode 1.

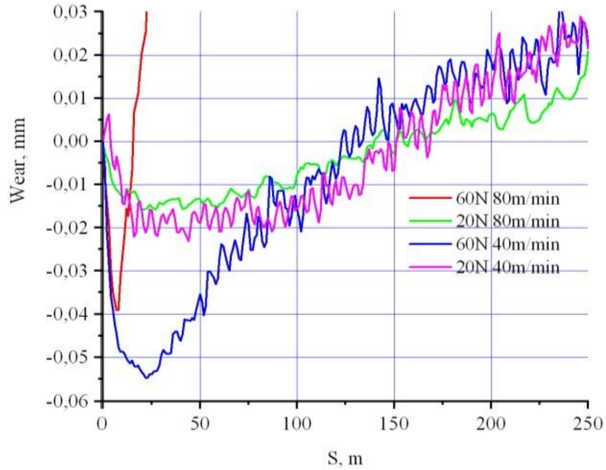

Fig. 2. Effect of friction modes on linear wear of AISI T31507 steel

The increase in the linear size of the growth is accompanied by a rapid increase in temperature and friction moment and depends on the modes of friction - the amount of contact stress and the speed of sliding (larger growth sizes corresponded to higher contact stress). Moreover, only at the maximum contact stress and the maximum sliding speed (Fig. 2, curve 1) is there a chipping of the growth and a sharp change in the linear size of the sample under study, for all other modes (Fig. 2, curves 2, 3, 4.) - smooth monotonic reduction of growth. This is clearly shown on the graphs when the scale is increased along the ordinate axis (traveled path). By reducing the discreteness of the measurement of the amount of wear to 0.5 s, the nature of wear of the material is clearly marked on the wear curves and, as can be seen from fig. 2, the wear process takes place, in our opinion, by periodic seizure of contacting micro-areas, destruction of the bridge, removal of wear products from the contact zone. This is evidenced by the dust-like wear curves. To verify such assumptions, it is necessary to carry out fine studies of the friction surface, which will allow us to judge the mechanism of wear.

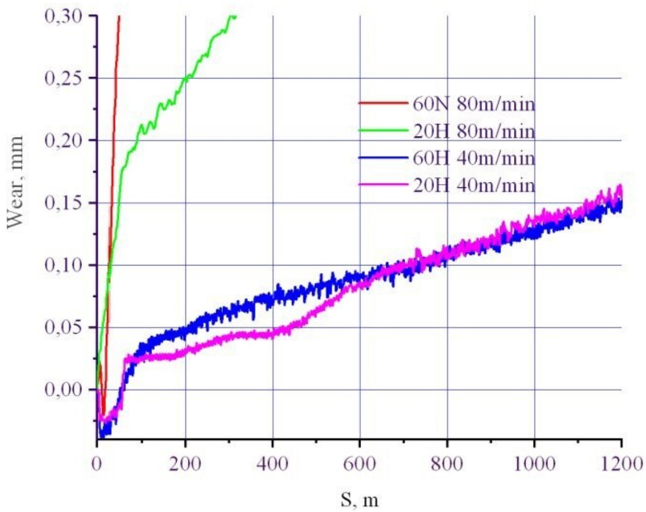

Fig. 3. Linear wear of AISI T31507 nickel-plated steel

It is known that all materials can be divided into materials that are not prone to or prone to growth. Technological methods of applying wear-resistant coatings were used to prevent growth.

After testing the electrolytic nickel coating of Fig. 3 for friction and wear, it was established that under the same regimes growth occurs again, and in general, the general pattern of wear has not changed, and in some cases the amount of wear has increased. The growth disappears after 100 m of the traveled path, while on the samples without coating the growth stops after 150 m of the traveled path. The wear process is carried out in the same way as the sample without coating.

Analysis of the above studies of the tribobehavior of AISI T31507 steel with a two-layer coating (sublayer of copper (Cu) and nickel (Ni)), which is presented in Fig. 4, indicates that the conditions for growth formation are created on the surface of this coating. A growth was formed, but the linear size of the growth was insignificant, the maximum size was equal to 0.035 mm. Moreover, this value was obtained according to test mode 4.

In other research modes, growth formation was not observed. In addition, after wear to a certain limit, there is a sharp decrease in the moment of friction, which, in our opinion, is a manifestation of the effect of copper on the change in the coefficient of friction.

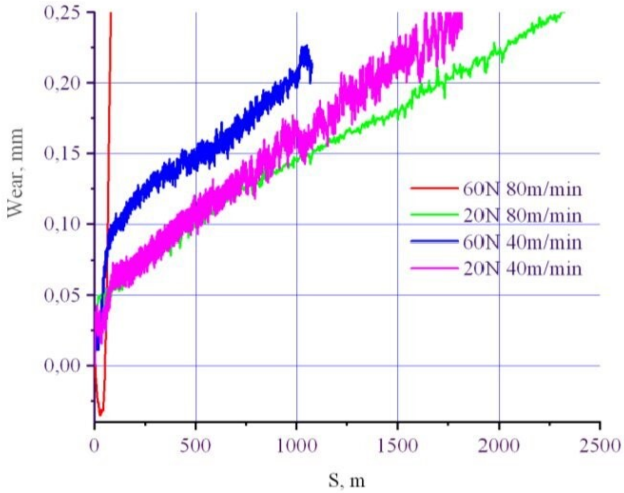

Fig. 4. Linear wear of steel AISI T31507 with two-layer copper-nickel coating

After a relatively successful attempt to solve the problem of build-up formation by applying a two-layer copper-nickel coating, the modes of build-up formation of a combined coating based on nickel (Ni) with particles of corundum (Al2O3) were determined, fig. 5, which was applied to the surface of AISI T31507 steel according to the technology proposed by the authors [11].

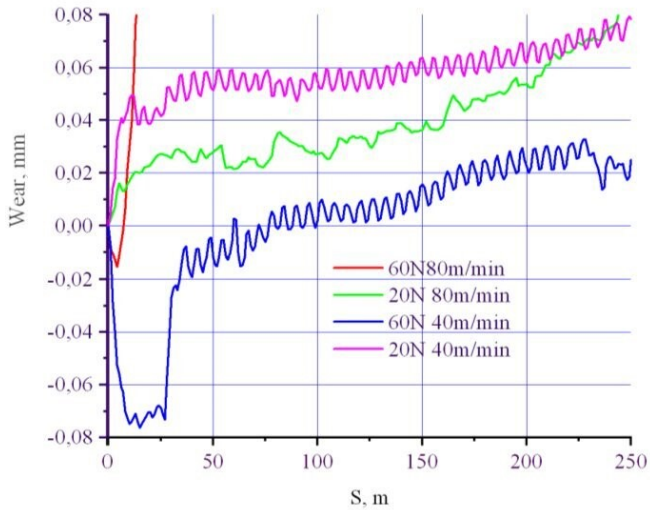

Fig. 5. Linear wear of T31507 steel with combined Al2O3-Ni coating

It was established that the growth process does not occur at all during experimental studies in modes 2, 4, but at the same time, an increase in the moment of friction, temperature, and more intense wear compared to the original material is noted.

Since nickel coatings, complex coatings based on nickel, copper and corundum on AISI T31507 steel are insufficiently effective against scale formation, the aim was to test the influence of chromium on the process of scale formation. For this, electrochemical and chemical chromium coatings were used, differing among themselves in the defectiveness of the surface layer. When a coating was applied to the base by chemical deposition of chromium and during the further study of tribological characteristics on a friction machine, no build-up was recorded (Fig. 7) in any mode, and the friction moment and average temperature in the friction zone also decreased.

For comparison, a chrome coating was applied using the electrolytic method. During tribological studies, intensive growth was established on friction modes 1, 2, 3; the intensity of growth formation depended on the modes of friction (Fig. 6).

From our observations and as a result of the analysis, it was established that the greater the force of clamping the sample, the greater the linear size of the growth.

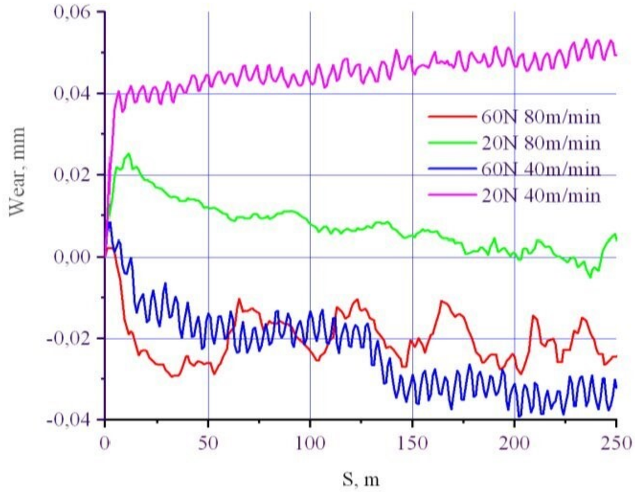

Fig. 6. Linear wear of AISI T31507 steel with electrochemical chromium coating

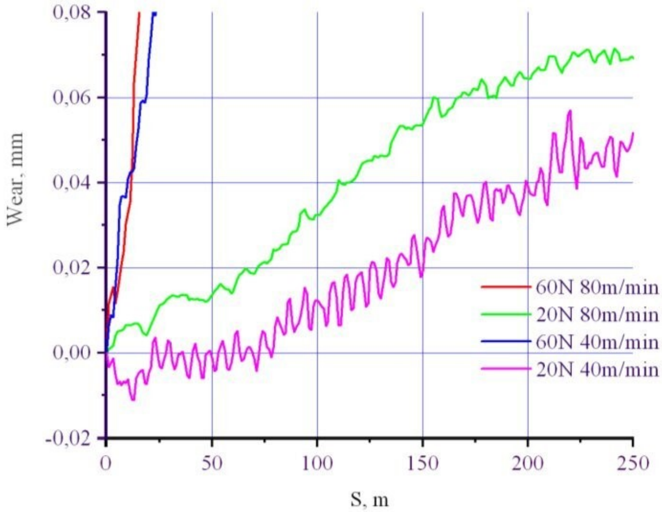

Fig. 7. Linear wear of steel AISI T31507 with chemical chromium coating

Since the active formation of growth with chromium coating applied by the electrolytic method and its almost absence on samples with chemically deposited chromium was detected, we decided to investigate its behavior on siliceous spring steels with different structural states of the matrix (steel AISI 9262, tempering temperature 200, 300, 400 0C), high-speed steel AISI M3.

During experimental studies, it was established that on the surface of a sample of AISI 9262 steel with a tempering temperature of 2000C and a chrome electrolytic coating, growth was not formed only on the fourth mode of friction (Fig. 8) curve 4. It should be noted that on friction modes 2, 4 wear curves 6, 8 was 0.05 mm per 2,000 m of travel, while, using a clean sample, the wear was already 0.4 mm after 200 m of travel.

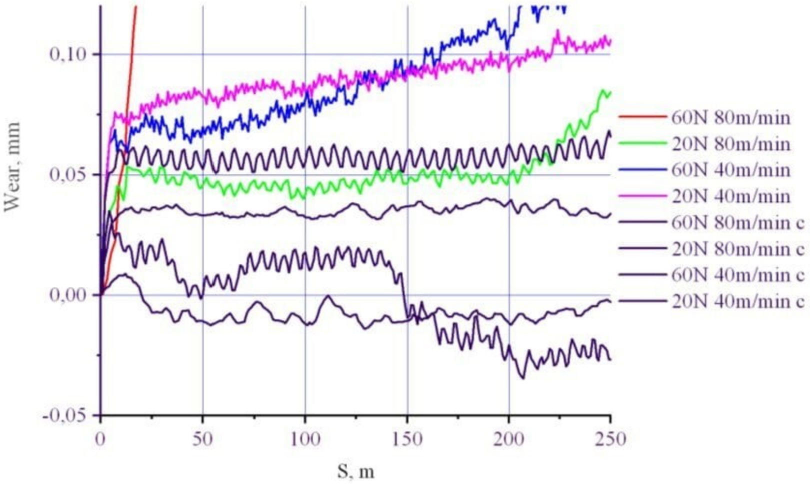

Fig. 8. Linear wear of steelAISI9262, tempering temperature 200 0C wear lines 1, 2, 3, 4 - material without coating; 5, 6, 7, 8 - with chrome electrolytic coating

Chromium electrolytic coating on AISI 9262 steel with a tempering temperature of up to 300 0C (martensite structure of tempering) behaved in a completely different way - at the same time, growth formation was observed in all modes of friction; moments and temperature jumps, which are interrelated, but with intense friction modes, the wear line fluctuates in the range of 5...6 μm, at 2000 m of the traveled path, while the wear of the uncoated sample when reaching 200 m was 0.2 mm (Fig. 9, mode 3, curve 3).

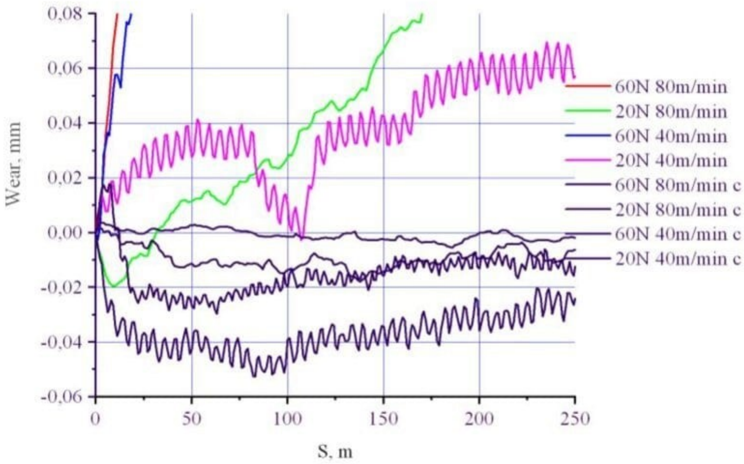

Fig. 9. Linear wear of steelAISI9262, tempering temperature 300 0C wear lines 1, 2, 3, 4 - material without coating; 5, 6, 7, 8 - with chrome electrolytic coating

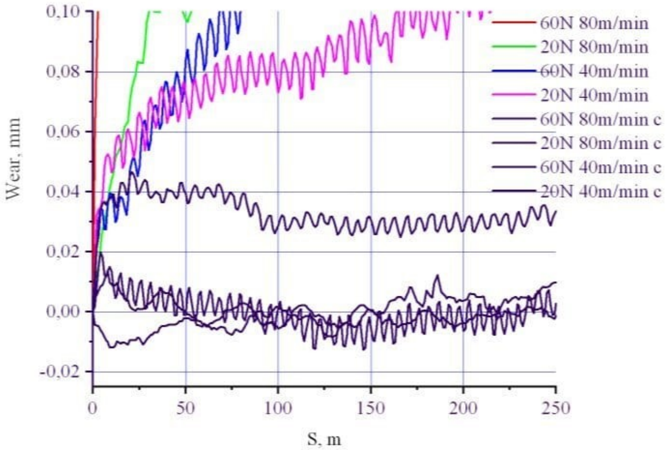

Fig. 10. Linear wear of steelAISI9262, tempering temperature 400 0C, wear lines 1, 2, 3, 4 material without coating, 5, 6, 7, 8 - with chrome electrolytic coating

When using AISI 9262 steel with a tempering troostite structure (tempering temperature 400 0C) for electrolytic chromium coating, growth formation is observed in all modes of friction, but wear decreased by 3-5 times, depending on the mode of friction when using this coating (Fig. 10).

Research on the wear resistance of AISI M3 steel (Fig. 11) showed that on the regimes (1-4 wear curves 5 - 8) growth formation is observed, but the wear of AISI M3 steel decreased by 2...3 times.

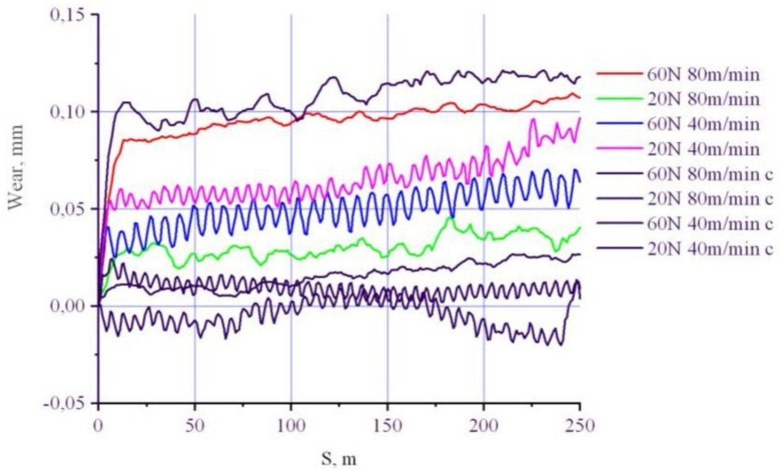

Fig. 11. Linear wear of M3 steel, wear lines 1, 2, 3, 4 - material without coating, 5, 6, 7, 8 - with chrome electrolytic coating

Conclusions

The technique of continuous, automatic recording of tribological characteristics allows to detect not only the tendency of materials to form growth, but also the microseizure of surfaces during the tests.

The nature of formation, destruction, and growth size of materials prone to growth depends on the chemical composition of the material and friction modes. High-strength chromium-manganese steels are most prone to growth and microseizures.

In order to prevent growth, it is not always possible to use the well-known recommendation - to increase the speed, but to achieve it by using single-layer and multi-layer coatings with a defect-free structure and moderate modes of friction.

It was found that electrolytic single-layer nickel and chromium coatings contribute to the formation of growth on the studied materials and this phenomenon does not depend on the modes of friction, while the same chemical coatings, which have an almost defect-free structure, are almost not prone to growth formation.

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Маковкін О.М., Диха О.В., Вальчук І.К. Адгезійний нарост на інструментальних сталях при терті і зношуванні

При обробці металів різанням існує ряд матеріалів схильних до наростоутворення. Це явище призводить до зміни геометрії різця, сил різання та якості поверхні, кінцевих розмірів деталі. У вузлах тертя: вал-втулка, поршень-гільза і т.д. це явище спричиняє заклинювання. В даній роботі проведені експериментальні дослідження процесів сухого тертя інструментальних сталей з покриттями для оцінки ефективності зменшення процесу наростоутворення. В результаті встановлено, що характер утворення, руйнування та розмір наросту матеріалів, схильних до наростоутворення, залежить від хімічного складу матеріалу та режимів тертя. Найбільш схильними до наростоутворення та мікросхоплювань є високоміцні хромо-марганцеві сталі. Показано, що дДля запобігання наростоутворення не завжди можна використовувати відому рекомендацію - збільшення швидкості, а досягнути шляхом використанням одношарових, та багатошарових покрить з бездефектною структурою та помірковані режими тертя. Виявлено, що електролітичні одношарові нікелеві та хромисті покриття сприяють утворенню наросту на досліджуваних матеріалах і це явище не залежить від режимів тертя, в той час, як такі ж хімічні покриття, що мають практично бездефектну структуру, майже не схильні до наростоутворення.

Ключьові слова: адгезія, нарост, тертя, зношування, контактний тиск, інструментальні сталі, хімічні та електролітичні покриття.