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Wear resistance of metal-cutting tools and formation of secondary contact structures during cutting

Abstract. This article presents the results of research funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant № AP14972884 "Increasing wear resistance of metal-cutting tools by the method of lapping"). There was investigated the state of the metal-cutting tools' wear problem in the conditions of machine-building enterprises of the Republic of Kazakhstan (RK). It is revealed that metal-cutting tools do not always endure the durability period according to the standards and are exposed to premature wear of cutting edges, breakage, and chipping. The factors affecting the wear resistance of metal-cutting tools and the existing possibilities for their improvement are also studied. The article proposes the method of pretreating cutting tools in order to improve the wear resistance and durability of metal-cutting tools under the conditions of domestic machine-building industries. The formation of secondary structures on the working surfaces of the tools, which is one of the manifestations of the fundamental law - structural adaptability was studied on the basis of the results of the analysis of previously conducted works.

Keywords: endurance period, wear resistance of cutting tools, pretreating method, secondary contact structure, structural adaptability, dislocation density.

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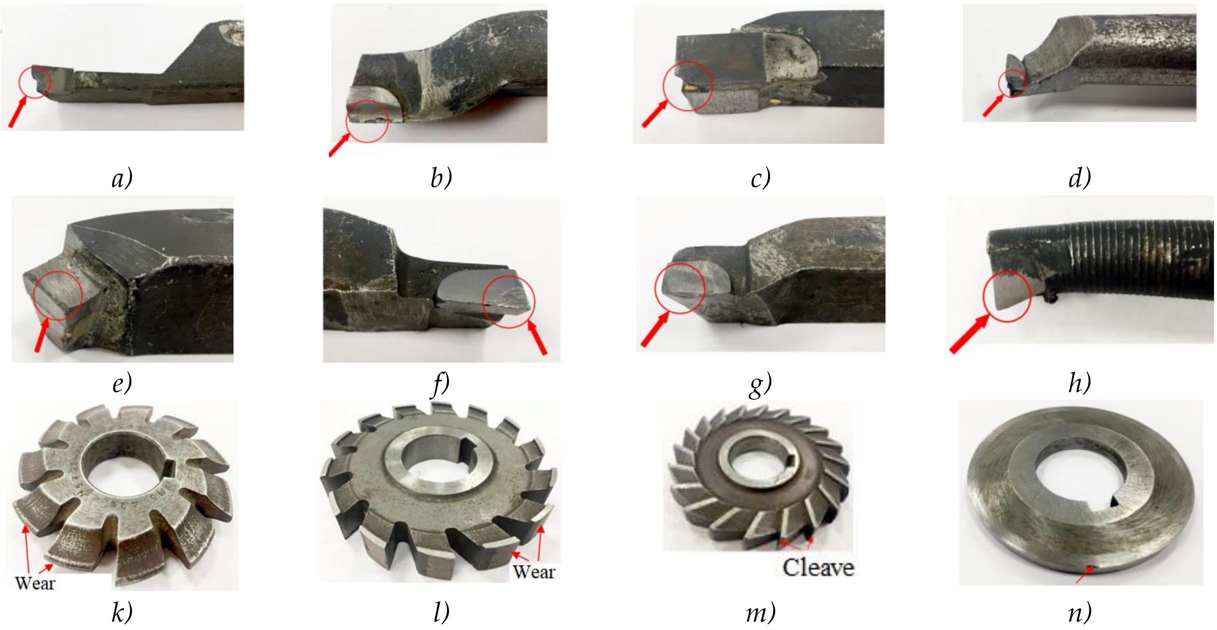
Introduction

Cutting machining is still the most preferred process for the final dimensioning of parts (despite significant progress in the development of such technological methods as precision casting, stamping, electro-physical processing, etc.) due to its flexibility and mobility, high accuracy and quality of the machined surface layer, and low cost [1].

In the system of measures to improve the machining process, the most effective link is the machining tool because it is the tool that largely determines the efficiency of using the technical possibilities of modern mechatronic systems equipped with high-speed devices with expensive microprocessor control (CNC and ADCS) and their payback period [1].

One of the acute problems in the machine-building enterprises of the Republic of Kazakhstan is the supply of high-quality and cheaper cutting tools for machining production. Currently, cutting tools are purchased from foreign manufacturers at significantly higher prices, which negatively affects the cost of machining.

The research conducted under the conditions of machine-building enterprises, in particular LLP "Astana electro-technical plant", LLP "Tselingidromash" (Astana), LLP "Mechanical plant RAPID" (Temirtau) and others, has shown that there is a problem with premature wear of cutting tools. (Temirtau) and others have shown that there is a problem with premature wear and failure of cutting tools. Photos of some cutting tools are shown in Figure 1.



a **- cut-off cutter;** ***b,c*** **- undercutting cutters;** ***d*** **- boring cutter;**
e **- straight turning cutter;** ***f,g*** **- undercutting cutters** ***h*** **- boring cutter;**
k **- modular disc;** ***l*** **- circular disc;** ***m*** **- circular tripartite disc;** ***n*** **- special rotary high-speed steel discs**
Figure 1. Photos of some metal-cutting tools subjected to wear and chipping

The type of tool wear is determined by the physical and mechanical properties of the contact materials as well as the mechanical and thermal conditions at the contact surfaces.

Figure 2 shows the dependence of wear on machining time [2].

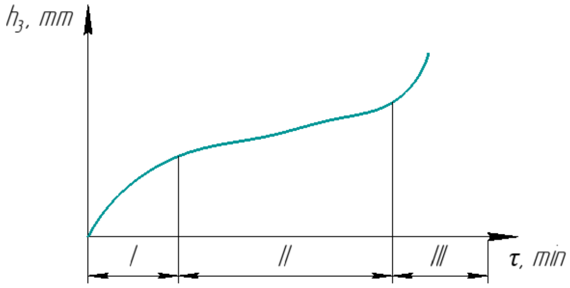
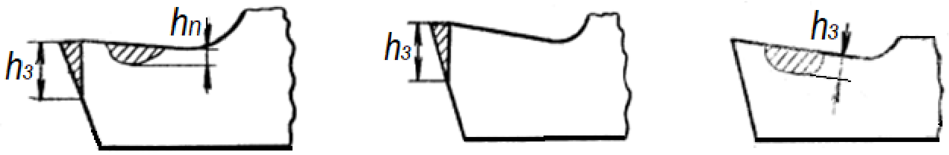


Figure 2. Dependence of wear on machining time

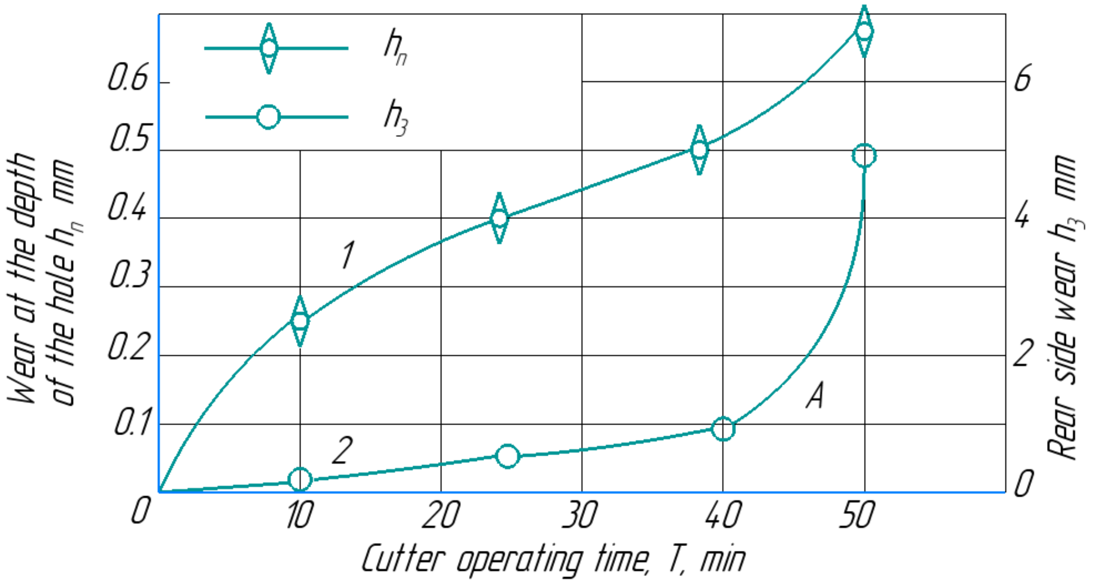
Three periods are characteristic for the given dependence: I - period of running-in, II - period of the normal wear, III - period of catastrophic wear. The intensity of the wear varies and is often accompanied by pitting on the cutting edge in hard alloys and plastic volumetric deformation in ductile tool steels. As a result, the tool wears more intensively. It is established by practice [3,4] that simultaneous wear on the back and front surfaces (fig.3, a) occurs when working with a thickness of the cut layer of more than 0.1 mm with low or average speeds for the given tool material. At work with a small thickness of the cut layer a ≤ 0,1 mm, the wear of cutters proceeds only on the back surface (fig. 3, b). At a thickness of the cut layer of more than 0,5 mm and cooling is applied, only the front side is worn (fig. 3, c).



a) b) c)

Figure 3. Simultaneous wear on the back and front surfaces of the tool

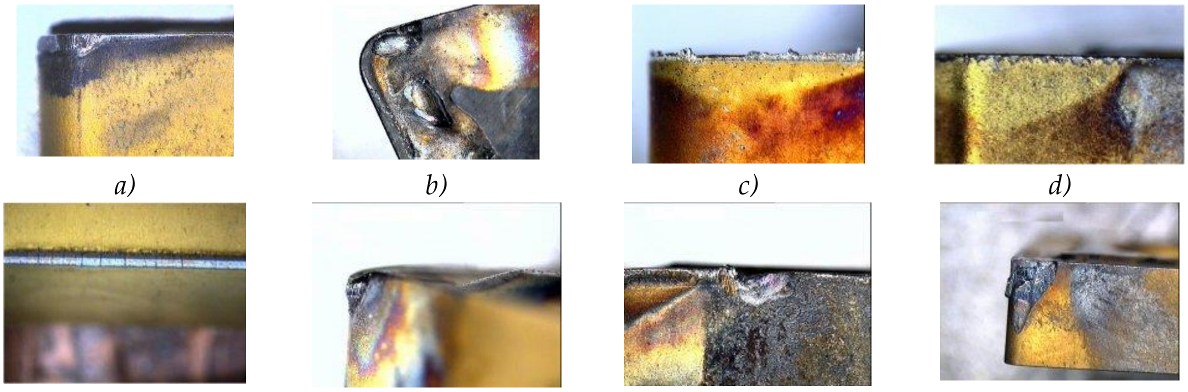
Figure 4 shows the graph of the pick wear on the front and rear surfaces [2,5]. On the diagram, you can see that line 1, showing the amount of wear on the front side, grows quite intensively during the whole operation of the pick, and line 2, showing wear on the rear surface, grows slowly until the point of inflection A, after which the wear occurs catastrophically fast and ends with the destruction of the pick. The wear corresponding to point A is called optimum wear, and it is not advisable to go beyond this point. This wear is the result of a combination of factors, such as damage to the cutting edge by mechanical and thermal stresses, wear by pressure welding (adhesion), mechanical wear, which is the removal of cutting edge particles by external forces, and at high temperatures the burning of cutting edge material (thermal wear).



Steel 45; δB=65 kg/mm2; t = 4 mm; S = 0.5 mm/rev; V = 44 m/min

Figure 4. Cutter wear graph for front and rear surfaces

The durability is usually evaluated by the wear of the cutting-edge tool. Figure 5 shows the types of tool edge wear [6].



a) b) c) d)

e) f) g) h)

a - natural wear of the cutting edge on the rear surface; b - hole formation on the cutting edge; c - growth on the cutting edge; d - pitting of the cutting edge; e - thermal and mechanical damage to the cutting edge; f - deformation of the cutting edge; g - formation of a groove on the cutting edge; h - mechanical destruction of the cutting edge

Figure 5. Types of tool cutting-edge wear

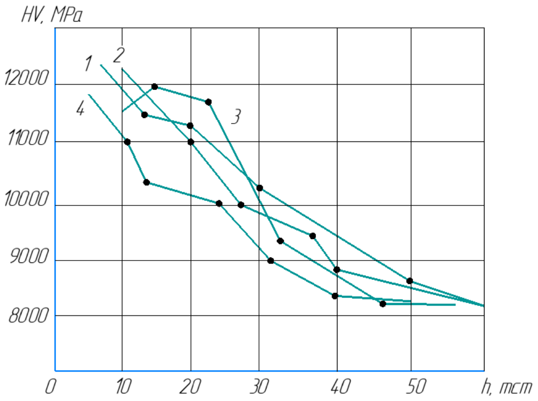
There is a relevant task of increasing the wear resistance and durability of metal-cutting tools and thereby reducing the consumption of expensive tools and increasing labor productivity.

Main part

The wear resistance of metal-cutting tools depends on a large number of factors. The most important factors are the tool material, the shape of the cutting edges, the cutting mode, the state of the crystal structure of material, and the presence of residual stresses caused by heat treatment [7]. There are many ways to increase the wear resistance of cutting tools by changing the internal structure of material, the state of magnetization and the chemical composition and condition of the surface layer. These methods include hardening, mechanical hardening, chemical heat treatment, application of wear-resistant coatings, magnetic-abrasive treatment, and magnetic-pulse treatment. Most tool steels and high speed steels, in particular, are well hardenable. The hardening process increases tool hardness from 40-45 HRC to 63-69 HRC, which increases tool wear resistance. For cutting tools, an increase in the hardness of a few HRC units leads to an increase in wear resistance by several tens of percent. The cutting tool is made of high-speed steel of tungsten and tungsten-molybdenum groups (P9, P12, P18; P6M3, P6M5) after hardening and following low-temperature tempering (aging) it gets hardness of 63...67 HRC. The negative side of the hardening process is the appearance of internal stresses in the tool structure, which cannot be removed even by low-temperature tempering. The internal stress points contain excess internal energy that causes tool warping and micro-cracking. These factors sometimes play a significant role in tool wear and fracture and make additional machining (straightening, straightening) necessary before tool use. Thermal chemically machining refers to methods based on changing the chemical composition of the tool's surface layer at elevated temperatures. The main methods of chemical heat treatment are cyanidation, nitriding and nitrocementation. The main influence on the increase in wear resistance is a layer representing at cyanidation a thin mixture of martensite, carbides, and carbidonitride phases, which hardness is 69-70 HRC, at nitriding complex tungsten nitrides and carbonitride phases which have a hardness of 1300-1400 HV, at nitrocementation also a carbide layer is formed, which has high hardness and wear resistance. With all the advantages of chemical heat treatment, it also has disadvantages. The main disadvantages include embrittlement of the treated layer and preservation of the layer until the first resharpening of the tool. These disadvantages limit the use of this method. Mechanical hardening of cutting tools consists in rounding their cutting edges to the required size and training the surface layer through vibration treatment. Change of geometrical parameters is expressed in rounding of cutting edges and in the improvement on their surface quality, changing physical and mechanical parameters is reduced to the surface layer formation of compressive residual stresses. Because of its high productivity, efficiency and low cost, this machining method is widely used in tool production. At the same time, it has its disadvantages. These include the facts that the tool is hardened only on the surface, while the core structure does not change, with the effect on the cutting edges lasting only until resharpening.

The authors carry out grant theme AP14972884 "Increase of wear resistance of metal-cutting tools by the method of lapping" which is directed to the decision of a question of an increase of wear resistance and the period of firmness of the tool. The research and analysis of the previously performed works in this area showed that the formation of the secondary structures on the working surfaces of the cutting tool is one of the manifestations of the fundamental law - of self-organization [8,9,10,11]. The optimal option of self-organization or structural adaptability is the formation process of secondary contact structures possessing strength properties tangibly superior to the initial one. This phenomenon is the result of complex physicochemical and mechanochemical processes accompanying friction during cutting and manifests themselves within a relatively narrow framework of frictional contact functioning [12,13,14,15]. The properties of secondary structures are determined by two simultaneously acting competing factors: hardening and softening or, the same thing, strain hardening and thermal rest. Structural adaptability in the applied variant is successfully used in the practice of operation of friction pairs and is realized by their running-in or running-in [16,17]. Principle laws of running-in of friction pairs are also applicable to the cutting tools, which pre-treatment at cutting modes optimal from the point of view of hardening of their working surfaces can be considered as an effective and one of the cheapest ways to improve durability.

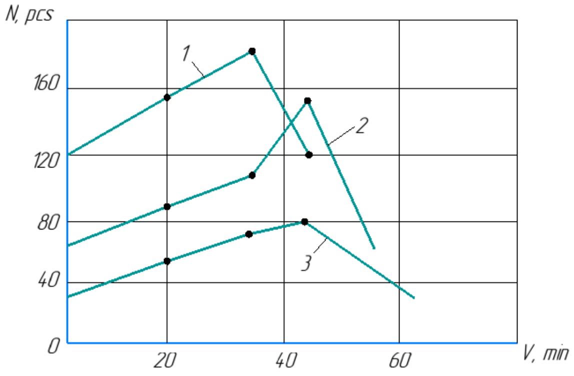
Figure 6 shows the dependences obtained in the study of hardening of worm cutter teeth on P6M5 at milling of gears m=10mm [18]. The nature of the curves at different modes can be explained by the presence of shock processes, accompanying milling, and periodic thermal cycling on the contact areas of the cutting teeth. The hardening value depends on the cutting modes and takes on a greater value in the presence of impact processes. However, a large value of scatter and insignificant numerical difference of their average values make it difficult to carry out a serious quantitative analysis to determine the connection between the cutting parameters and contact interaction with the degree of hardening of secondary structures. In view of this, one of the objective and quite informative methods of analysis of the properties of secondary tool structures is to determine its wear resistance on cutting modes exceeding those in which its formation occurred.



1 - in the initial position (after hardening); 2 - after 15 minutes of work at V=0.541 m/s; 3 - after 15 minutes of work at V=0.7 m/s; 4 - after 15 minutes of work at V=0.833 m/s

Figure 6. Distribution of microhardness in the contact layer of a worm cutter m = 10 mm of R6M5F with cylindrical gears of steel 40Ch

The extreme character of the dependence of the pretreatment rate effect on the wear resistance of the contact surfaces of the tool, as well as the presence of the cutting speed limit above which there is no effect of the pre-treatment confirms the dominant role of the deformation hardening in the secondary structure adaptation process. The extreme nature of the dependence of the wear resistance of the secondary structure on the cutting speed can be explained as follows. With the increase in cutting speed, the sliding speed in the frictional contact zone increases, leading to an increase in the speed and degree of plastic deformation of the contact layers of the tool. It leads to an increase in the density of crystalline structure defects, which determine the hardening value. As the cutting speed increases, the process temperature increases, which facilitates deformation up to a certain level, stimulates more hardening. However, when the temperature reaches a certain value equal to the recrystallization temperature, the crystalline structural defects become active. As they move to the surface or annihilate with each other, they reduce the overall defect density, reducing the amount of hardening. In addition, as the temperature increases, the stability of the defect decreases, and its "dissolution" in the main crystal increases [19]. Thus, the presence of the wear resistance extremum on the cutting speed is the result of two competing processes of deformation hardening and thermal rest. Consequently, the optimal regimes of pretreatment should correspond to the condition of the formation of secondary contact structures with an increased density of crystalline structure defects. However, high dislocation density is not sufficient to increase the wear resistance of the material. Another condition is the formation of thermally stable dislocations capable of maintaining their structure at high process temperatures. Consequently, the same structure can manifest itself differently at different temperature regimes, which in turn means that in practice there is no optimal regimes uniform for all operating conditions. Figure 7 shows a graph showing the effect of the running-in speed of a P6M5F worm cutter (m=10mm) when cutting spur gears from steel 40Ch.



1 - V = 42m/min; 2 - V = 50m/min; 3 - V = 62m/min

Figure 7. Diagram of the effect of the running-in speed of the hobbing cutter from P6M5Ф (m=10mm) when cutting spur gears from steel 40Ch

This is confirmed by the results shown in Fig. 7, reflecting the effect of the pre-processing speed of the worm cutter for different operating modes. The optimum running-in speed corresponds to the dependence extremum. However, the location of the maximum is different at various cutting speeds; in this case, an even tendency is observed that with the increase of the cutting speed, the optimal pre-treatment speed also increases. So, for gear hobbing of cylindrical gears at V= 62 m/min, the optimum running-in speed is 42.0 m/min, and for cutting speed of 42 m/min it drops to V= 32.5 m/min.

Discussion

This allows us to liken the formation of hardened secondary structures on the working surfaces of the tool to the process (HTMTT) of high-temperature mechanical-thermal treatment. In this case, in the traditional HTMTT method, the plastic deformation and thermal influence in the process of running-in are combined in time and implemented at the expense of the energy of the cutting process itself. Considering that the thermal influence during HTMTT stimulates the disappearance of thermally unstable dislocations, it follows that the heat resistance of the hardened structures increases with the process temperature [18,19]. On this basis, the results presented in Fig. 7 can be interpreted as follows. At low cutting speeds, when the process temperature is low, hardening is realized by forming a high dislocation density, thermally unstable. Such a structure will naturally work well only at thermally low cutting speeds. At high cutting speeds due to the high temperature of the process, the growth of dislocation density will be accompanied by intensive loss of thermally unstable crystalline structure defects. As a result, the secondary structure will have less high dislocation density but be thermally stable. Such a structure will perform well at high cutting speeds and not effectively at low speeds. It is known that the wear of cutting tools can vary within a wide range, proceed by various mechanisms, but in all cases, it is a consequence of friction. For each tribosystem formation of secondary structures on surfaces of friction which represent some "third" body carrying out protective functions, limiting distribution of interaction inside rubbing bodies are characteristic [1]. Formation of secondary structures and wear are connected with transformations of energy at friction which can be considered from positions of nonequilibrium thermodynamics and self-organization. At the same time, the problem of selecting contacting materials that are capable of adapting (adapting) to each other in the process of mutual movement, providing entropy reduction on friction surfaces, and increasing their wear resistance under the adopted lubricating medium (or absence of lubrication) and a given friction mode comes to the fore. At present in mechanical engineering cutting tool materials and coatings with the predictable adaptation of friction surfaces have not yet found noticeable application, meaning the ability of friction pair "tool - workpiece " in given conditions of cutting to adapt to external influences with reduction of wear intensity due to formation of secondary structures on contact surfaces with minimum entropy production [1]. The reason for this is the insufficient study of the structural-phase adaptation of the near-surface layers of contacting tools and machining materials, considering the passage of nonequilibrium processes and the interaction of irreversible processes during metal cutting friction, which complicates the practical use of this phenomenon to improve the wear resistance of cutting tools.

Conclusion

1. The results of the research on the state of the problem of metal-cutting tools wear in the conditions of machine-building enterprises of the Republic of Kazakhstan showed that metal-cutting tools do not always endure the durability period according to the standards and are exposed to premature wear of cutting edges, breakage and chipping. The solution to this problem is the use of a resource-saving, affordable method of increasing the wear resistance of the working surfaces of metal-cutting tools by pre-treatment.
2. Based on the analysis of the results of earlier work, it was found that the optimal pre-treatment modes should correspond to the condition of forming secondary contact structures with an increased density of crystalline structure defects capable of preserving their structure at high process temperatures.
3. The optimal variant of self-organization or structural adaptability is the process of formation of secondary contact structures with strength properties tangibly exceeding the initial one. This phenomenon is the result of complex physical-chemical and mechano-emissive processes accompanying friction during cutting and is manifested within a relatively narrow framework of frictional contact functioning.

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Металл кесуші құралдың тозуға төзімділігі және кесу кезінде қайталама жанасушы құрылымдардың түзілуі

Андатпа. Бұл мақалада Қазақстан Республикасы Қазақстан Республикасы Ғылым және жоғары білім министрлігінің Ғылым комитеті қаржыландыратын зерттеу нәтижелері келтірілген (№AP14972884 «Ысқылап қалыптастыру әдісімен металл кескіш құралдардың тозуға төзімділігін арттыру» гранты). Қазақстан Республикасының (ҚР) машина жасау кәсіпорындары жағдайында металл кесуші құралдардың тозу мәселесінің жай-күйі зерттелді. Металл кесетін құралдар әрдайым нормативтерге сәйкес төзімділік кезеңін сақтай бермейтіні және кесу жиектерінің мерзімінен бұрын тозуына, сынуына және жырашық пайда болуына ұшырайтыны анықталды. Сондай-ақ, металл кесуші құралдардың тозуға төзімділігіне әсер ететін факторлар және оларды арттырудың бар тәсілдері зерттелді. Отандық машина жасау кәсіпорындары жағдайында металл кесуші құралдардың тозуға төзімділігі мен төзімділігін арттыру үшін металл кесуші құралдарды алдын ала ысқылап қалыптастыру әдісі ұсынылады. Бұрын орындалған жұмыстарды талдау нәтижелері бойынша құралдың жұмыс беттерінде қайталама құрылымдардың қалыптасуы зерттелді, бұл іргелі заңдылық көріністерінің бірі – құрылымдық бейімделу.

Кілтті сөздер: төзімділік кезеңі, кескіш құралдың тозуға төзімділігі, алдын-ала ысқылап қалыптастыру әдісі, қайталама байланыс құрылымы, құрылымдық бейімделу, орналасу тығыздығы.

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Износостойкость металлорежущего инструмента и образование вторичных контактных структур при резании

Аннотация. В данной статье приводятся результаты исследования, финансируемого Комитетом науки Министерства науки и высшего образования Республики Казахстан (грант №AP14972884 «Повышение износостойкости металлорежущих инструментов методом приработки»).

Исследовано состояние проблемы износа металлорежущих инструментов в условиях машиностроительных предприятий Республики Казахстан (РК). Выявлено, что металлорежущие инструменты не всегда выдерживают период стойкости согласно нормативам и подвергаются преждевременному изнашиванию режущих кромок, поломке и сколам. Также исследованы факторы, влияющие на износостойкость металлорежущих инструментов, и существующие способы их повышения. Для повышения износостойкости и стойкости металлорежущих инструментов в условиях отечественных машиностроительных предприятий машиностроительных производств предлагается метод предварительной приработки металлорежущих инструментов. По результатам анализа ранее выполненных работ исследовано формирование вторичных структур на рабочих поверхностях инструмента, которое является одним из проявлений фундаментальной закономерности – структурной приспосабливаемости.

Ключевые слова: период стойкости, износостойкость режущего инструмента, метод предварительной приработки, вторичная контактная структура, структурная приспосабливаемость, плотность дислокаций.

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