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USE OF THE THEORY OF SIMILARITY IN THE STUDY OF CUTTING TOOL WEAR

WYKORZYSTANIE TEORII PODOBIEŃSTWA W ANALIZIE ZUŻYCIA NARZĘDZI SKRAWAJĄCYCH

Key words: cutting tools, wear intensity, cutting conditions, dimensionless numbers.

Abstract The paper highlights the methods to define wear intensity of cutting tools using the theory of similarity. The dimensionless numbers of the cutting procedures, which are necessary in calculating cutting tool wear intensity, are defined with regard to the cutting conditions, cutting tool geometry, and the physico-mechanical properties of the work stock and the tool materials.

Słowa kluczowe: narzędzia skrawające, intensywność zużywania, parametry skrawania, parametry bezwymiarowe.

Streszczenie W artykule przedstawiono metody określania intensywności zużywania narzędzi skrawających z wykorzystaniem teorii podobieństwa. Bezwymiarowe liczby dotyczące procesu skrawania, które są konieczne do obliczenia intensywności zużycia narzędzia tnącego, są wyznaczane w odniesieniu do warunków skrawania, geometrii narzędzia skrawającego i właściwości fizykomechanicznych materiałów obrabianych oraz materiału narzędzia.

INTRODUCTION

The study of various processes is associated with obtaining valid mathematical dependences that will allow the management of the process and to determine its results. However, the dependences must be precise enough and have a wide range of applications.

It is known that the theoretical method is the most reliable and multi-purpose of all methods of research. Its results sufficiently describe the physical essence of the process. However, it is often impossible to define the exact quantitative relationship of process parameters due to the large complexity of the process under study. In these cases the experimental method of research is applied, which also has a significant drawback, i.e. its results can be distributed only in a very narrow range of similar processes. There is, however, a third method.

Developing a sufficiently accurate and versatile mathematical model is possible by means of a theoretical-experimental method using the theory of similarity, which is widely used in various fields of science to describe complex processes **[L. 1]**. Using this method first with the theoretical analysis of the process under study, a set of dimensionless numbers of similarity reflecting the impact of various factors is identified, and the quantitative relationship between the obtained numbers of similarity is then set experimentally. This approach allows combining the advantages of theoretical and experimental methods, avoiding the inherent disadvantages to a large extent.

THE BODY OF RESEARCH

The wear of a cutting tool is an integrated process caused by complex and interacting phenomena in the contact of tool with the chip and the work piece taking place at high temperatures and pressures. As a result of wear, the change of technological conditions of processing, changes the status of the surface and dimensions of the machined work piece.

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Currently, there is a large number of relations for the calculation of cutting tool wear intensity, but they all have significant disadvantages, e.g., low accuracy (theoretical) or a narrow scope of application (empirical) **[L. 2, 3]**.

Currently, the main causes of cutting tool wear during processing are considered as follows:

- Abrasive interaction between the work stock and tool materials (abrasive wear);
- Adhesive interaction between the work stock and tool materials (adhesive wear);
- The diffusive invasion of the tool material into the work stock material (diffusion wear); and,
- Oxidation processes occurring on the front and rear surfaces of the tool (oxidative wear).

Abrasive wear takes place when the solid micro-components of the work stock material friction against the contact surfaces of the tool. It becomes stronger with the larger ratio of the hardness of the work stock and tool materials under the cutting temperature.

It is known that there is a strong correlation between the mechanical properties of materials and the abrasive wear that is shown in **Figure 1**. Statistical analysis of the results allowed determining the abrasive wear intensity from the dimensionless numbers of the cutting process as follows **[L. 5]**:

$$I_{h\text{abr}} = f\left(\frac{\sigma_{\text{в}}}{c\rho}, БB, E\right),$$

where $\sigma_{\text{в}}$ is the yield stress of the work stock material; $c\rho$ is the specific volumetric heat capacity of the work stock material; $Б = \frac{v a_1}{a}$ is the dimensionless number of the cutting procedure characterizing the degree of impact of cutting conditions comparing to the impact of heat-transfer properties of the work stock material; a_1 is the thickness of cut; a is the thermal diffusivity of the work stock material; $B = tg\beta_1$ is the dimensionless number of the cutting process characterizing the process of chip forming **[L. 4]**; β_1 is the inclination of the conditional shear plane of the material in the cutting area; $E = \frac{\rho_1}{a_1}$ is the dimensionless number characterizing the impact of the radial cutting tool edge on the cutting procedure; and, ρ_1 is the tool tip corner radius.

The adhesive wear occurs due to adhesion of the work stock and the tool material at the points of contact. During relative movement of the tool and the work stock, continuous formation and destruction of seizure bridges takes place, which results in cyclic loading of the contact surfaces of the tool and, due to brittleness of the tool material, in its destruction.

Then the adhesive wear intensity is defined by the following formula:

$$I_{haa} = f\left(\frac{\sigma_{\text{в}}}{\sigma_{\text{и}}}\right).$$

At temperatures above 800°C, intense diffusion of the components of the tool material with the work stock starts and vice versa. The tool surface layer compared to the main body softens, which leads to its cutting by the moving chips. As in the cutting process, the contact surfaces of the tool are always in contact with the new surface of chips and the work stock, and a high rate of diffusion is maintained.

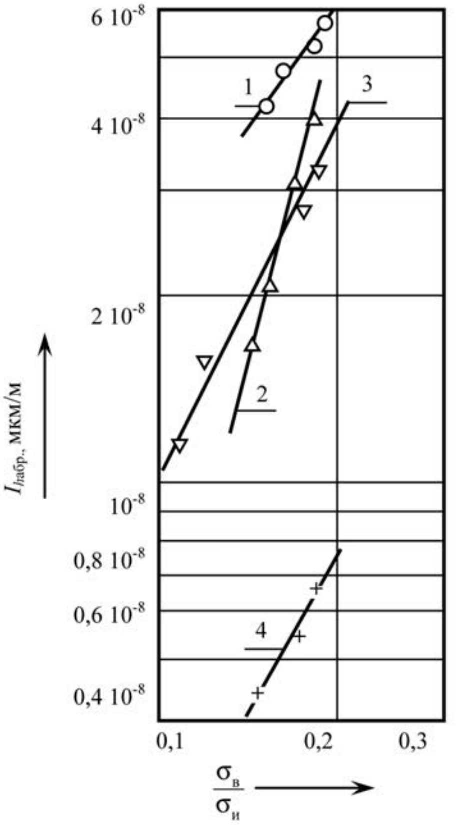

Fig. 1. Dependence of the cutting tool wear intensity on the tensile strength of the work stock material. $\sigma_{\text{в}}$ is the yield stress of the work stock material. $\sigma_{\text{и}}$ is the ultimate compression strength of the tool material: 1 – The work stock material ХН73МБТЮ, the tool material ВК8, БВ = 10, E = 0.18; 2 – the work stock material ВТ3-1, the tool material ВК8, БВ = 20, E = 0.53; 3 – the work stock material 1Х18Н9Т, the tool material Т15К6, БВ = 20, E = 0.27; 4 – the work stock material 1Х12НВМФШ, the tool material ВК8, БВ = 20, E = 0.27

Rys. 1. Zależność pomiędzy intensywnością zużywania narzędzia skrawającego a wytrzymałością na rozciąganie materiału obrabianego; $\sigma_{\text{в}}$ oznacza granicę plastyczności materiału obrabianego, $\sigma_{\text{и}}$ oznacza maksymalną wytrzymałość na ściskanie materiału narzędzia skrawającego; 1 – materiał obrabiany ХН73МБТЮ, materiał narzędzia skrawającego ВК8, БВ = 10, E = 0,18; 2 – materiał obrabiany ВТ3-1, materiał narzędzia skrawającego ВК8, БВ = 20, E = 0,53; 3 – materiał obrabiany 1Х18Н9Т, materiał narzędzia skrawającego Т15К6, БВ = 20, E = 0,27; 4 – materiał obrabiany 1Х12НВМФШ, materiał narzędzia skrawającego ВК8, БВ = 20, E = 0,27

Analysis of the criterion equations by S.S. Silin **[L. 1]** leads to the conclusion that the intensity of diffusion wear depends on the product of dimensionless numbers Б, В, and Е. Then the diffusion wear intensity can be represented in the following form (**Figures 2** and **3**).

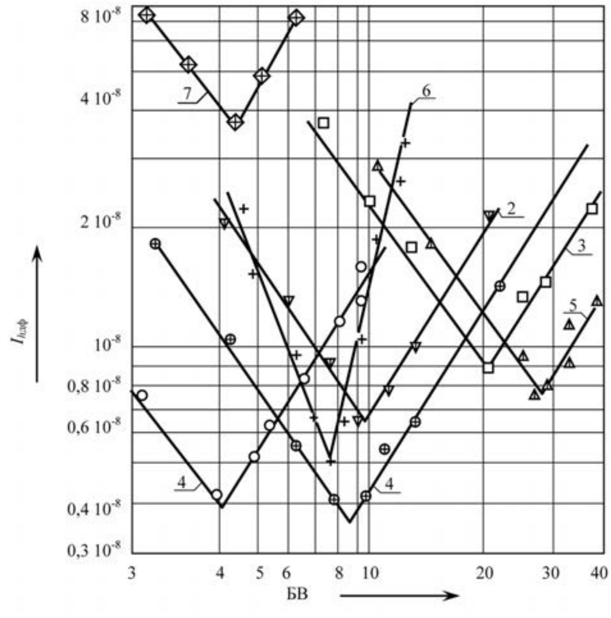

Fig. 2. Dependence of wear on the БВ criteria product: 1 – the work stock material 1X12HBMФШ, the tool material ВК8, E = 0.53; 2 – the work stock material 1X12HBMФШ, the tool material ВК8, E = 0.27; 3 – the work stock material 1X12HBMФШ, the tool material ВК8, E = 0.18; 4 – the work stock material 1X18H9T, the tool material T15K6, E = 0.53; 5 – the work stock material 1X18H9T, the tool material T15K6, E = 0.27; 6 – the work stock material ВТ3-1, the tool material ВК8, E = 0.27; 7 – the work stock material XH73МБТЮ, the tool material ВК8, E = 0.5

Rys. 2. Zależność zużycia od iloczynu БВ: 1 – materiał obrabiany 1X12HBMФШ, materiał narzędzia skrawającego ВК8, E = 0,53; 2 – materiał obrabiany 1X12HBMФШ, materiał narzędzia skrawającego ВК8, E = 0,27; 3 – materiał obrabiany 1X12HBMФШ, materiał narzędzia skrawającego ВК8, E = 0,18; 4 – materiał obrabiany 1X18H9T, materiał narzędzia skrawającego T15K6, E = 0,53; 5 – materiał obrabiany 1X18H9T, materiał narzędzia skrawającego T15K6, E = 0,27; 6 – materiał obrabiany ВТ3-1, materiał narzędzia skrawającego ВК8, E = 0,27; 7 – materiał obrabiany XH73МБТЮ, materiał narzędzia skrawającego ВК8, E = 0,5

If we ignore the change in the concentration of the diffusing tool material in the work stock material during the contact of any point on the machined surface with the rear surface of the cutter, due to smallness of the time of this contact, we get the following criterion dependence:

$$I_{h_{дф}} = f(БВ;\, E).$$

At temperatures above 800°C, the oxygen in the air reacts with cobalt, titanium carbides, and tungsten, softening the tool material, which creates favourable conditions for its destruction. The intensity of oxidative wear can be represented as follows:

$$I_{h_{ок}} = f(БВ;\, E)$$

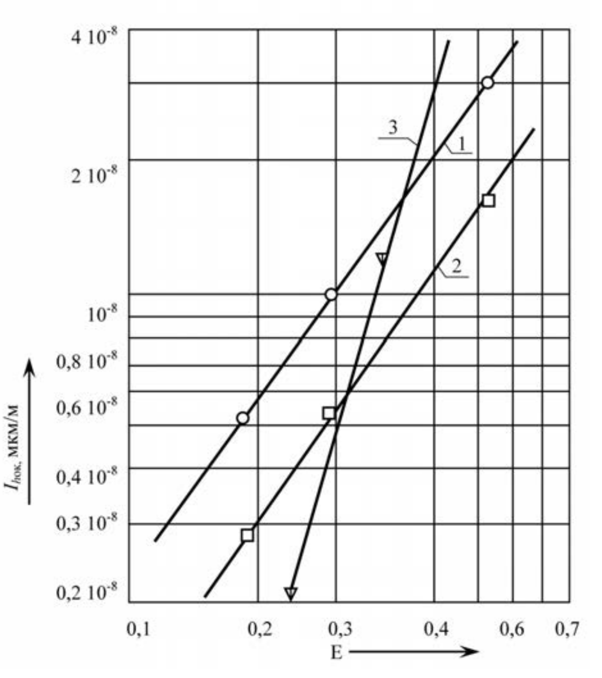

Fig. 3. Dependence of wear intensity on criterion E: 1 – The work stock material 1X18H9T, the tool material T15K6, БВ = 50; 2 – the work stock material 1X12HBMФШ, the tool material ВК8, БВ = 10; 3 – the work stock material ВТ3-1, the tool material ВК8, БВ = 12

Rys. 3. Zależność pomiędzy intensywnością zużywania a bezwymiarowym parametrem E: 1 – materiał obrabiany 1X18H9T, materiał narzędzia skrawającego T15K6, БВ = 50; 2 – materiał obrabiany 1X12HBMФШ, materiał narzędzia skrawającego ВК8, БВ = 10; 3 – materiał obrabiany ВТ3-1, materiał narzędzia skrawającego ВК8, БВ = 12

Therefore, the integral cutting tool wear intensity in terms of the abrasive, adhesive, diffusion and oxidation wear can be represented in the following criteria view:

$$I_h = f\left(\frac{\sigma_в}{\sigma_и};БВ;E\right)$$

or

$$I_h = c\left(\frac{\sigma_в}{\sigma_и}\right)^x (БВ)^y (E)^z \tag{1}$$

where c, x, y, z are the experimentally defined coefficients.

As work stock materials, aluminium, copper, magnesium, titanium and nickel alloys, carbon, alloy, stainless and heat-resistant steels are used. As the tool materials, mono carbide and dicarbide hard alloys and high speed steels are used.

The values of coefficients *c, x, y, and z,* obtained after statistical analysis of the results of the experiments are given in the **Table 1**.

Table 1. Values of the coefficients in formula (1)
Tabela 1. Wartości współczynników z równania (1)

Material groups	***c***	***x***	***y***	***z***
Aluminium alloys	$1.79*10^{-3}$	0	$3.14\sqrt{kl}$	2.03
Copper alloys	$1.34*10^{-3}$	0	$3.80\sqrt{kl}$	2.63
Magnesium alloys	0.26	0	$2.71\sqrt{kl}$	2.26
Carbon and alloy steels	$6.68*10^{-3}$	0	$2.70\sqrt{kl}$	3.79
Stainless and heat-resistant steels	$1.38*10^{-8}$	1.88	$1.10\sqrt{kl}$	1.66
Titanic alloys	$2.79*10^{-11}$	3.49	$3.14\sqrt{kl}$	6.31
Nickel alloys	$2.05*10^{-7}$	2.30	$0.92\sqrt{kl}$	1.70

Note: $k = 1$ for mono carbide tungsten-cobalt hard alloys; $k = 1.8$ for dicarbide titanic-tungsten-cobalt alloys; $k = 1.5$ for high-speed steels; l is the ratio of heat conduction factors of the tool λ_p and the work stock materials λ_g.

CONCLUSION

Application of the methods of the similarity theory allowed obtaining universal dependence of cutting tool wear intensity on the parameters of the cutting process, and the physico-mechanical and heat transfer properties of the work stock and tool materials. The obtained dependence can be used to calculate the cutting errors caused by cutting tool wear to determine the optimal cost or performance of processing cutting data and to select the brand of tool material for finishing and semi-rough turning, for adaptive control of the cutting process.

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