

# Dependence of the diffusion wear of the hard alloy surface on its fractal dimension

V P Nesterenko, A A Kondratyuk, E B Belousova and I A Shulepov

Tomsk Polytechnic University, 30, Lenin ave., Tomsk, 634050, Russia

E-mail: nest2004@bk.ru

**Abstract.** The paper presents the research results in the synergies between the wear resistance of carbide cutting tools of P-group applicability and fractal dimension of the wear surface occurring on the rake face of the tool when processing the material, which causes intensive diffusion wear. It was found that the resistance of carbide cutting tools increases as the fractal dimension of their wear surface reduces.

## 1. Introduction

Austenitic, perlitic and ledeburitic steels exposed to the P-group cutting tools treatment are used to manufacture details and components for nuclear-power reactors. High operational performance of the tools provides high quality standard of the output product and operational safety. Therefore, the accurate prediction of the cutting tool wear during machining is very important.

While manufacturing and operating, the surface structure of the P-group hard alloys undergoes oxygenation and nitrogenization when exposed to the surrounding gaseous atmosphere [1]. The intensity of the oxygen interaction process with a hard alloy composition depends on the presence of a tungsten constituent, and that of nitrogen compounds is determined by the titanium constituent. The surface oxycarbide structures, formed at high temperatures, effectively prevent the insert contact surfaces from the devastating effect of the most active workpiece elements and phases. The increase of the titanium carbide constituent in the hard alloy composition results in the decreased thickness of the oxycarbonitride film and the increased screening capacity, which limits the mass and velocity of the work piece material diffusion into the boundary layers of the hard alloys interfaces. This occurs due to densification of the chemically inactive nitride compounds in the composition of oxycarbonitride structures.

When cutting, the structure of the contact surface is continuously subjected to the destruction and regeneration due to interaction with the elements of gaseous atmosphere. As a rule, the wear surface microrelief of the P-group cutting inserts exhibits its poor development and an insignificant fractal dimension value. As the titanium constituent in the hard alloy composition increases, its density and screening capacity, tend upwards. Simultaneously, the fractal dimension of the wear surface, which causes an intensive chemical interaction in contact zones, decreases. The radiation preprocessing of carbide cutting inserts with a gamma-quantum promotes the intensification of the hydrogen desorption process from the hard alloy structure at the stage of its operation. This process results in high oxidation characteristics of the contact surfaces, an increase in the wear microrelief development and fractal dimension, and some decrease in the wear resistance.

## 2. Materials and methods

The investigation of the wear resistance of the P-group carbide cutting inserts was carried out with the help of a turning lathe of model 163. Steel 50, which causes intensive diffusion wear, was used as a processed material [2]. Machining was performed by the carbide cutting inserts of the industrial TZ0K4grade related to the above specified group. The cutting conditions were as follows: cutting speed = 180 m/min (and it was optimal as it provided the minimum wear rate), feed rate = 0.23



mm/rev and cutting depth = 1.5 mm. The wear resistance was estimated in minutes of the tool operating time up to the specified criterion of tool dulling that was 1.0 mm. The treatment of tools by the gamma quantum was performed in a special radiation unit. The radiation fluence was  $10^{17}$  gamma-quantum/cm<sup>2</sup>.

The morphology of the wear surface was investigated with the help of non-contact three-dimensional profilometer MICROMEASURE 3D STATION by STIL. The wear surface testing was carried out with the pulsed light beam, generated by the halogen lamp with the frequency of 10Hz. This frequency provided the more exact simulation of the wear lines. The dimensions of the microrelief peaks and dimples were determined from the difference between the incident and reflected light intensities.

The roughness of the surface profile was estimated based on its measurements in the interval of 0.5 mm. The profiles were processed using a special computer program, a part of the profilometer equipment. The fractal dimension value was identified automatically using the roughness parameters of the measured profile. Roughness control and fractal dimension measurement were performed on the flank land located in the central part of the insert. For all the worn inserts, the running coordinates of the flank land were similar.

### 3. Results and Discussion

Materials, which cause intensive diffusion wear are usually processed by the P-group carbide cutting tools. At high temperatures, these materials have a tendency to oxygenation and nitrogenization. The aeration process of the hard alloys takes place not only at the stage of preparation of different components and their sintering, but also during the use of manufactured cutting tools. Surface and subsurface oxide and oxycarbide structures occurring while cutting steels act as a screen that prevents chemical solid-phase interaction between the workpiece and hard alloy materials. Testing shows that the microrelief of the wear surface has fractal properties [3]. The main characteristic of fractal surfaces is their fractal dimension. The level of the wear surface roughness, fractal dimension, correlates with the material wear resistance and recovery properties of the damaged objects.

Figure 1 shows the dependence of cutting inserts operating time up to the specified criterion of tool dulling on the fractal dimension value. The data in the figure indicate that the decreased roughness development of the flank wear leads to the increase in the wear resistance of the cutting inserts. From this, it can be expected that the higher chemical, thermal and mechanical stability of the oxycarbonitride film structure, occurring on the contact surfaces, the less the possibility of the formation of the developed wear microrelief, and the lower the value of fractal dimension, the higher the expected wear resistance of the cutting tool. The key factors that influence the formation of the fractal dimension of the wear surface are the mechanical and chemical characteristics of the surface film structure. The experiments showed that when the mechanical and chemical stability, occurring in the hard alloy material during the cutting process of the surface structure, grows, the fractal dimension of the wear microrelief reduces, and the operating time of the cutting inserts up to the specified criterion of tool dulling increases.

Generally, the composition of the P-group hard alloys is presented by titanium carbide, the solid solution of tungsten carbide in titanium carbide, titanium carbide and cobalt binding. The base of these hard alloys is titanium carbide [4]. As the titanium constituent in the composition of hard alloy increases, its brittle strength decreases, and the chemical stability grows. However, brittle strength does not affect the wear resistance of the cutting tools since the materials intended for the processing of these alloys do not cause intensive adhesion.

The overall thermodynamic stability of these hard-alloys depends on their bulk and surface structure. In its turn, the thermodynamic stability of the surface structure depends on the composition of the formed thin oxide, oxycarbide and oxycarbonitride films. The following film structures shield the diffusion processes that develop at high temperatures between the workpiece and tool materials, and reduce the likelihood of the solid-phase reactions [5]. Eventually, the resultant working capacity of the cutting tool depends on the high temperature chemical stability of both surface and bulk

structures. Thus, the stability of the occurring surface structures greatly depends on the composition of the bulk structure including the gas elements content and the kinetics of the mass transfer of these elements from the bulk to the contact zone. This depends on the operating conditions of the cutting tools. As a result, it can be assumed that the fractality of the cutting tool contact surface occurs in the course of self-organization of various processes. In addition, the directivity of the self-organization processes can be controlled with the help of a composition and a structure. To provide a low fractal dimension of contact surfaces, it is necessary to create the conditions for the formation of surface structures with high mechanical, thermal and chemical stability.

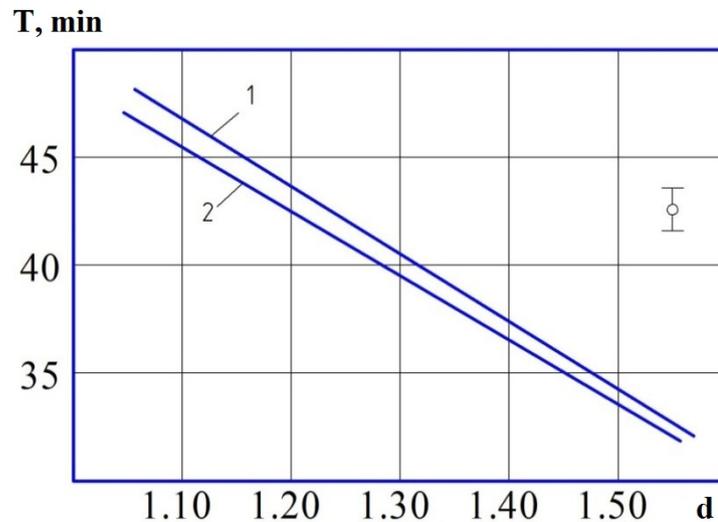
The film structure is formed from separate areas of tungsten, cobalt and titanium oxides. Simultaneously, the surface relief may be affected by the degree of interaction of hard-alloy individual components and gaseous atmosphere. As a result, the surface consists of peaks and dimples. When the film thickness grows, the difference between peaks and dimples reduces. Under the wear conditions, separate areas of the surface microrelief perform special functions. At specific correlation between the surface peaks and dimples, the operational effectiveness becomes maximal.

The intensity of the interaction of hard alloy deep layer components and the elements of gaseous atmosphere decreases. At the same time, while heating, the boundary layers actively interact with gas elements of the bulk structure. It should be noted that the composition of the environment gas and the gaseous atmosphere of the hard alloy vary widely. As a result, the properties of the occurring film structures will significantly differ within the distance from the surface to the depth. It was found that when the temperature grows, the content of titanium and cobalt oxides in the composition of the surface film increases. The concentration of the tungsten constituent is observed to decrease insignificantly. The results of the phase analysis showed that the probability of the oxycarbonitride titanium compound formation in the composition of the surface film is considerably low. At high temperatures, the probability of formation increases. Therefore, the increased content of titanium oxide in the composition of the surface film structure leads to the increase in the tool wear resistance while cutting perlitic and ledeburitic steels.

The process of the surface film structure formation depends on the stoichiometry of the carbide systems in the hard-alloy content. It can be assumed that increased carbide nonstoichiometry increases the probability of oxide and nitride structures formation. As a result, the mechanical properties of the surface and bulk structures deteriorate. Hence, the fractal dimension of the formed wear surface increases.

At higher temperatures, the intensity of the contact surfaces oxidation changes. As a result, the balance between the separate phases of the surface polyoxide structure changes, and new phases or phase compounds occur. In this case, oxidation spreads deeper. The transformation from the carbide bulk to the transitional oxy-carbide and then to the surface oxide structure is more regular. The diffusion resistance of the surface structure is higher. However, after formation of this surface structure, its mechanical properties deteriorate. Due to adhesive wear, occurring in the areas of intensive oxidation and directed into the bulk structure, formed drag lines can differ in their height and development. As a result, the fractal dimension of the wear surface increases.

During oxide films formation, compressive and tensile stresses develop in their structure. The type and the stress value are closely related to the specific aspects of the hard alloy oxidation. In oxide structures, the actual stress impacts diffusion resistant and mechanical characteristics of films and the formed microrelief of the wear surface in particular.



**Figure 1.** The dependence of wear resistance of the T30K4 grade hard alloy on the value of the fractal dimension of the flank land: 1 – controlled inserts; 2 – radiation pretreated inserts.

The increase of tensile stress in the film structure encourages the formation of a porous structure at phase boundaries. It results in the intensification of diffusion processes, solid-phase reactions and oxidation processes in this area. As the result, the possibility of the developed structure formation on the hard alloy surface increases and the tool wear resistance decreases.

The functional efficiency of the cutting tools generally depends on the hard alloy composition as well as surfaces film composition that influences mechanical, chemical and thermal characteristics. The bonding strength between the surface film and the base material is a very important fact. This property fully depends on the coherence between the film and the base material. In its turn, the degree of coherence depends on many factors; one of them is the presence of impurity oxide and oxide compounds in the material composition. It is notable that the creation of the reinforced contact surfaces by means of different modifications is related to the increased adhesion strength between the base material and the surface thin-film structure.

While using the cutting tool, the degree of coherence between the film and the base material is continuously changing due to the wear processes and the elements diffusion of the processing material, hard alloy base and gaseous atmosphere into the film structure. An optimal intensity rate of the processes provides the higher quality of the forming surface structure. The minimal fractal dimension of the forming wear surface corresponds to the highest wear resistance of the tool.

The conformance of the lattice parameters of the forming film and the base material also depends on the temperatures and load bearing characteristics (stresses) in the contact zones. When the temperature increases, the chemical reaction of contact zones with the gaseous atmosphere and gas constituents of hard alloy intensifies. At the same time, the processing material stresses on the forming film structure decreases, and the closeness of the interfacing elements grows. In this case, the surface structure is formed due to the interaction of the tool contact zones with gas elements of the hard alloy bulk. The formed surface film has a more homogeneous structure, and its crystallographic parameters coincide with the base material parameters.

The value and the nature of the strain-stress state in the film structure is a factor of the reaction order and the oxidation intensity of hard-alloy components. The surface film structure includes tungsten oxide, titanium oxide and cobalt oxide. The concentration of oxycarbide compounds in the film structure decreases when its formation temperature grows. At the same time, the formation of the nitride compounds is possible.

If the balance in this system is upset due to the alteration of the wear rate, temperature fields, interface stresses or due to gas flows rearrangement, another form of coherence between the film and the base material can be observed. Through this process the wear microrelief, the fractal dimension value and the wear rate of the wiping surface of the insert change. It is possible to consider that the processes of formation, destruction and regeneration of the oxide and oxycarbide surface structures follow the laws of self-regulation.

Processing of materials, which cause an entirely intensive diffusion wear, is generally performed by the carbide cutting inserts that under the optimal conditions of operation must set up a high correspondence between the forming oxide film structure and the crystallographic boundaries. In this case, the surface film plays the role of a diffusion-resistant and heat protection shield, and the formed wear microrelief exhibits low fractal dimension.

The process of oxide film formation in the contact zones of the cutting insert starts with the capture of gas elements from the gaseous atmosphere [6]. More often, open and closed pores of the hard-alloy surface structure, formed as a result of tribological interaction of the workpiece and tool materials are more efficient areas of gas capture. Different types of adsorption may occur in the contact zones of the cutting insert depending on the available and forming cavities, their surface and gas access rate. The capture of gas elements by the juvenile surface of the forming microcavity is usually followed by the chemical adsorption. The high concentration of juvenile surfaces speeds up the process of the film structure formation. When the gas elements are captured by the juvenile pore surface, physical adsorption takes place first. In this case, the process of the surface film formation slows down even at high concentration of the cavities. In practice, the process of the film structure formation is caused by both physical and chemical adsorptions with the predominance of one of them in each particular case. As a consequence of oxygen adsorption, the sections of oxide structure occur, expand and gradually unite into large areas.

The energy of thermal activation necessary for the formation of the oxide compound in a juvenile pore space is significantly lower than that in the preliminarily contaminated pore. After adsorption of gas molecules, the surface needs some time and energy consumption for binding the reacting atoms and the oxide compound synthesis.

Physical adsorption of molecules does not always end with decomposition into atoms, taking part in the formation of new compounds. However, the molecule physically adsorbed by the cavity, which is not susceptible to active decomposition into atoms, can be exposed to desorption and adsorbed again by the pore formed nearby with the more active internal surface.

The compounds formed in the internal spaces of juvenile and non-juvenile pores can grow and form the so-called island structure [7]. The bonding between the islands and the surface is the factor of the internal space diameter and the adsorption history on the pore walls at the initial stage. When islands grow, they overlap and form a solid surface. The formation of the oxide and oxycarbide structures and their regeneration due to inevitable damage continue throughout the whole period of the tool life, and their microrelief undergoes the continuous transformation. Because of layering, the surface structure can be assumed as mobile and its composition and properties — as inhomogeneous. First of all, it depends on the level of uniformity of the hard-alloy composition, the temperature pattern and actual stresses on the contact surface. Consequently, the chemical activity of different parts of the cutting insert interfaces and the aeration velocity will vary.

When increasing the uniformity of thermal and mechanical patterns, occurring on the interfaces the stay-put feature of the surface oxide and oxycarbonitride structures, under the conditions of intensive diffusion wear, the fractal dimension of the wear roughness decreases. This process results in improvement of the cutting tool wear resistance.

The least developed rough surface occurs on the insert rake face at some optimal temperature corresponding to an optimal cutting speed. At temperatures (speeds) lower than optimal, the high development of the wear surface microrelief and the high value of fractal dimension are specified by the considerably low intensity of formation of the surface oxide and oxycarbonitride compounds in

hard alloy. This leads to the formation of low quality film structures with low screening capacity to resist diffusion processes.

The failure of the oxide structures also results from the low level of stoichiometry. Due to oxygen deficiency, the low activity of the desorption processes can be observed. At temperatures higher than optimal, the development of the wear surface microrelief and the value of fractal dimension are higher than that caused by the intensive oxide and oxycarbonitride film destruction due to the intensification of their sublimation. This is due to the high adsorption activity, the high oxidation rate and the high transition rate of oxides and oxycarbonitride into a gaseous state. This process is accompanied by the intensification of the diffusion wear.

#### 4. Conclusion

The radiation pre-treatment of the carbide cutting tools causes an intensive desorption of impurity hydrogen that decreases the formation of the oxide and oxycarbide structures on their surfaces and subsurfaces [8]. This involves an increase in the fractal dimension of the flank wear and a decrease in the wear resistance of the cutting tool inserts. It is possible to conclude that the wear resistance of the carbide insert is specified by the optimal composition of the surface and subsurface oxide, the oxycarbide structures, and the decreased fractal dimension of the wear surface results in the increased wear resistance of the cutting insert.

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