Composite structure formation on the surfaces of geometrically complex products

B M Brzhovskii¹, N S Azikov¹, V V Martynov² and E P Zinina²

¹ Institute of Machines Science named after A.A. Blagonravov of the Russian Academy of Sciences, 101990, Moscow, Russia
² Yuri Gagarin State Technical University of Saratov, 410054, Saratov, Russia

E-mail: v_martynov@mail.ru

Abstract. The paper examines the main issues of ensuring necessary indicators of product durability, shows the viability of additional technological impact on the surface layer of products during their manufacture, and presents a method for improving the surface layer properties due to the composite structure formation through its exposure to low-temperature plasma of the combined discharge. The paper provides the results of comparative tests of products with a formed composite structure and similar conventional products.

1. Introduction

The real resource of many products often differs from the resource required by the conditions of their efficient (including economically justified) operation. This is due to the fact that even at the product design stage, resource indicators are determined only with a certain probability, expressed as a percentage (γ-percentage resource and average resource), along its distribution curve. The resource value is influenced by many factors, most of which are random. As a result, the values of resource indicators are scattered, therefore, the distribution curve can be identified either presumably or based on statistical data that are most often absent at the design stage, especially for new products.

The dominant factors influencing the values and scatter of resource indicators are the quality of the product, the level of its manufacturing technology, as well as the stability of operating conditions and loading conditions [1].

The product quality is important due to the fact that today it includes parameters that were practically not considered a few years ago, in particular, microhardness, residual stresses, relative deformation and depth of the surface layer with modified physical and mechanical properties. Insufficient information on these parameters in the existing reference literature used in engineering, its ambiguity and low statistical reliability lead to increased scatter of resource indicator values.

The level of product manufacturing technology is characterized by many factors. An important place among them is occupied by the production level, unification degree, standardization and specialization of manufacturing, availability of objective quality control means, stability of the parameters of the materials used, the use of advanced technological processes. The lower the level of technology, the more reasons there are for increasing the spread of values of resource indicators.
Operating conditions determine the values and variation of resource indicators through the degree of climate impact on the product and the level of its maintenance. The influence of loading modes is determined by the values of the loads they form: at maximum loads, the spread of resource indicator values is less than at average ones.

The stated means that in order to provide the specified resource indicator values, it is necessary to use additional methods of technological impact on the product during manufacture. First of all, this treatment should be applied to the surface layer of the working part of the product, on the properties of which the resource depends to the greatest extent. At the same time, it is necessary not only to increase the indicators characterizing the properties, but to ensure their long-term preservation by searching for and creating conditions in which the formation of properties will be targeted.

2. State of the question

The analysis of publications devoted to improving the operational reliability of metal parts and products by durability parameters, including through changing their surface properties, showed that most often for this purpose, various methods of surface hardening treatment are used, which in varying degrees change the properties of the surface layer and contribute to the increase in its hardness to various degrees. At the same time, it is known that the best processing results are achieved when it contributes to the surface layer nanostructuring, since in this case its hardness is the highest. However, the methods of surface hardening treatment do not provide the surface layer nanostructuring, since the main mechanisms for changing the properties of the surface layer are diffusion intercalation and doping. In addition, the technological processes that implement these methods are of long duration (from 2 to 22 hours), and the equipment is characterised by high energy consumption (from 20 to 210 kW) [2]. In this regard, methods of chemical (CVD) and physical (PVD) deposition of coatings are being developed and actively introduced into practice. These methods allow obtaining nanostructures in a thin layer, the thickness of which can reach nano- to several micrometers, as well as multilayer coatings with small layer thickness which increase the abrasive and erosion resistance of various parts and products, for example, turbine blades, cutting tools, etc.

However, the coatings structure may turn out to be non-identical (since it is formed in different working temperature ranges) and manifest itself in the form of microdefects: microvoids, discontinuity flaws and discontinuities at the solder joints of solidified droplets and microcracks which negatively affect surface stability in operation and, thus, reduce product durability. Moreover, it should be mentioned that it is possible to produce nanoscale coatings by CVD and PVD methods only if the substrate is heated insignificantly (within 100...200°C) and, as a consequence, the diffusion processes are inhibited, which, however, leads to a low coating rate. For this reason, modern units are equipped with additional devices that combine several methods of coating, such as magnetron and ion beam sputtering, pulsed arc evaporation, ion deposition, etc., which dramatically increases their cost.

The widespread use of these methods is also hampered by:

− change in the dimensional accuracy of precision products due to coating;
− distortion (in some cases) of the finished product after hours of processing and high temperature;
− lack of possibility to process small-size complex and high-precision parts and products;
− the unresolved issue of ensuring a long-term bonding of the coating with the substrate.

In addition, the coating is soon abraded during the operation of the product, especially in extreme conditions, and its repeated application is not possible. As a result, coated product operational reliability improvement in terms of durability is not obvious.

The foregoing allows us to conclude that the development of methods for forming nanostructured surface layers under surface hardening treatment, and further improvement of the efficiency of obtaining nanostructured coatings as tools to increase operational reliability in terms of durability is a pressing scientific and practical problem.
3. The method of low-temperature plasma formation of composite structures

One of the promising ways to change the properties of the product surface layer, especially complex profile precision product, is its exposure to a combined gas discharge of low-temperature plasma [3]. During the process, the surface layer is heated by charged plasma particles to the molten state. Subsequent quenching in the absence of plasma stimulates nanocluster self-assembly and amorphous binder formation in the surface layer. This imparts the surface layer with unique properties (figure 1), first, by creating a composite structure (amorphously bound nanoclusters) with hardness that is 1.5 times higher than the original; secondly, by «healing» surface defects, first of all microcracks; thirdly, by asperity reduction, which ensures increased product durability.

![Figure 1. Raster electron microscopic images of the original (a) and composite (b) structures of the solid alloy product surface layer: D_i – nanoclusters, arrows – the places of microcracks «healing» with amorphous bond.](image)

As examples, tables 1-4 show the results of comparative tests of replaceable multi-faceted carbide inserts and carbide drills: conventional, with coatings and with a formed composite structure, used in the manufacture of products from various materials for various industries. The results showed increased indicators characterizing durability, including in conditions that are not normal.

| Tool point | Cutter Plate  |
|------------|--------------|
|            | Reference    | With composite structure | Resource increase, times |
| 1          | 40           | 68                      | 1.70                   |
| 2          | 40           | 97                      | 2.42                   |
| 3          | 40           | 75                      | 1.88                   |
| 4          | 40           | 71                      | 1.78                   |
| Average resource increase, times |            |                         | 1.95                   |

Table 1. The results of comparative tests of T490 E90LN plates (Israel) in 35HGS8 steel parts manufacture.
Table 2. The results of comparative tests of MB plates and M772 BCR inserts (Sweden) in ARMKO steel parts manufacture.

| Product       | The number of machined parts | Resource increase, times |
|---------------|-----------------------------|--------------------------|
|               | Reference                   | With composite structure |                        |
| Cutter Plate  | 20                          | 58                       | 1.8                     |
|               | 26                          |                           | 2.9                     |
|               | Average resource increase, times | 1.3                     |
| Insert        | 50                          | 80                       | 1.6                     |

Table 3. The results of comparative tests of LNMX 301940 CB plates (Russia) in 45GSF steel products manufacture.

| Parameter                                    | Cutter Plate |
|----------------------------------------------|--------------|
|                                              | Reference    | Coated AlTiN | Coated AlSiTiN | With composite structure |
| The amount of metal removed during operation, cm³ | 8015.77      | 8143.0       | 7634.06       | 9415.34                  |
| Average wear rate on the back surface, mm/product | 0.17         | 0.22         | 0.10           | 0.13                     |

Table 4. The results of comparative tests of drills (Russia) in 20X13 steel parts manufacture.

| Product       | Work time, min. | Resource increase, times |
|---------------|-----------------|--------------------------|
|               | Standard for reference drill | With composite structure |                        |
| Drill Ø2.15 mm | 5               | 11.65                    | 2.33                     |
| Drill Ø4.5 mm  | 5               | 77.2                     | 15.44                    |

The study of the post-operational state of the tool with the composite structure formed by optical microscopy showed the following:

- cutter plates (figure 2(a)–(c), 500× increase): in the course of processing, a layer-by-layer displacement of the composite structure edge microvolumes occurred in the direction from the cutting edge with gradual formation of lapped surfaces; the wear type was that of gradual abrasion to the condition when the cutting wedge loses stability and minor defects are stripped. After operation, micro build-ups and traces of adhered metal were recorded on the front surfaces of some plates;
- drills (figure 2(d), 400× increase): cutting edges are plastically deformed only in the maximum external load area; webs are in the initial wear stage; front surfaces are lapped; the condition and geometrical position of the connection points of major and minor cutting edges have changed insignificantly; the defects formed were of micropitting type.

The state quantitative analysis showed that all parameters of all recorded changes did not exceed 100 microns. This allows us to conclude that the behavior of the composite structure is significantly different from the behavior of the material of a conventional carbide tool.
Figure 2. Post-operational state of the working part of the cutter plate (a-c) and drill (d): 1 – cutting edge; 2 – offset composite structure; 3 – deformed cutting edge; 4 – defect (micropitting) with run-in edges; 5 – traces of adhered metal; 6 – lapped surfaces.

4. Conclusion
The obtained results determined the possibilities for further efficiency improvement of the method. They are related to taking into account the surface layer electrical properties since their parameters, changing in the process of structure formation, reflect its course quantitatively. These properties consideration based on the parameter registration creates prerequisites for solving a set of issues in managing the structure formation process according to the ratio criterion of the volumes occupied by clusters and amorphous bundles. For numerical expression of this criterion, the structure density or its increment with respect to the surface layer initial density can be used.

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