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RESEARCH OF DEFORMATION AND THERMAL PROCESSES IN THE STRUCTURAL ADAPTABILITY OF TOOLS

Abstract: *This article presents the results of studies of deformation-thermal processes in the structural adaptability of the tool , implementation of the running-in of the tool by analogy with the running-in friction units of machines, which is one of the effective and mandatory ways to increase the working capacity.*

Key words: *tool, microhardness, running-in, structural adaptability, deformation, hardening, durability.*
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Introduction

The most important condition for the economic development of society is the intensification of production and increasing its efficiency based on the acceleration of scientific and technological progress, the rational use and saving of all types of resources, the creation and widespread use of high-performance technologies that improve the quality of manufactured products and their competitiveness. The successful development of each production largely depends on how it is provided with tools, equipment, etc. of the proper quality. Practice shows how important metal-cutting tools are for modern mechanical engineering.

The formation of secondary structures on the working surfaces of the tool is one of the manifestations of a fundamental regularity—self-organization [1, 2]. The properties of secondary structures are determined by two simultaneously acting competing factors: hardening and softening or, something the same, strain hardening and thermal rest.

Structural adaptability in the applied version is successfully used in the practice of operating friction pairs and is realized due to their running-in or running-in [3, 4]. The fundamental regularities of running in friction pairs are also applicable to cutting tools, whose preliminary running-in at cutting conditions that are optimal in terms of hardening of their working surfaces can be considered as an effective and one of the cheapest ways to increase tool life [5].

The depth of the transformed structure of the working surface of the tool is a thin layer several tens of micrometers thick, which seriously complicates the study of its strength properties. One of the available and widely used methods of mechanical testing is the measurement of microhardness on specimens of the "oblique sections" type, which convincingly confirms the very fact of the presence of structural adaptability and allows a rough estimate of the degree of hardening and the depth of the modified layer. The amount of hardening and its depth is determined both by cutting modes and by the nature of the contact process.

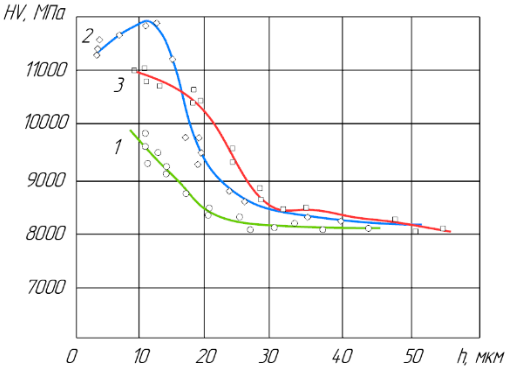

Fig.1. Distribution of microhardness in the contact layer of R6M5 cutters when turning steel 40X (S = 0.2 mm/rev; t = 0,5 мм).

1- in the original state (after hardening)
2- after 10 minutes turning at *V = 0.583 m/s*
3- after 10 minutes turning at *V = 0.833 m/s*

In Fig.1. curves of distribution of microhardness in the contact layers of the tool in the initial state, obtained by grinding (curve 1) and after short-term cutting in various modes (curves 2 and 3) are presented. The nature of microhardness change in depth has a typical form, similar to those taking place in the surface layers of hardened machine parts, and the thickness of the transformed structure is on average 30–50 µm. Figure 2 shows similar dependences obtained in the study of hardening of the teeth of a worm cutter according to R6M5 when milling gears m = 10 mm. The nature of the arrangement of the curves is fundamentally preserved in comparison with Fig. 1. However, the hardening value is significantly higher on average by 10…15%, and the depth of the modified layer reaches average values within 40…60 µm, which is 10…30% higher than those obtained with turning. Such a numerical difference can be explained by the presence of impact processes accompanying milling and periodic thermal cycling on the contact pads of the cutting teeth. Turning with imitation of shock processes when cutting a cylindrical roller with a pre-milled groove confirms this assumption. On fig. 3 shows the distribution of microhardness in the contact corresponding to the experimental value of Fig.1. The obtained values of hardening and occurrence depths are numerically close to the result of the analysis of worm cutters, i.e. higher than with smooth turning.

Considering the above, one of the objective and sufficiently informative methods for analyzing the properties of the secondary structures of a tool is to determine its wear resistance at cutting conditions that exceed those at which it was formed. The methodology for such an analysis is as follows. Secondary structures, as transformed from the original ones, formed in the contact process during short-term cutting (for example, for 10 minutes) under various regime conditions, are subsequently tested for wear at higher regimes fixed for each experiment. In this case, the nature of wear and tool life parameters will be largely determined by the conditions of contact interaction of the initial cutting process, in which the formation of secondary structures was realized.

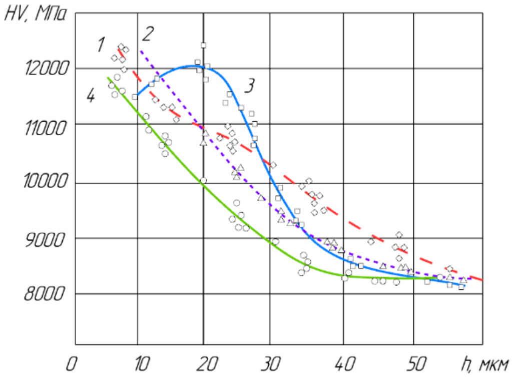

Fig. Fig. 2. Distribution of microhardness in the contact layer of a worm cutter m =10 *mm* made of R6M5F when machining cylindrical gears made of steel 40X.

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

It can be assumed that the modes of initial cutting (or preliminary running in), corresponding to the maximum tool life, will determine the conditions of contact interaction, under which the formation of the most wear-resistant, and, consequently, more hardened structure, is stimulated. As can be seen from the description, the technique largely uses the idea of preliminary running in, but is considered not as a method of increasing durability, but as a methodical technique for analyzing the state of the transformed surface structure.

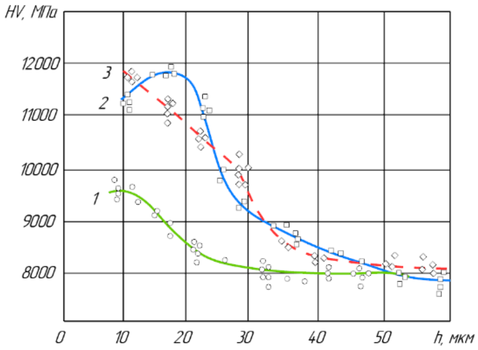

Fig. 3. Distribution of microhardness in the contact layer of cutters made of R6M5F during turning steel 40Kh with shock loads.

S = 0.2 mm/rev; t = 0.5 mm:
1 - in the initial state (after hardening);
2 - after 10 minutes of cutting at V = 0.583 m/s;
3 - after 10 minutes of cutting at V = 0.833 m/s

Consider some of the results obtained using the described technique.

On fig. 4 and 5 show the resistance of turning tools made of R6M5 when turning steel 45 in modes V = 1.0 m/s; S = 0.2 mm/rev; t = 0,5 ммafter pre-running. The choice of such cutting conditions was justified by the fact that the tool blunting curve, as a function of time, in these modes had a character close to linear, i.e. the running-in period was practically indistinguishable from the steady-state wear zone (Fig. 3.6, curve 1). Therefore, it could be assumed that in this case, the transformation of the original structure during the running-in occurs under conditions of dynamic equilibrium of hardening and softening. Preliminary running-in of all tested cutters was carried out during conventional turning (Fig. 4) and when cutting a shaft with a groove simulating an impact process (Fig. 5). The intensity of wear was determined in the area of the steady process by calculation using the formula

$$J = \frac{dh}{dt} \approx \frac{\Delta h}{\Delta t}$$

where Δh is the increment in the value of the wear chamfer on the back surface of the tool in the zone of the steady process over a period of time Δt .

Some wear curves are shown in fig. Analyzing the obtained results, the following can be noted:

- preliminary running-in when turning a conventional roller in the considered range of cutting conditions gave a positive effect, while the maximum increase in tool life was 1.50 ... 1.7 times;

- optimal running-in modes, corresponding to the maximum resistance itself, were determined by the speed range V=20…35 m/min;

- preliminary running-in during turning with imitation of shock processes also in the considered range of modes gave a positive effect, however, the effect was more tangible, namely: the decrease in wear intensity compared to the initial state was more than 2.75 times;

- the optimal running-in mode when turning a shaft with a groove was V=15…25 m/min; those. lower than the traditional one.

The last remark is more clearly shown in fig. where the effect of the pre-running speed on the tool wear rate is shown when cutting a conventional roller (curve 1) and a shaft with a groove (curve 2). The significance of shock processes is manifested not only in the mixing of the optimal running-in rates to a lower region, but also in the change in the nature of blunting. Indeed, the wear of a tool that has been run in according to the traditional version of turning when operating at elevated modes undergoes additional secondary adaptation, which manifests itself in the presence of a pronounced period of initial wear. So if, after running in, the blunting value was 0,25 мм, then after the second run-in, it reached 0,45 мм, after which the tool left the steady-state wear zone. A different picture takes place in the case of preliminary running-in of the tool when turning a shaft with a groove. The amount of run-in wear in this case was 0,2 мм, however, during further operation, the secondary running-in of the tool in operating conditions practically does not appear.

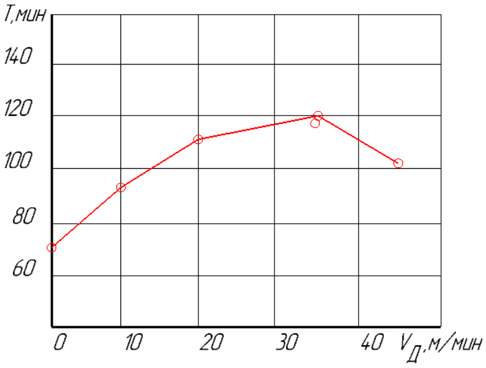

Fig. 4. Influence of the running-in speed on the tool life of the R6M5 cutter when turning 40X steel at V = 60 m/min, S = 0.2 mm/rev; t = 0,5 мм. Run-in on steel 40X

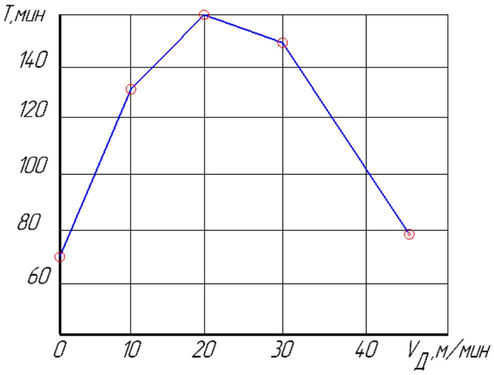

Fig. 5. Influence of the running-in speed on the tool life of the R6M5 cutter when turning 40X steel at V = 60 m/min, S = 0.2 mm/rev; t = 0,5 мм.
Running-in on steel 40X with imitation of impact processes

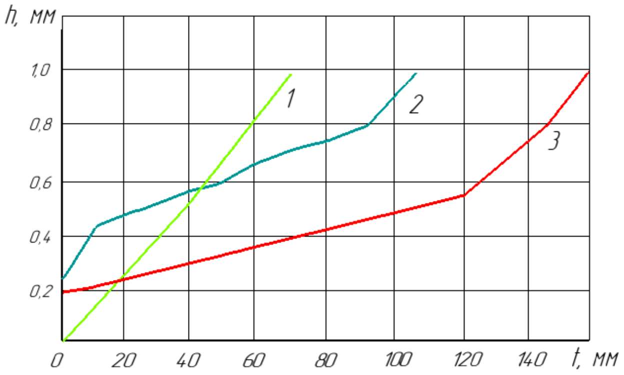

Fig. 6. Wear of the R6M5 cutter when turning steel 40X at V = 60 m / min, S = 0.2 mm / rev; t = 0,5 мм.
1 - normal cutting:
2 – after running-in on V_p =20 m/min;
3 – after running in at V_p =20 m/min with impact simulation.

The absence of a pronounced secondary running-in of the tool when working under shock processes is a characteristic moment that occurs during the operation of worm cutters. Figures show the wear curves of conventional and run-in cutters, clearly demonstrating the noted circumstance.

The effectiveness of pre-running can be estimated by the ratio of the tool life of a run-in tool to a conventional tool, i.e.

$$\eta = \frac{T_n}{T}$$

where T_p - resistance of the run-in tool; T - resistance of a conventional tool.

And the optimal pre-running mode can be set as a first approximation by the ratio of the pre-running rate to the operating rate, i.e.

$$k = \frac{V_{\text{п}}}{V_{\text{э}}}$$

where V_p is the speed of preliminary running-in; V_e - operating speed

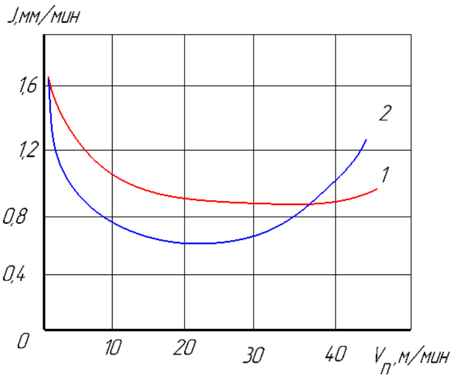

Fig. 7. Influence of the running-in speed on the wear rate of the R6M5 cutter when turning 40X steel at V = 60 m/min, S = 0.2 mm/rev; t = 0,5 мм.

1 - normal running-in on steel 40X;

2 - running-in on steel 40X with imitation of impact

The dependence $\eta = f(k)$ is shown in Figure, analyzing which we can note the following. $\eta = f(k)$ is nonmonotonic with a pronounced maximum corresponding to the optimal ratio k_0. In this case, the value k_0 for turning has a larger value ($k_0 \approx 0.75$) in comparison with the variant of gear milling ($k_0 = 0.68$). The tool life increase effect in the latter case reaches $\eta = 3.25$, while in turning $\eta = 1.85$. Dependence $\eta = f(k)$ for the case of preliminary running-in when turning a roller with a groove is located in the interval between gear milling and turning, however, the value of the optimal ratio in this case takes the smallest value and amounts to $k_0 = 0.39$.

Figure 8 also shows the dependencies $\eta = f(k)$ for spline milling and cutting bevel gears. The maximum effect of tool life increase after preliminary running-in takes place during spline milling and gear milling and reaches more $\eta = 3.0…3.25$. Determination of the optimal modes of preliminary running in by the ratio V_n / V_e does not reflect the physical essence of the hardening process, but can be used in the approximate determination of the conditions for running in by cutting, which is guaranteed to provide a positive effect.

The extreme nature of the dependence of the influence of the preliminary running-in speed on the wear resistance of the contact surfaces of the tool, as well as the presence of a limiting cutting speed, above which there is no running-in effect, confirms the dominant role in the secondary structure of the work hardening adaptability. The extreme nature of the dependence of the wear resistance of the secondary structure on the cutting speed can be explained as follows. With an increase in the cutting speed, the sliding speed in the friction contact zone increases, leading to an increase in the speed and degree of plastic deformation of the contact layers of the tool. This, in turn, leads to an increase in the density of defects in the crystal structure, which determine the amount of hardening. As the cutting speed increases, the process temperature increases, which, to a certain level, facilitates deformation, stimulating more hardening. However, when the temperature reaches a certain value, equal to the recrystallization temperature, the defects in the crystal structure come to an active state. Moving to the surface or annihilating with each other, they reduce the overall density of defects, reducing the amount of hardening. In addition, with increasing temperature, the stability of the defect decreases and its “dissolution” in the main crystal increases [7, 8]. Thus, the presence of an extremum of wear resistance as a function of cutting speed is the result of two competing processes of work hardening and thermal rest.

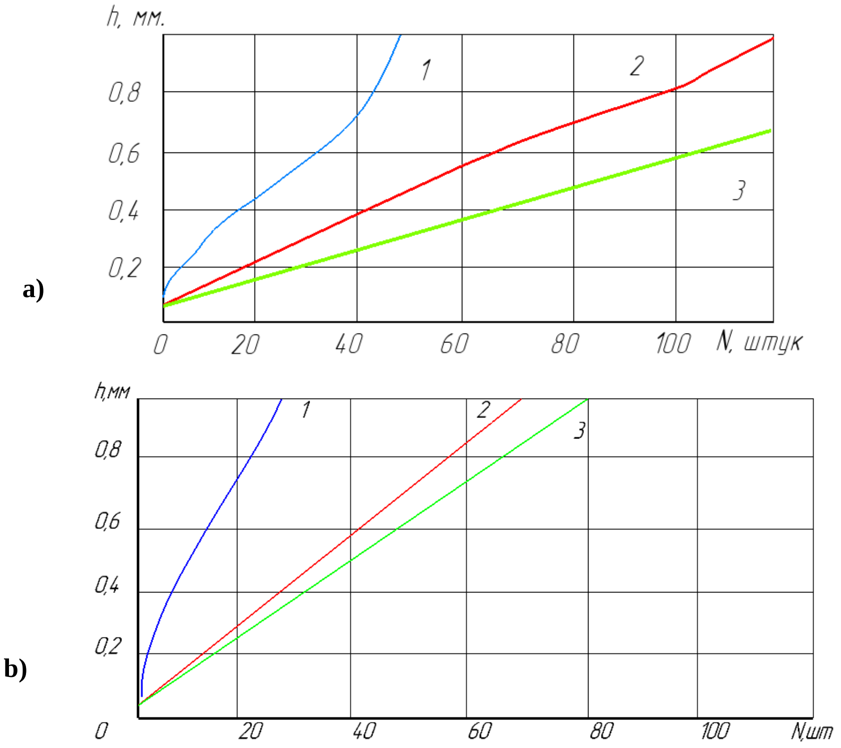

Fig. 8. Wear of a worm cutter made of R6M5F m = 10 *mm* when machining gears made of steel 40X. a) V = 50 m/min; b) V = 62 m/min.

1 - normal cutting;
2 - after running in at V = 32.5 m/min;
3 - after running in at V = 42 m/min

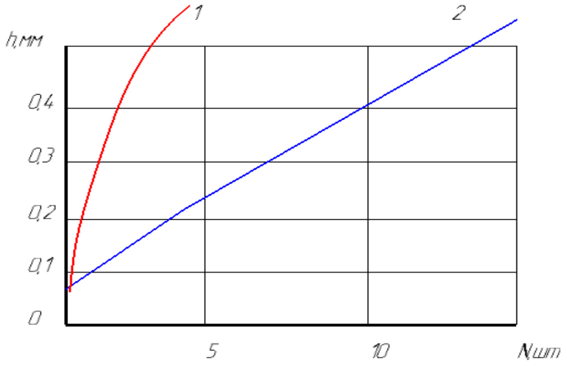

Fig. 9. Wear of a worm spline cutter made of R6M5 when cutting splined shafts according to 30KhGSA at V = 45 m/min

1 - normal cutting; 2 - with running-in at V = 17.5 m/min

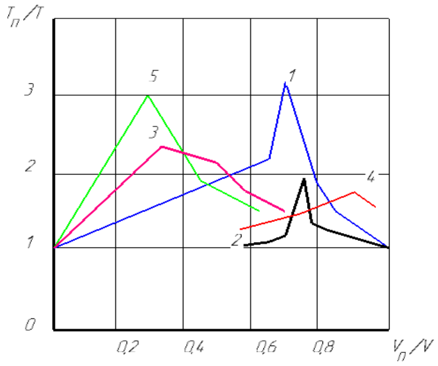

Fig.10. Influence of the ratio of running-in and cutting speeds on the degree of tool life increase.

1 - gear milling R6M5F - 40X;
2 - turning - P6M5 - 40X;
3 - turning with imitation of impact - R6M5 - 40X;
4 - milling of bevel gears - R6M5F - 30KhGSA;
5 - slot milling R9K5M - 12KhGSA.

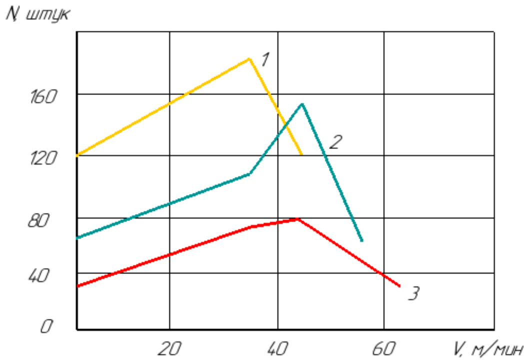

Fig. 11. Influence of the running-in speed of a worm cutter made of R6M5F 9 (m = 10 mm) when cutting cylindrical gears made of steel 40X
1 - V =42 m/min , 2 - V =50 m/min , 3 - V =62 m/min

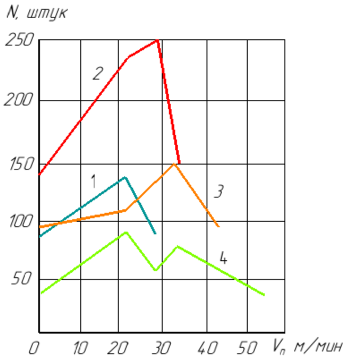

Fig. 12. Influence of running-in speed on the durability of the gear-cutting head (R6M5F) when cutting bevel gears from steel 30KhGSA
1 - V =29 m/min., 2 - V =34 m/min ., 3 - V =42 m/min ., 4 - V =52 m/min.

Figures 11 and 12 show the experimental results showing the effect of the pre-running speed of the hobbing cutter and gear cutting head for various operating conditions. Studies show that each operating mode of the tool has its own optimal pre-running mode. Indeed, the optimal running-in rate corresponds to the extremum of the dependence. However, the location of the maximum is different at different cutting speeds, and there is an even tendency that with an increase in cutting speed, the optimal pre-running speed also increases. So for gear milling of cylindrical gears at a speed V = 62 m/min, the optimal running-in speed is V_p = 42.0 m/min, and for a cutting speed V = 42 m/min it drops to V_p = 32.5 m/min. The same is true for the gear head. Thus, at cutting speeds V = 42 m/min and 52 m/min, the optimal running-in speed is 34 m/min. For cutting speed V = 34 m/min, it decreases to V = 29 m/min, and when cutting at V = 29 m/min, the optimal run-in speed drops to V_0 = 21 m/min.

The foregoing makes it possible to liken the formation of hardened secondary structures on the working surfaces of the tool to the process of high-temperature mechanical -thermal treatment (HTMT). At the same time, in the traditional HTMT method, plastic deformation and thermal effects during the running-in process are combined in time and are realized due to the energy of the cutting process itself. Taking into account that the thermal effect during HTMT stimulates the disappearance of thermally unstable dislocations, it follows that with the name of the process temperature, the heat resistance of the strengthened structures should increase [5]. Based on this, the results presented in Fig. 11 and 12 can be interpreted as follows. At low cutting speeds, when the process temperature is low, hardening is realized due to the formation of high dislocation density, thermally unstable in nature. Such a structure, of course, will work well only at low thermal cutting conditions. At high cutting speeds, due to high temperature, the growth of dislocation density will be accompanied by an intense decrease in thermally unstable defects in the crystalline structure. As a result, the secondary structure will have a not so high dislocation density, but thermally stable. Such a structure will perform well at high cutting speeds and is not effective at low ones.

An effective way to increase the thermal stability of dislocations is to fix them with alloying elements [3, 4, 5]. This is explained as follows. The thermal instability of dislocations consists in their movement during heating. The decrease in the cost of dislocations occurs in this case due to their escape from the surface or annihilation when two dislocations meet with opposite Burger vectors. A dislocation can be retarded by blocking it with foreign atoms and their compounds or another dislocation moving in a plane perpendicular to the first one [8]. The source of alloying elements for the contact layer of the tool can be a wear-resistant or other special coating.

The papers [4] showed the fundamental possibility of increasing the efficiency of wear-resistant coatings by preliminary running-in of the tool. Figure 13 presents some of the results of these studies. Analyzing them , it can be noted that the preliminary running-in of the tool without a coating gave a minimal positive effect, which practically did not manifest itself at cutting speeds above V = 21 m/min.

Wear-resistant TiN coated by CIB also did not give a significant effect, however, it should be noted that the coating slightly increased the heat resistance of the tool. This was manifested in the fact that the cutting speed at which the tool life of a conventional tool coincided with the tool life of a coated tool turned out to be higher for a run-in one. The small effect of the wear-resistant TiN coating when turning stainless steel 12Kh18N10T is explained by the manifestation of strong adhesive processes during cutting, associated with the presence of titanium both in the coating and in the material being machined. It should be noted that the positive role of the wear-resistant coating at high thermal cutting conditions does not decrease with a decrease in cutting speed.

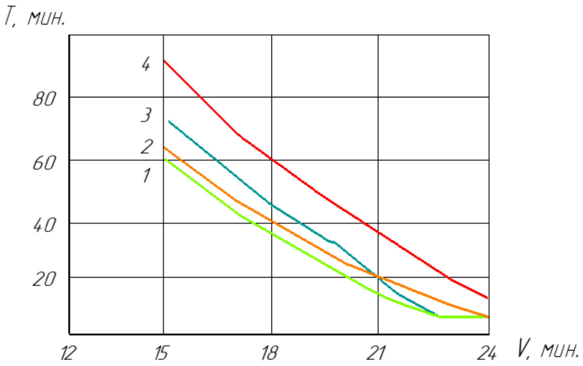

Fig. 13. Influence of cutting speed on the tool life of R6M5 when turning steel 12X18H10T (S = 0.2 mm/rev; t = 0,5 мм).
1 - normal cutting , 2 - after running in at V = 7.0 m/min , 1 - normal cutting with TiN coating , 2 - after running in with TiN coating at V = 7.0 m/min

The pre-running of the tool with a wear-resistant coating significantly increased the tool life of both conventional and coated tools. At the same time, there is an increase in heat resistance. Indeed, at the cutting speed, at which tool life reached the same value with coating and normal, pre-running increased it by more than 10 times.

Similar studies were carried out during the operation of worm cutters from R5M5F when processing gears m = 6,0 ммfrom steel 12KhGSA. On fig. 14. summarized test results are presented, which in their content are adequate to the conclusions obtained during turning. The tests were carried out in the workshop conditions of the Production Association "Navoi Machine-Building Plant".

Tool life was evaluated by the number of machined gears, which had the following parameters: number of teeth Z = 72; module m = 6 мм; crown width B = 40 мм. The cutting conditions corresponded to the condition of semi-finishing gear milling and were: V = 42 m/min; S_0 \u003d 2.01 mm / rev; t = 12 мм. The speed of preliminary running-in was assumed to be V_p = 28 m/min.

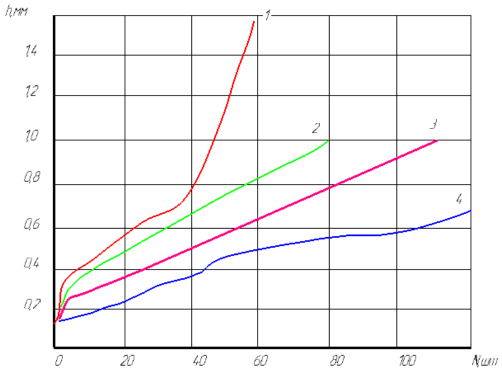

Fig. 14. Wear of a worm cutter made of R6M5F 9 (m = 10 mm) when machining gears made of 12HGSA at V = 42 m/min; S_0 =0.2 mm/rev; t = 12 мм; m =6 mm
1-ordinary worm cutter , 2- mill with TiN coating (KIB), 3-plain cutter with running-in at V = 28 m/min; 4-running cutter with TiN coating on V

Conclusion

The initial period of the tool operation is characterized by the transformation of the original structure of the tool associated with its adaptation to the modes of contact interaction. Depending on the deformation -thermal conditions of frictional interaction in contact, the surface layers of the tool can be hardened or hardened. The latter circumstance is the main one for the implementation of the running-in of the tool, by analogy with the running-in friction units of machines, which is one of the effective and obligatory ways to increase the working capacity.

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