Results of testing the rationality of tool materials using the experimental method and the method of simulation modeling

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Abstract. Growing requirements for physical and mechanical characteristics and operational properties lead to the development of ever new structural materials, the range of which is constantly expanding. This complicates the selection of rational tool materials required for machine processing, which requires considerable time. Currently, there are no regulatory recommendations for such work, so there is a need for a quick and less costly choice. Experimental studies, trial and error methods are not suitable for this. Therefore, it is necessary in a universal way, in the use of a model of the cutting process, which has not yet been developed due to the complexity of the simultaneously occurring processes. The absence of such a model of the cutting process can be temporarily replaced by computer simulation modeling. This work presents such modeling in the Deform software environment as applied to process turning of corrosion-resistant specialized stainless steel.

1. Introduction
The lack of a mathematical model of the cutting process with a blade tool impedes solution of many problems in improving the design of metal cutting tools and their tool material. The available examples are of private nature. This prompts tool designers and researchers to solve these problems without using a mathematical model. At least using computer simulation modeling. There are certain opportunities for this. First of all, this is the ANSYS software environment. There are simplified versions of it, for example, the Deform software environment. Its Deform-3D software package was developed by an American company Forming Technologies Corporation (SFTC) and is based on the use of finite element analysis and is aimed specifically at the simulation of metalworking technological processes. With regard to solving problems of improving a metal cutting tool, there are various kinds of publications, including those with the participation of the authors [1, 2].

2. Results and discussion
The objective of this work is to determine, by means of simulation modeling, the most rational coating for tooling solid carbide of the VK8 grade in relation to turning process of the corrosion-resistant
specialized stainless steel 09H17N7U. This steel is in demand in many industries. All previously available recommendations for it on the use of the processing tools and on the cutting conditions are out of date. There is a need to develop new recommendations for modern operating conditions.

To simplify presentation of the results, the following information is provided:

a) the same operating conditions of the tool during full-scale experiments (cutting speed 50 m/min, feed 0.21 mm/rev. workpiece, cutting depth 1 mm) using a screw-cutting lathe;

b) for a replaceable square solid carbide plate with a central hole (the diameter of the circumscribed circle is 17.5 mm) with various options for the tool material, namely:

- VK8 + TiCN (5 μm) + (TiAl)N (3 μm) + Al2O3 (5 μm) + TiC (5 μm) (the number in brackets indicates the thickness of the given coating layer);
- VK8 + Al2O3 (2 μm) + TiCN (5 μm) + (TiAl)N (3 μm) + TiN (3 μm);
- VK8 + (TiAl)N (3 μm) + Al2O3 (3 μm) + (TiAl)N (3 μm) + Al2O3 (3 μm);
- VK8 + TiN (3 μm) + TiC (3 μm) + TiN (3 μm) + TiC (3 μm);
- VK8 + TiC (3 μm) + TiN (3 μm) + (TiAl)N (2 μm);
- VK8 + TiCN (2 μm) + TiC (3 μm) + TiN (1.5 μm);
- VK8 + TiC (1.5 μm) + TiN (3 μm);
- VK8 + TiN (2 μm) + TiC (5 μm);
- VK8 + TiCN (0.5 μm) + TiN (1 μm);
- VK8 + TiN (0.5 μm) + TiC (1 μm);
- VK8 (basic version).

It was these coatings on the VK8 substrate that we selected due to the fact that there were opportunities and equipment for their manufacture.

To measure the achieved wear rate, the processing was interrupted every 15 minutes. Wear was measured on a Micro Vu Sol 161 multisensor measuring center (video measuring machine). An example of plotting the dependence of the wear rate \( h_w \) on the time \( t \) of the operation of a solid carbide plate of grade VK8 is shown in figure 1.

![Figure 1. An example of plotting the dependence of the wear rate \( h_w \) on the time \( t \) of the operation of a solid carbide (VK8) tool (cutting mode \( v = 50 \text{ m/min}, s = 0.21 \text{ mm/rev}, t = 1 \text{ mm})\).](image_url)

On a bold, straight line, the corresponding wear values are indicated, this is 0.22 mm after 15 minutes of operation of the cutting plate, 0.24 mm after 30 minutes and 0.5 mm after operating for 45 minutes. A thin line draws a straight line, which, with a dispersion of \( R^2 = 0.9197 \) (see the upper left corner of figure 1) represents a linear approximation of the experimental curved line. In the same place, in the upper left part of figure 2, an equation describing this approximating line is given. The results obtained experimentally were systematized by arranging them according to the ranking according to the operating time until the wear of the plates reaches 0.5 mm along the rear face. The results that were obtained by simulation modeling, were also systematized in a similar way.
The adequacy of the results of simulation modeling and full-scale experiments were compared according to the position in the ranking of these tool materials. Graphs similar to the graph shown in figure 2 were obtained from experimental studies of several different interchangeable cutting plates. Part of the equations describing the dependence of the wear rate on the tool operating time obtained during field experiments are shown in table 1.

Table 1. Examples of equations describing approximating equations for a number of experimentally tested plates (with dispersion $R^2$, $h_w$ is the wear rate, $x$ is the current value of the plate operating time).

| Number of the tested plate | Equation and its dispersion $R^2$ |
|----------------------------|----------------------------------|
| 1                         | $h_3=0.00000007x^3 - 0.00002x^2 + 0.0044x \quad R^2=0.9806$ |
| 2                         | $h_3 = 0.000001x^3 + 0.0001x^2 + 0.005x \quad R^2 = 0.9973$ |
| 2.1                       | $h_3 = -0.0003x^2 + 0.0224x \quad R^2 = 1$ |
| 2.2                       | $h_3 = 0.0011x^2 - 0.0293x \quad R^2 = 1$ |
| 4                         | $h_3 = 0.00002x^3 - 0.0014x^2 + 0.0311x \quad R^2=1$ |

Figure 2. Graphic illustration of simulation modeling results (vertically – parameter values, horizontally – conditional numbers of tool materials.

The above stated information was obtained during experimental studies. This made it possible to build different tool materials (indicated above VK8 with different ten coatings) by ranking. For ranking, we used the indicator "operation time to reach wear of 0.5 mm." These data are shown
below and used to assess the adequacy of similar ranking in simulation modeling by indicators (some of them are mentioned above) “temperature”, “stress”, “strain”, “tool wear”. In figure 2, this ranking is shown by numbers affixed to the corresponding tool material.

Figure 2 shows a direct correlation of the wear rate with the magnitude of the stress in the tool material and with the cutting temperature. A more complex correlation is noted between the wear rate and strain of the tool material. To understand the reasons for such a more complex correlation, an analysis of additional parameters was performed, namely, “total cutting force”, “strain rate of the tool material” and “maximum stress in the tool material”. It is established that this is due to the feature of the properties of the coatings used.

Since one of the objectives of this article is to assess the adequacy of the results obtained by simulation modeling, the results of such control are given below. The results are presented in the form of a comparison of the location of tool materials in the ranks (in the order of magnitude) for each of the considered parameters (temperature, strain, stress, wear). This is summarized in table 2.

Table 2. The result of comparing the data obtained experimentally and by simulation modeling of tool materials for the considered parameters.

| Tool material | Results of the simulation modeling | The serial number of the location of the tool material by parameter | Experimental result |
|---------------|------------------------------------|---------------------------------------------------------------|-------------------|
|               |                                    | temperature | stress | strain | wear |                |
| A             | 1                                   | 1           | 1      | 1      | 1    | 1               |
| B             | 2                                   | 2           | 2      | 2      | 2    | 2               |
| C             | 3                                   | 3           | 3      | 3      | 3    | 3               |
| D             | 4                                   | 4           | 4      | 4      | 4    | 4               |
| E             | 5                                   | 5           | 5      | 5      | 5    | 5               |
| F             | 6                                   | 6           | 6      | 6      | 6    | 6               |
| G             | 7                                   | 7           | 7      | 7      | 7    | 7               |
| H             | 8                                   | 8           | 8      | 8      | 8    | 8               |
| I             | 9                                   | 9           | 9      | 9      | 9    | 9               |
| J             | 10                                  | 10          | 10     | 10     | 10   | 10              |
| K             | 11                                  | 11          | 11     | 11     | 11   | 11              |

Annotations:
1) The number (serial number) in columns 2, 3, 4, 5 indicates the location of the tool material in the randometric row for this parameter based on the condition, the smaller the number, the more rational the parameter value with respect to the steel turning process 09H17N7U according to the results of simulation modeling.
2) The number (serial number) in column 6 indicates the location of the tool material in the randometric row according to the wear rate of the tool material, based on the condition, the smaller the number, the more rational this tool material (in one of its operation modes).
3) Letters A – J indicate tool materials. This is a VK8 grade solid carbide with different coating options, namely (the thickness of the coating layer is indicated in brackets with a dimension of microns):

- A – VK8 + TiCN (5 μm) + (TiAl)N (3 μm) + Al2O3 (5 μm) + TiC (5 μm);
- B – VK8 + Al2O3 (2 μm) + TiCN (5 μm) + (TiAl)N (3 μm) + TiN (3 μm);
- C – VK8 + (TiAl)N (3 μm) + Al2O3 (3 μm) + (TiAl)N (3 μm) + Al2O3 (3 μm);
- D – VK8 + TiN (3 μm) + TiC (3 μm) + TiN (3 μm) + TiC (3 μm);
- E – VK8 + TiC (3 μm) + TiN (3 μm) + (TiAl)N (2 μm);
- F – VK8 + TiCN (2 μm) + TiC (3 μm) + TiN (1,5 μm);
- G – VK8 + TiC (1,5 μm) + TiN (3 μm);
- H – VK8 + TiN (2 μm) + TiC (5 μm);
- I – VK8 + TiCN (0,5 μm) + TiN (1 μm);
- J – VK8 + TiN (0,5 μm) + TiC (1 μm);
- K – VK8.
The data shown in table 2 indicate the coincidence of the experimental data and the data obtained by simulation modeling. Based on this, it was concluded that simulation in the selected software environment can be used to achieve the goal, the results of simulation modeling are adequately confirmed by the experimental data.

At the same time, an additional study of the results of simulation modeling by the parameters of “wear”, “temperature”, “stress”, “strain” was carried out to establish the trend of their change over time. In figure 4, this is illustrated for one of the tool materials for a limited period of time.

![Figure 4. Illustration of the relationship between the trend of wear and with other parameters studied (temperature, stress, strain) using an example of one of the tool materials in the initial cutting period (up to 600 seconds).](image)

From the data from figure 4 it follows that all four parameters tend to increase in time. This does not contradict the prevailing notions. But the growth rate of these parameters is slightly different. The most intensive growth rate is that of the “wear” and “strain” parameters. According to the “wear” parameter this is due to the well-known different nature of the increase in wear rate in the tool running-in the steady-state cutting area. In terms of the “strain” parameter, this is explained by the fact that, despite a balanced temperature increase (second row on the left), strain develops more rapidly in this tool material than temperature and stress do, which is associated with low heat resistance of the TiC and TiN layers.

It should be noted that a long time ago Betaneli A.I. showed that the relationship between stresses and strains is described by the equation (generally accepted designations) of the general form:

\[
\sigma_x = \frac{E}{(1 - \mu^2)} (\varepsilon_x + \mu \varepsilon_y);
\]

\[
\sigma_y = \frac{E}{(1 - \mu^2)} (\varepsilon_x + \mu \varepsilon_y);
\]

\[
\tau_{xy} = \frac{G_{xy}}{2(1 + \mu)} E.
\]

In our studies, this is exactly what is illustrated in figures 3 and 4.

Based on this, we can conclude that simulation modeling is a reliable tool for obtaining information on comparative assessment of the performance of various tool materials. It can significantly reduce the time and cost of choosing rational tool materials. Partially materials were published in [3, 4, 5].
3. Conclusion

It has been established that with regard to the turning process of corrosion-resistant specialized stainless steel 09H17N7U, the most rational are tool materials VK8 + TiCN (5 μm) + (TiAl)N (3 μm) + Al₂O₃ (5 μm) + TiC (5 μm); VK8 + Al₂O₃ (2 μm) + TiCN (5 μm) + (TiAl)N (3 μm) + TiN (3 μm); VK8 + (TiAl)N (3 μm) + Al₂O₃ (3 μm) + (TiAl)N (3 μm) + Al₂O₃ (3 μm). This is mainly explained by the fact that the coating is multilayered (microcracks growth is inhibited at each interface between the coating layers). But the architecture of these coatings is also important.

Instrumental coatings, in comparison with the VK8 substrate, significantly reduce the levels of temperature, stress, and strain. The maximum cutting temperature and the maximum rate of its growth was noted for tool material VK8 without coating.

The nature of the course of strain processes when using a tool with a coating is higher than when using a tool without a coating. This allows one to predict a decrease in cutting force and, accordingly, an increase in the wear resistance of a coated tool.

References

[1] Vereshchaka A, Mokritsky B, Mokritskaya E, Sharipov O and Ohanyan M 2017 Two-component end mills with multiplayer composite nanostructured coatings as a viable alternative to monolithic carbide end mills Mechanics & Industry 18 705 DOI: 10.1051/meca/2017052

[2] Grigoriev S N, Tabakov V P and Volosova M A 2011 Technological methods for increasing the wear resistance of contact pads of cutting tools: monograph (Stary Oskol: TNT) p 380

[3] Kruglov A I, Zubarev Y M, Zhelnov D V and Shvetsov I V 2019 IOP Conf. Ser.: Mater. Sci. Eng. 656 012028

[4] Shvetsov I V, Zhelnov D V and Zubarev Y M 2019 IOP Conf. Ser.: Mater. Sci. Eng. 656 012048

[5] Shvetsov I V, Vasilkov D V and Tarikov I Ya 2019 IOP Conf. Ser.: Mater. Sci. Eng. 656 012049