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A NEW PHYSICALLY DEFINED EQUATION TO DESCRIBE THE WEAR OF CUTTING TOOLS

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Abstract: The aim of the project described in this paper is to examine if it is possible to use the tool surface degradation model that better describes the real wear processes than other currently applied models and is simple enough to be used even in practical technological planning. Generally, we can conclude that the common characteristics shared by all tool wear descriptions are as follows: wear is described as a function of cutting distance in friction and as a function of time in diffusion processes, or adhesion and abrasion that are independent of thermal activation which is ignored.
Keywords: cutting tool, crater wear, flank wear

1. INTRODUCTION

The wear and life of tools has always been an interesting topic for technologists as the book written by Schallbroch and Bethmann already referenced 106 sources [1]. Yet it is true that Finnie's retrospective analysis written in 1956 [2] about the history of the previous 100 years only touched on the issues of wear, but considerable amount of studies dealing with this topic have been written since.

The development of this topic took two directions. On the one hand, researchers tried to determine the empiric function of the tool wear based on practical experiences and technological measurements. Zorev [3] used the $h_z=ct^x$ power function for flank wear, where x=0.5-1. The power function was also applied by Zhao et al. [4] with exponent x=1/3 in the recent past. The empiric time function developed by Müller [5] to describe the increase in wear also has an inflexion.

On the other hand, many researchers sought to explore the physical processes of wear [6], which we seek to do in this paper. The complex approach to this issue, which can be regarded as up-to-date even today, probably goes back to the research carried out by Shaw and Dirke [7] and Trigger and Chao [8].

Takeyama and Murata [9] introduced a general equation for the description of complex processes determining the wear of tools. Ignoring brittle fracture and other mechanisms they assumed that total wear rate is the sum of mechanically and thermally activated processes. They are of the opinion that abrasive and adhesive processes are predominantly determined by the cutting length, while thermally activated diffusion and oxidation processes are determined by temperature. Koren [10] elaborated a comprehensive theory of the flank wear of the cutting tool using linear control theory, where he made assumptions similar those made by Mathew [11], and Liu et al. [12].

Thus, these models ignored the fact that a sort of mechanical wear effect influencing wear rate also occurs during thermally activated wear. Although the wear model of Usui et al. [13] does consider the cutting length in thermally activated processes, they ignore adhesion and abrasion that are independent of these processes. Generally, we can conclude that the common characteristics

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shared by all tool wear descriptions are as follows: wear is described as a function of cutting distance in friction and as a function of time in diffusion processes, or adhesion and abrasion that are independent of thermal activation which is ignored. The aim of the project described in this paper is to examine if it is possible to use the tool surface degradation model that better describes the real wear processes than other currently applied models and is simple enough to be used even in practical technological planning.

2. ON THE PHYSICAL NATURE OF WEAR

The development of the traditional materials of cutting tools was essentially manifested in the increase of hard phases in materials. At the beginning of the last century, carbides present in high speed steel increased wear resistance for the first time, to be followed by sinter carbides and ceramics. As the importance of carbide tools rapidly increased in cutting from the 1930s, naturally, many researches studied wear processes including diffusion, and significant results were achieved already in the middle of last century. Dawihl [14] showed that the TiC content of carbides slows down wear during the surface damage of the structure weakened as a result of diffusion. Altenwerth [15] studied the reactions occurring on the carbide/steel boundary land and the importance of Co diffusion in detail. Schaller [16] made quantitative statements about the role of Co dissolving substitutionally in Fe, as well as the quantity and effect of various carbide components, such as Ti, TaC complex carbides. He also performed model experiments and mapped the dominant transformation, diffusion processes at various temperatures, and the effect of the presence and C content of α-Fe and γ-Fe in the steel workpiece on the degradation of carbide structure. As α- γ transformation can also occur in the surface layer of the steel workpiece when the intensity of the cutting process is increased, which significantly changes the conditions of the diffusion processes, which was explored in detail by various researchers.

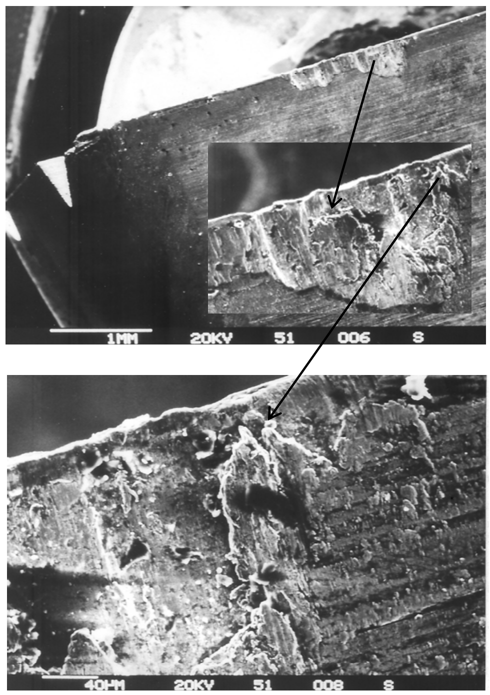

Figure 1. „Fe” stuck on the TiN coated high speed steel tool

The wear process of tools has continued to be a subject of intensive research until recently. Flank wear examinations mainly focus on the study of the effect of hard phases in the workpiece. Using the wear model of Usui et al [13] and a FEM, Lorentzon és Jävrstråt [17] examined the movement and wearing effect of hard carbides in the workpiece in the environment of the tool edge. Poulachon et al [18] studied the wearing effect of hard phases in the turning of hardened steels the hardness of which was the same but whose structure was different. The abrasive wear of the CBN tool was dominant in the cutting of workpieces containing much carbide, while only moderate wear was experienced in the cutting of materials containing mainly martensite.

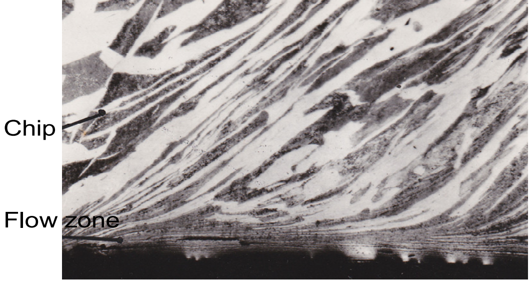

Figure 2. Chip root in cutting C35 steel

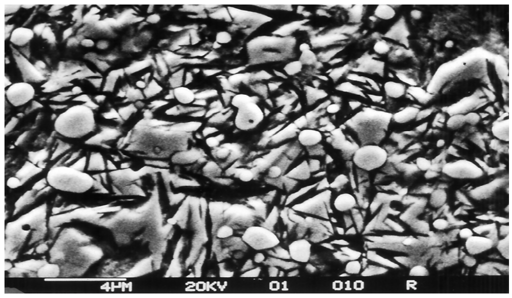

Figure 3. Etched surface of an intact HSS tool

The rake face of the tool is subject to a massive mechanical and thermal impact in cutting. The layer of the chip in contact with the tool, the so-called flow zone, is deformed rather significantly and gets heated. In these cases diffusion processes can also occur, as a result of which chips and the tool can even weld locally and temporarily. Figure 2, which was obtained by suddenly withdrawing the tool downwards (quick stop technology), is a direct evidence of this. The chip and the tool got welded at some places, which is shown by the small pegs sticking out downwards from the chip.

It is known that high wear resistance in high speed steel is caused by carbide grains embedded in a martensite structure (Figure 3). Martensite can transform easily at the temperature developing on the contact surface of the chip and the tool, hardness decreases and the material of the matrix gets worn off. Figure 4 was taken of a worn crater surface after etching. It can be seen that carbide grains behave like pebbles in a stream bed against wear. The direction of the flow is indicated by an arrow. So in summary we can conclude that the process of the flank land and crater wear of high speed steel happens as a joint impact of the thermally activated textural/structural transformation and adhesion/abrasion. So both the friction length and temperature need to be taken into consideration here.

Figure 4. The crater surface of HSS tool

3. A NEW MATHEMATICAL MODEL OF WEAR

3.1. Geometrical relationships of flank wear

Wear can be studied in two dimensions in orthogonal cutting. The mass which is worn-off shown in Figure 5/a. is $m=\rho V$, and $V=(F_1+F_2)b$. F_2 depends on the diameter of the workpiece and the approach angle of the tool's edge, although it is usually ignored. We also did the same except that we limited the proportion of F_2 to F_1 to a maximum 3% in our cutting examinations, as recommended by Müller [5]. The geometrical relationships of wear, using the above simplification, is shown by Figure 5/b. The relationship between wear of direction x and flank wear W measured on the tool is $W=(\cot an\alpha-\tan\gamma)x$, volume dV worn away during time dt is

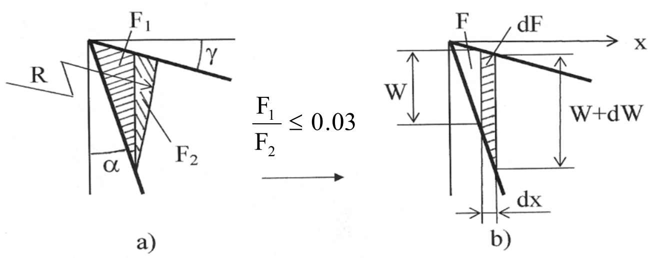

Figure 5. The geometry of flank wear

$$dV=b(\cot an\alpha-\tan\gamma)\,xdx=\frac{b}{\cot an\alpha-\tan\gamma}WdW\,, \quad (1)$$

so the velocity of volume wear is

$$\frac{dV}{dt}=\frac{b}{\cot an\alpha-\tan\gamma}W\frac{dW}{dt} \quad (2).$$

3.2. Geometrical relationships of crater wear

The wear of the rake face of the tool can be characterised by two measures, the depth (KT) and width (KB) of the crater (Figure 6).

Based on practical experiences, KT and KB are in a nearly linear relationship, which makes the description of the wear process easier, i.e.

$$KB\approx KB_o+C_{KB}KT, \quad (3)$$

where K_{Bo} and C_{KB} are constants that can be simply determined by cutting measurements. For instance, according to measurements in C45 plain steel $KB_o=1224$ μm, $C_{KB}=3.36$, if [KT] = μm ($R^2=0.9363$).

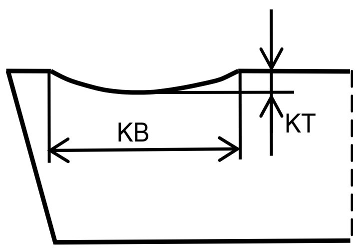

Figure 6. Typical measures of crater wear

It must be taken into consideration in crater wear that $v_{chip}<v$, because the thickness of the chip (h_{chip}) is mostly larger than undeformed chip thickness h, except for the cases of hard cutting and super high-speed cutting.

This is expressed by the ratio

$$\xi(v) = \frac{h_{chip}}{h} = \frac{v}{v_{chip}} \tag{4}$$

which depends of cutting speed and can easily be determined in practice, and can be written numerically by the empirical formula

$$\xi(v) \cong \xi_0 + C_f \exp - \alpha v \tag{5}$$

Here constants ζ_o, C_f and α can also be determined by simple technological experiments.

It must also be noted that the temperature developing on the boundary land of the chip and the tool also depends on wear, therefore, formula (1) must be extended with a term proportionate to wear.

3.3. The new mathematical model

Based on the results of our morphological examinations and cutting experiments conducted on the worn surface of cutting tools we came to the conclusion that the rate of flank wear must be studied as a function of both cutting distance and the developing temperature, i.e.

$$\frac{dm}{dL} = \frac{\rho}{v}\frac{dV}{dt} = C_1 + C_2 \exp - \frac{Q}{R\theta}, \tag{5}$$

where L cutting length, t cutting time, v cutting speed, Q apparent activation energy, R general gas constant and θ temperature. The right side of the equation describes the physical processes of wear by summarizing the adhesive/abrasive and thermally activated processes, i.e diffusion and oxidation occurring on the surface or in the surface layer of the tool. Using equation (2), this takes the form of

$$\frac{dW}{dt} = \frac{v}{W}\left[A_a + A_{th} \exp - \frac{Q}{R\theta}\right] \tag{4}$$

where A_a, A_{th} and Q are constants. This is an autonomous non-linear differential equation that includes a feedback, as θ = θ (W) depends on flank wear. This function may be determined by measurements, by the use of data to be found in scientific literature, and by means of finite element analysis (FEM). Here we use formula $\theta = C_v v^x$, used in previous literature, and assume that cutting temperature increases in proportion to flank wear, that is

$$\theta \cong C_v v^x + C_W W = C_v (v^x + KW) \tag{6}$$

where $K = C_W / C_v$.

Thus, the new model of the flank wear of cutting [19] tools is

$$\frac{dW}{dt} = \frac{v}{W}\left[A_a + A_{th} \exp - \frac{B}{v^x + KW}\right] \tag{7}$$

and

$$B = \frac{Q}{RC_v}. \tag{8}$$

According to the statement made about the nature of crater wear in the previous chapter, friction length and thermal impact jointly determine wear rate. This complex model of wear could be successfully used in flank wear [14]. In this case, taking the geometrical characteristics of crater wear into consideration (Figure 6), using (4), (5) and (6), the speed of crater wear can be described by differential equation

$$\frac{dKT}{dt} = \frac{v}{\xi(v)} \frac{A_a + A_{th} \exp[-B/(v^x + K_{KT}KT)]}{KB_0 + 2C_{KB}KT} \tag{9}$$

It is practical to divide the constants into two groups as cutting theory has many research results with respect to constants x and K of empirical formula (6), as we have already noted above. Thus, we need to find a practical calculation strategy to determine three constants A_a, A_{th} and B in the new wear model (7) and (9), which can be achieved in different ways.

4. THE CRATER WEAR OF TIN COATED CUTTING TOOL

Cutting experiments were conducted with uncoated and TiN-coated high speed steel tool, which was used to cut C45 quality rolled steel. The chemical composition of the workpiece was C: 0.42%, Mn: 1.04%, Si: 0.24%, P: 0.016%, S: 0.020%. The tool was HSS2 quality and rake angle was γ_o=14°. The technological parameters of cutting were: cutting speed v = 52m/min, feed f = 0.25 mm/rev, depth of cut a = 2.5 mm. The average thickness of TiN layer was 4 μm.

The result of measurements are summarised by Figure 7. The constants of equation (8) could be calculated from the data measured on the uncoated HSS tool: A_a = 5.5.10^9 μm, A_{th} = 5.2.10^{12} μm, B =1 02, K_{KT} = 0.006. Another valuable feature of this method is that the K_{KT} constant derived from the thermal characteristics of cutting could be calculated from the wear measurement results. The parameter showing the temperature excess developing as a result of wear in formula (6) is C_{KT} = $K_{KT}C_v$ = 0.006 x 210.2 = 1.26°C/μm.

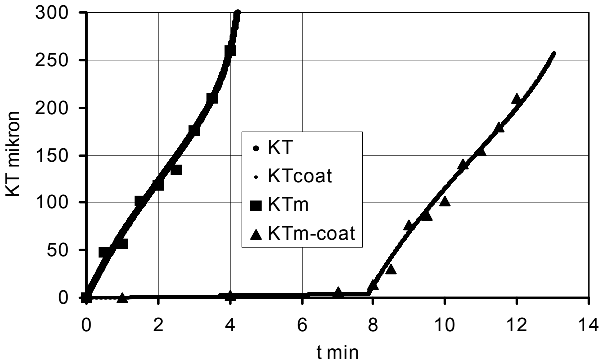

Figure 7. Calculated (KT) and measured (KT_m) crater wear in uncoated and coated HSS tool (v=52m/min, f.a=0.25x2.5mm^2)

The wear of the TiN coated tool was naturally significantly slower initially, being only KT=6μm after a 7 minute cutting, so the coating was just broken through. The cutting quotient was ζ=2.93 at a speed of v = 52 m/min, thus, the wear distance was L = 7*52/2,93 = 1067 m, so the wear rate of the TiN layer as a function of the wear distance was KT/L ≈ 6 μm/1067 m = 0,0056 μm/m = 5,6*10^{-9} m/m. Then the constants of equation (8) were nearly the same as those determined for the uncoated tool: A_a = 4.5x10^9 μm, A_{th} = 2.4x10^{12} μm. The value of B and K_{KT} remained the same. It can be seen that the constants that are related to adhesive/abrasive processes are a bit smaller in the case of the TiN-coated tool.

Q activation energy of wear can also be calculated from formula (8), considering the fact that that the constant of formula (1) in this technology is C_v=269.2°C [6]:

$$Q=C_vRB=269.2x8.314x102=228.3kJ/mol$$

According to Friberg and Torndhal [20] the self-diffusion of Fe in ferrite and in austenite is Q = 240kJ/mol and Q = 286 kJ/mol, respectively. So according to the chip hardening experiment, in spite of the fact that the tool gets in contact with a material partially turned into austenite, the presence of ferrite is dominant. According to a later source [21], in the case of γ-Fe, Q = 284,1 kJmol^{-1} in self-diffusion occurring in crystal lattice, while Q = 180,5 kJmol^{-1} in grain boundary self-diffusion. So this is a mixed process.

5. SUMMARY

The microscopic examination of worn surfaces showed that the degradation of the tool is the result of adhesive/abrasive and thermally activated processes, therefore both friction length and temperature must be taken into consideration in the modelling of crater wear. Wear rate can be described by a non-linear autonomous equation. TiN coating, which increases tool life in high speed steel, changes and slows down the wear of the tool. The activation energy of wear can be calculated from the constants of the wear equation determined by cutting experiments.

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