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NEW TECHNOLOGIES IN MECHANICAL ENGINEERING

The Main Directions for Increasing the Tool Life of a Metal Cutting Tool with Modified Working Parts

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Abstract—In this paper, studies aimed to substantiate the directions of improving the reliability of a metal-cutting tool with working parts modified in terms of its service life by application of low-temperature plasma are presented. These investigations employed a database generated by the results of the pilot production operation of a modified hard-alloy tool and the mathematical software developed for data processing. The results of data processing show that the increase in the service life of the modified tool is related to optimization of the working feed parameter.

Keywords: modified metal cutting tool, durability, defects, database, feed optimization.

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INTRODUCTION

The global landscape of the machine tool industry developed by the end of the 1990s encompassed many techniques aimed to increase the reliability of metal-cutting tools, including the parameters of durability: technological, thermal, chemical and chemicothermal, electrophysical, mechanical, and thermomechanical [1, 2]. By now, new technological branches have emerged, and their development is associated with the application of a variety of materials including new and difficult-to-machine materials. The methods based either on application of wear-resistant coatings (single- and multicomponent) on the working part of the tool [3, 4] or tool hardening [5] are the most promising. Analysis of the methods shows that the application of a coating increases the wear resistance mostly in constructional material machining [6]. When special materials are treated, such as titanic alloys, steels with specific properties, or high-strength cast irons, or complicated loading conditions are applied (sign-variable loads or intermittent cutting), the coatings do not provide the necessary level of protection for the tools, primarily, hard-alloy tools, since the kinetics of their wear is dissimilar in such conditions [7]. In this regard, the hardening methods of modification of the working part of the tool are noteworthy, for example, tool exposure to a low-temperature combined charge plasma [8]. The main technological feature of the method is the initial gradual heating with subsequent shock cooling of the tool; plasma is formed directly near the treated surface. This approach to plasma formation is quite different from other methods known; it considerably simplifies the configuration of manufacturing equipment and makes its operation reliable and efficient.

The examination of the properties of the tools equipped with modified replaceable many-sided plates made of T15K6 and VK-10 hard alloys, including plates with protective coatings, as well as wear resistant tests in conditions of real production of items of constructional and alloyed steels [9, 10] showed that the most typical outcome of the modification was an increase in the working part resistance to defect formation (both traditional and new) on the working surfaces of plates [11]. Traditional defects differ in appearance from similar defects of an ordinary tool. The attrition of working surfaces of a modified tool proceeds without the initial matrix exposure or a network of crack formation. Surfaces are fit-in; the surface edges are not sharp and have no ledges. Cratering is insignificant and arises only on the tool without a protective coating. On the auxiliary rear surface, grooves with a contact site on the rounding radius are formed. The grooves are distributed in the direction of the billet rotation. The largest grooves originate in the zone of the billet material division into chipping and machined surface.

Formation of new defects is associated with the behavior of the modified layer under the action of temperature and power loads, which is different from the traditional behavior of an ordinary layer: there is a displacement of the layer microvolumes in different directions within the zone of contact interaction with the separated material. As a result, prominences and rossette-shape defects form on the cutting face of the tool; these are multiple point formations having high adhesion with the base material and dislocated across the rake face. The matrix is locally deformed on the edges near the grooves and areas with an increased power load. Overhangs form above the cutting edge in the zone of interaction with the separated material. The overhangs are flowed round by the separated material on both sides, and their shapes depend on the direction of motion of the separated material. The integrity damage of the overhang material induces the destruction (plastic deformation) of adjacent areas, local displacement of the coating along the rake face, and its partial sliding along the back surface with the formation of new grooves.

Hence, the specifics of the modified surface properties determine the expediency of studies aimed at searching for conditions in which the properties should be best displayed to form a steady streamline shape, primarily of the tool cutting edge, which should decrease the frictional force and, consequently, heat generation upon cutting. Then, even if the defects form, the structure of the modified surface layer remains resistant to prevent the matrix from exposure and promotes an increase in the reliability of the tool in terms of the total operating time parameter that characterizes the longevity.

THE SUBJECT MATTER OF THE SOLUTION

Since the formation and display of defects in the modified tool depends on different stochastic factors, a special database (DB) was developed for the studies [12].

Structurally, the DB consists of three interrelated tables (two-dimensional matrices) with the number of rows equal to the number of tools that have passed the wear-resistance tests.

The number of columns (fields) of the first table of defects is determined by the defect types (19 in total), while the content of cells is determined by the parameters (area or volume occupied by the defects on the working part and the level of significance in probability terms [13]). The table is formed by the results of analysis of micrographs of the working surfaces of tools.

The columns (fields) of the second table of factors that determine defect formation and development contain information on the tool parameters, modification mode, cutting mode, and the machine tool brand, material treated, type of machining, and the efficient life of the tool in the accepted units: time or number of manufactured workpieces.

The third table contains data about the chemical composition in weight percent and the sizes of the grain structure of the tool matrix before and after modification, and the modified layer. The elements of chemical composition are chosen taking into consideration the most common protective coatings of the hard-alloy tool (including plates): TiN and AlTiN.

The part of the third table containing information about the microhardness parameters is of special importance; the number of its rows differs from the number of rows of other tables. In the first case, this is determined by the fact that the tool can have several vertices (generally, it is m); therefore, the tool number is placed in the second column of this matrix as many times as the number of its vertices is. In the second case, the number of rows equals two, which is the number of microhardness measurements at each checkpoint located along the auxiliary cutting edge.

The considered DB structure indicates most completely the requirements imposed by the contents of the problem of determining the directions of improving the service reliability of the modified tool and is convenient for statistical processing, since each of its columns is a sample of the general population of a particular parameter or factor.

The DB developed makes it possible to implement the probabilistic approach to assessment of the operational quality of the modified tool taking into consideration the whole range of operational conditions.

In order to carry out the assessment, mathematical software written in the C# programming language [14] was generated. The assessment can be performed using both traditional and special methods of mathematical statistics, in particular, prospecting analysis and nonparametric methods [15]. The main purpose of the assessment is to obtain information about the principal regularities of building the service reliability characteristics of the modified tool. The variance analysis procedures based on the Kruskal–Wallis statistics or Friedman statistics are used to assess repeatability of the tool operation process, i.e., the stability of conditions in which the process is carried out. If it is necessary to assess the influence of one known factor or another on the stability, the rank correlation analysis procedures are used.

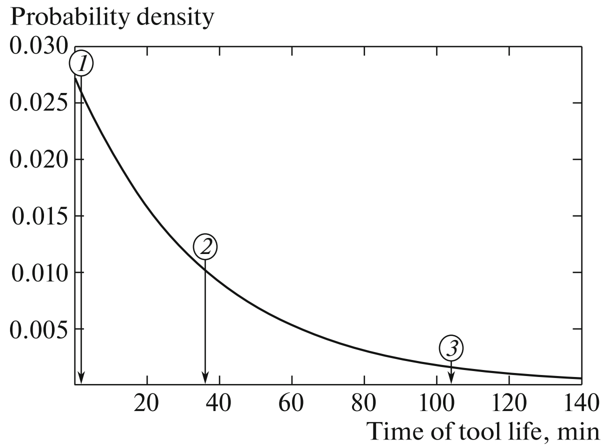

Fig. 1. Distribution of the time of the modified tool life: (*1*) and (*3*) quartiles 0.05 and 0.95, respectively, and (*2*) mean value.

RESULTS AND DISCUSSION

The principal statistical characteristic of the modified tool reliability indicating the regularities of defect origin is the time distribution of the tool life, which is a quantitative characteristic of the service life of the plates, since these are nonrestorable items.

The processed data from the generated database show (Fig. 1) that this distribution is exponential, which is quite scarce in practice due to its typical statistical features, primarily, its coefficient of variation equal to unity. However, the check performed shows that, in the case considered, this condition is met, since the coefficient of variation is 1.0062; i.e., it differs by only 0.62% from unity, which is negligibly small. The probabilistic characteristics of the distribution are the following: 5% tool life, i.e., the time longer than the time when the tool works with a probability less than 0.05—1.5 min; the mean tool life is 36.5 min; 95% tool life, i.e., a time shorter than the time when the tool works with a probability less than 0.05—104.5 min. Based on the fundamental principles of the theory of reliability and mathematical statistics, the result obtained means the following [16, 17]:

(1) The mechanisms of disturbance of operation of the modified tool are different; i.e., there are several mechanisms.

(2) The failure rate is constant; failures are independent sudden events, the moments of origin of which are distributed according to the Poisson law.

(3) Each failure (1) is a consequence of an accidental adverse combination of external and internal factors and can be independent of the modified layer condition and (2) can have a nonexponential distribution of time intervals between occurrences and does not render a significant influence on the distribution of time intervals between failures in the aggregate.

(4) The physicomechanical and chemical properties of the modified layer of the tool remain generally unchanged during the tool operation.

The foregoing allowed us to conclude that the exponential distribution: (1) is a statistical model of the distribution of the durability time of both a tool having a low quality and a tool of good quality; (2) it fixes the fact that the operating conditions of the tool, in terms of temperature and power and/or dynamic loads, were either unfavorable or extreme; (3) tool failures are related not so much to the ageing and wear processes as to the processes of formation and evolution of defects, which provoke sudden failures manifested in the form of chippage in this case, and (4) in order to increase the tool resistance to sudden failures, the optimization of its operation process, i.e., the search for optimal combinations of operating parameters, is needed.

With the purpose of searching for these combinations, the procedure of statistical assessment of data from the generated database of technological (operational) and physicomechanical (density increment) parameters based on the criterion of their influence on the lifetime of a tool equipped with modified hard-alloy plates, which had been applied at two Saratov factories for performing (1) operations of semifinish turning of ShH-15 steel workpieces (11 plates of the T15K6 alloy) with a cutting speed of 58 m/min, cutting depth of 2 mm, and feed of 0.26—0.38 mm/rev, and (2) operations of contour milling of 30HGSA and 35HGSL steel workpieces (8 plates of the VK-10 alloy) with the following parameters of operational mode: cutting speed 75.5—197 m/min, cutting depth 0.2—2.0 mm, and feed 0.17—0.52 mm/rev.

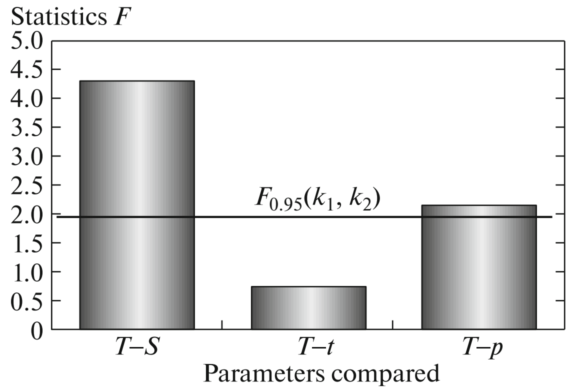

Fig. 2. Results of the rank correlation analysis of data based on a tool with T15K6 alloy plates.

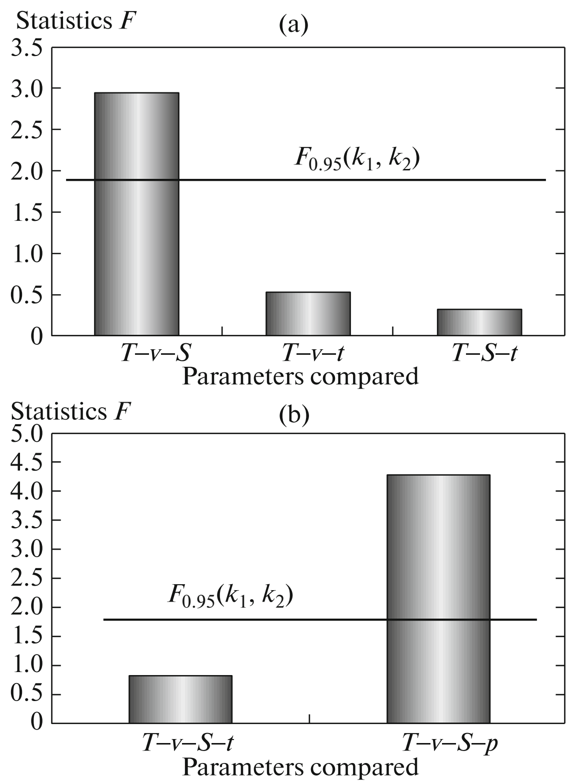

Fig. 3. Results of the rank correlation analysis of data based on a tool with VK-10 alloy plates.

The combinations of the operating parameters were set taking into account the recommendations [18] to ensure compliance with both the machined surface roughness and the machining efficiency. The dimensional accuracy of the manufactured parts was accepted as the criterion of finalizing the plate operation. After the operation was finalized, the service duration and the defects formed on the plates were registered.

The assessment of the time data obtained was carried out using the nonparametric correlation analysis based on calculation of the concordance coefficient [15]. The influence on the tool life takes place, if the following inequality is true: $F \geq F_{0.95}(k_1, k_2)$, where F is the Fisher statistics value calculated by the coefficient of concordance and $F_{0.95}(k_1, k_2)$ is its reference value at the number of degrees of freedom k_1 and k_2 and the confidence coefficient 0.95.

The results presented in Figs. 2 and 3 show that (1) the lifetime T of the tool with T15K6 alloy plates (Fig. 2) depends on the feed per revolution S (to a greater extent) and the modified layer density ρ (to a lesser extent) and does not depend on the cutting depth t (the latter coincides with the results obtained by

(a) (b)

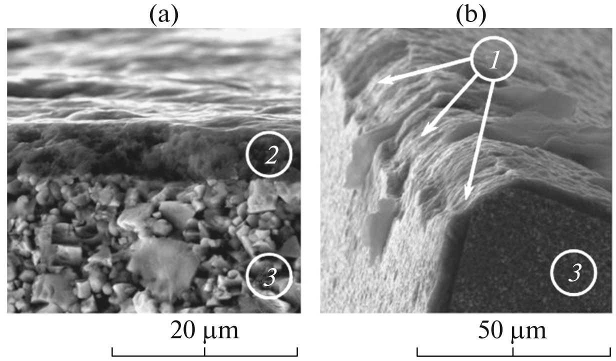

Fig. 4. REM images of the working surfaces of plates: (a) of the T15K6 alloy and (b) of the VK-10 alloy after operation: (*1*) worn-out modified layer; (*2*) undamaged modified layer; (*3*) tool matrix with (a) an undamaged and (b) a deformed near-edge part.

A.D. Makarova [19]), and (2) the lifetime of the tool with VK-10 alloy plates depends on both the combination of the cutting speed v and the feed per revolution, i.e., the feed per minute (Fig. 3a), and their combination and the modified layer density (Fig. 3b) (in the latter case, to a greater extent), and does not depend on the cutting depth.

The results obtained are certainly expected, since they are stipulated by the difference in the physico-mechanical characteristics of the plate materials. In particular, the influence of the modified layer density (mean density is 28.61 GPa/μm) on the life of the stronger T15K6 alloy is manifested to a lesser extent than for the less strong VK-10 hard alloy (with a mean density of 18.86 GPa/μm). The greater influence of the feed per revolution on the life of the former alloy indicates the prevailing changes that occur in the modified layer along the direction tangential to the rake face of the plates, i.e., in the horizontal plane. However, this is possible only in the case of stability of the tool matrix, which is confirmed by the raster electron microscope image (REM image) of the surface in Fig. 4a. The influence of both the feed per minute and the density on the life of the VK-10 alloy indicates the prevailing changes that occur in the modified layer along the direction normal to the cutting edge, i.e., in the vertical plane. This is possible only in the case of instability of the tool matrix, which induces its local strain (subsidence), which is also confirmed by the REM image in Fig. 4b.

CONCLUSIONS

(1) The life of a metal-cutting tool with working parts modified by applying low-temperature plasma depends on the defects that change its state to different extents. In this regard, the search for methods aimed to increase the tool life, including in terms of longevity parameters, should be carried out on the grounds of special databases organized to cover the entire range of conditions that determine the data about the state of the modified tool and make it possible to implement the probabilistic approach to their assessment.

(2) It is expedient to represent the assessment scientific software as an integrated program package intended for the successive analysis of information contained in the data about the results of this process. The principal conditions securing the assessment productivity are (1) using both traditional and special mathematical statistics methods, in particular, the exploratory analysis and nonparametric methods as assessment instruments and (2) making efficient decisions during the assessment and based on its results.

(3) The following directions securing the increase in the lifetime of the modified metal-cutting tool can be considered as principal: (1) optimization of the value of the feed per revolution (Fig. 5a) for the tool, the hardening of the working part of which due to modification extends to greater depths from the surface, since this indicates that a transition layer (sublayer) is formed between the modified surface layer and the matrix, and consequently increases the durability of the latter, and (2) optimization of the feed per minute value (Fig. 5b) of the tool, the hardening of the working part of which occurs near the surface, since this indicates the absence of a sublayer and consequently does not provide an increase in the durability of the tool matrix.

The implementation of these directions will ensure the creation of an operating mode of the tool such that the process of gradual attrition of the modified layer will dominate over the processes of formation and development of defects that provoke sudden failures. It will also ensure improvement in tool reliability

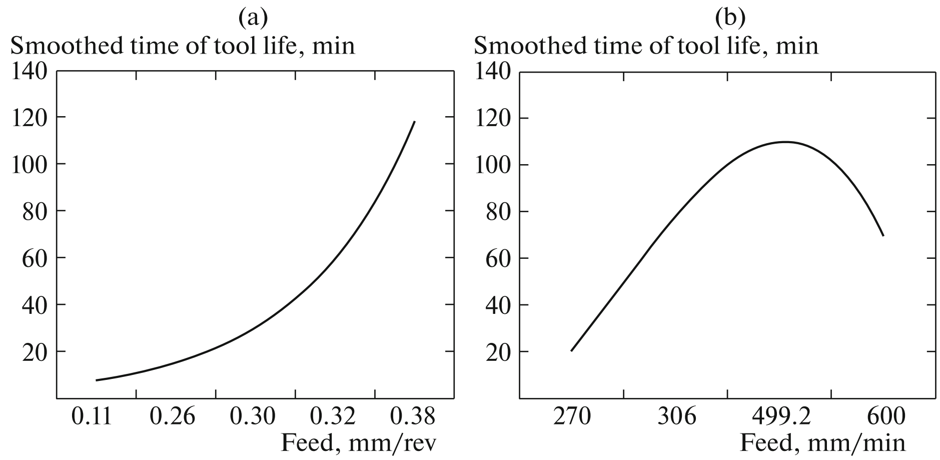

Fig. 5. Behavior of the time of the tool life at variations of the (a) feed per revolution and (b) feed per minute for different results of modification of the working part of the tool.

in terms of longevity parameters, since gradual failures need greater time of development than sudden failures that are the consequences of relaxation in the case considered, i.e., that result from a sudden change of state emerging from gradual development of the failure. In particular, the results of the pilot production operation of the modified tool of the VK-10 hard alloy with the optimal feed per minute values display the options of increasing the tool service life 2.0- to 3.5 times, and boosting its machining productivity 1.43 times.

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CONFLICT OF INTEREST

The authors declare they have no conflict of interest.

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