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A NEW MATHEMATICAL MODEL OF THE SURFACE DEGRADATION CAUSING WEAR ON THE CUTTING TOOL'S FLANK LAND

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НОВА МАТЕМАТИЧНА МОДЕЛЬ ЗНОСУ РІЗАЛЬНОГО ІНСТРУМЕНТУ ПО ЗАДНІЙ ПОВЕРХНІ

Після розгляду великої кількості літератури по зносу ріжучого инструменту, ми обрали теоретичний опис зносу інструменту по задній поверхні метою даної роботи. Грунтуючись на оптичних, електронно-оптичних і морфологічних дослідженнях фізичних особливостей зносу, ми прийшли до висновку, що переміщення інструмента має бути враховане не тільки в абразиві, але також і в активізованому поширенні температури, процесах окислювання. Отже, ми пропонуємо математичну модель норми зносу, автономне нелінійне відмінне рівняння, що приймає до уваги ефект прискорення зносу й технологічні параметри різання й температури, що поширюється по задній поверхні інструмента. Технологічні параметри можуть також змінюватися. Складне рівняння зношування було підтверджено результатами тестування, що були проведені з карбідом P20 на сталі C45. Ми змоделювали несприятливий ефект швидко змінюваної швидкості, різання на зношування інструмента викликаний вібрацією.

После рассмотрения большого количества литературы по износу режущего инструмента, мы выбрали теоретическое описание износа инструмента по задней поверхности целью данной работы. Основываясь на оптических, электронно-оптических и морфологических исследованиях физических особенностей износа, мы пришли к выводу, что перемещение инструмента должно быть учтено не только в абразиве, но также и в активизированном распространении температуры, процессах окисления. Следовательно, мы предлагаем математической модели нормы износа, автономное нелинейное отличительное уравнение, которое принимает во внимание эффект ускорения износа и технологические параметры резания и температуры, развивающейся на задней поверхности инструмента. Технологические параметры могут также измениться. Сложное уравнение износа было подтверждено результатами тестирования, выполненных с карбидом P20 на углеродистой стали C45. Мы смоделировали неблагоприятный эффект быстро изменяющейся скорости резания на износ инструмента вызванный вибрацией.

Having reviewed the extensive literature on the wear of the cutting tool, we chose the theoretical description of flank wear as the subject matter of this paper. Based on the optical electron-optical and morphological studies of the physical characteristics of wear processes we came to the conclusion that the cutting distance need not only be taken into consideration in abrasive, adhesive processes but also in thermally activated diffusion, oxidation processes. Consequently, we propose the application of a mathematical model of wear rate, an autonomous nonlinear differential equation that takes into account the wear-accelerating effect of both the technological parameters of cutting and the temperature developing on the tool flank land. Technological parameters may also change depending on time. The complex wear equation was validated by the results of the cutting tests performed with P20 carbide on C45 carbon steel. We could model the adverse effect of the rapidly changing cutting speed on the wear of the tool during vibration.

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 ever since. The development of this topic took two directions. On the one hand, researchers tried to determine the empiric function of the tool life based on practical experiences and technological measurements. As it is widely known, many researches like this have been conducted since Taylor, such as the comprehensive study by Colding and König [3].

Koren [4] elaborated a comprehensive theory of the flank wear of the cutting tool using linear control theory. He assumed that flank wear is composed of the sum of mechanical and thermally activated processes, in which the former phenomena relate to the length of work cut, while the latter relate to the duration of cutting. He described temperature as a feedback process through wear. Usui és Shirakashi [5] also studied flank wear in thermally activated wear processes, and they concluded that the length of work cut must be taken into consideration. Nevertheless, they ignored abrasive, adhesive processes. Their wear equation is

$$\frac{dW}{\sigma_t dL} = C_1 \exp - \frac{C_2}{\theta}, \tag{1}$$

where $\boldsymbol{\sigma_t}$ is normal stress, and $\mathbf{C_1}$, $\mathbf{C_2}$ are constants.

The next step in the theoretical description of the wear processes of tools was when researchers took both friction and diffusion processes into consideration in the study of flank wear [5, 6, 7]. These models, however, ignored the fact that a sort of mechanical wear effect influencing wear rate also occurs during thermally activated wear. Generally we can conclude that the common characteristic that all tool wear descriptions share is that wear is described as a function of cutting distance in friction and as a function of time in diffusion processes. However, based on experience and also in line with what Schaller showed long ago [8], friction, i.e. adhesive, abrasive wear also have an important role in thermally activated processes. If we are to elaborate a complex theory for this process, all these factors need to considered together.

2. GEOMETRICAL RELATIONSHIPS OF FLANK WEAR

Wear can be studied in two dimensions in orthogonal cutting. The weight of the actually worn material of V volume shown in Figure 1/a. is $m=\rho V$, and $V=(F_1+F_2)b$ (where $\boldsymbol{\rho}$ is density, **b** is the width of the removed layer). 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 it was recommended by Müller [9].

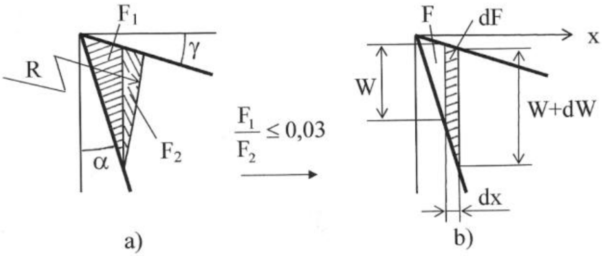

Figure 1 – The geometry of flank wear

The geometrical relationships of wear, using the above simplification, is shown by Figure 1/b. The relationship between wear of x direction and flank wear W measured on the tool is

$$W = (\mathrm{ctg}\alpha - \mathrm{tg}\gamma)x\ , \tag{2}$$

dV volume worn away during time **dt** is

$$dV = b(\mathrm{ctg}\alpha - \mathrm{tg}\gamma)x dx = \frac{b}{\mathrm{ctg}\alpha - \mathrm{tg}\gamma} W dW \tag{3}$$

so the velocity of volume wear is

$$\frac{dV}{dt} = \frac{b}{\mathrm{ctg}\alpha - \mathrm{tg}\gamma} W\dot{W} \tag{4}$$

3. A NEW MODEL OF FLANK WEAR

In accordance with the above considerations, 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 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 (4), this takes the form of

$$\frac{dW}{dt} = \frac{v}{W}\left[A_a + A_{th} \exp - \frac{Q}{R\theta}\right] \tag{6}$$

where $\mathbf{A_a}$, $\mathbf{A_{th}}$ and **Q** are constants. The new model is not yet complete with this because the circumstances of chip formation also change as wear increases. As we noted earlier, we are going to ignore the impact of flank wear on normal stress developing there. We will, however, consider that cutting temperature increases during the increase of wear. For this purpose, we will use formula

$$\theta \cong C_v v^x + C_W W = C_v(v^x + KW) \tag{7}$$

where $K = C_W / C_v$.

which expresses interaction, feedback since increasing temperature accelerates wear. Thus, the new model describing the flank wear of cutting tools is

$$\frac{dW}{dt} = \frac{v}{W}\left[A_a + A_{th} \exp - \frac{B}{v^x + KW} \right], \tag{8}$$

where
$$B = \frac{Q}{RC_v}. \tag{9}$$

Here R=8,29 J/mol.^{o}K is the universal gas constant, $\mathbf{C_v}$ is the constant of empirical temperature function (7), **Q** is the activation energy of the thermally activated wear component on the tool flank. It is important that we do not impose any restrictions on cutting speed v in equation (8), so it can be constant or periodically or continuously changing.

(8) is a non-linear autonomous differential equation whose solution is simple with numerical methods. There is no restriction regarding the initial condition. The radius of the rounding-off of the edge can be chosen for a new tool, while in the case of a used tool, the value of wear developed during previous usage is the initial condition. This also means that equation (8) can be used repeatedly for various cutting processes if we consider the simplifying assumption that we made in respect of the relationship of segments $\mathbf{F_1}$ and $\mathbf{F_2}$ in Figure 1. An important characteristic of the new, complex wear equation is that we can use the data of the wear measurements performed in the factory during manufacturing and no special experiments are necessary.

4. THE VALIDATION OF THE NEW WEAR MODEL

We performed the long-time examinations of wear with uncoated carbide of P20 quality. The initial workpieces were cylinders cut to 280 mm diameter and 1700 mm length out of a large block. Hardness was HV20 196±16, the examined microstructure is shown by Figure 2. The chemical composition of the C45 quality steel used in the experiment was **C** 0.45%, **Mn** 0.78%, **Si** 0.26%, **P** 0.025%, **S** 0.026%, **Al** 0.13%. The **Al** content here is an order of magnitude higher than usual; this is how we could make sure that only rigid inclusions should develop. Figure 3 shows the picture of such a typical inclusion. By this we limited the scatter of the results of wear measurements.

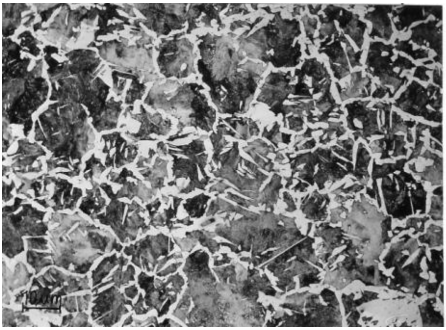

Figure 2 – Micrograph of the material of cutting experiments

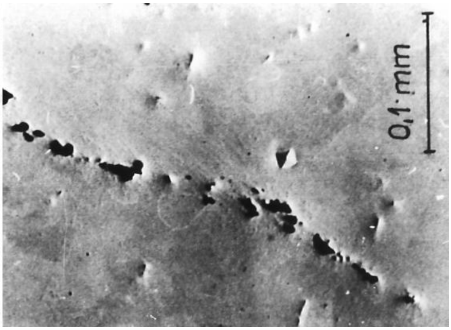

Figure 3 – A typical rigid Al_2O_3 inclusion of steel over-deoxided with **Al**

We chose f=0.25mm/rev, a=2.5mm and γ=+6°. We chose the radius of the rounding-off of the edge of the commercial carbide as an initial condition, which was W0≈30 μm. Measurement results of the flank wear of the tool are shown by Figure 4. The curves that can be determined by the new wear equation needed to be optimally tailored to these results.

Calculating with formula (7) out of the technological parameters chosen for the experiments we get Cv=281.6 K, and using this K=0,002 K/μm and x=0.27. Having these numbers, constants Aa, Ath and B can be determined by a regression analysis in which we are looking for constants where R2 Pearson correlation factor takes the maximum value.

So the constants of the wear equation regarding the experimental C45 material, the P20 tool and the applied technology are Aa=2 μm/min, lnAth=16.81125 and B=65. The consistency of calculated and measured results is reflected by Figure 4 and Figure 5.

The apparent activation energy of wear is Q=BRCv=65·281.5·8.29=151.7 kJ/mol. We can see that the degradation of the tool during cutting is a complex process that is the resultant of several reactions, but the process determining the intensity of wear here is the diffusion of Co from the sintered carbide structure into steel.

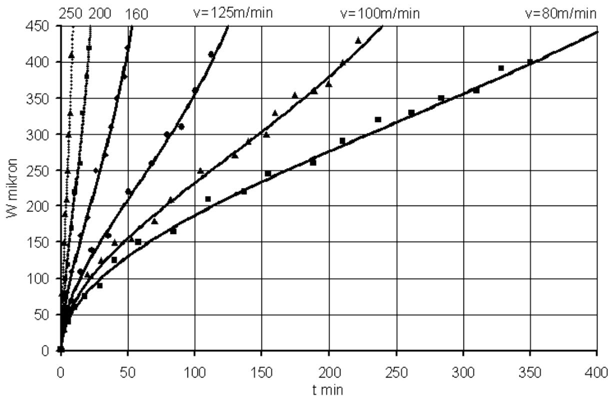

Figure 4 – Wear curves calculated from measurement results

As previously shown, this wear equation is based on the fact that even though thermally activated processes dominate wear there is still abrasion, since this causes a part of the surface layer to become permanently degraded after all. Constant $\mathbf{A_a}$ shows the abrasive characteristics of the complex wear process, while constant $\mathbf{A_{th}}$ is related to diffusion in equation (8). The change in the ratio of these values represents how much abrasive processes and diffusion are responsible for the degradation of the tool. It is interesting to see how the ratio of these values changed numerically. For example, if we set velocity to v=160 m/min with an initial wear of W=30μmand abrasive component A_a=2 in equation (8), the value of thermal component $A_{th}expB/(v_x+KW)$ is only 1.4, but if wear is W=400 μm the thermal component becomes 22.5. So the initial 2:1.4 ratio shows the dominance of the abrasive component, but if the tool is worn out, approaching the end of its life time, the thermal component is increasingly dominant as the ratio has changed to 2:22.5.

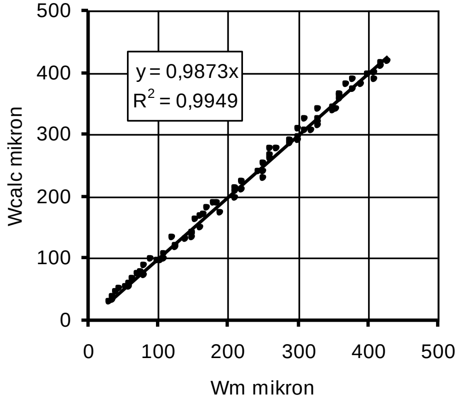

Figure 5 – Wear measured and calculated with differential equation (8)

5. APPLICATION

The rapid change of cutting speed is vibration, which is a nightmare to engineers. The complex wear equation is also suitable for describing the extreme wear process, often leading to a fracture, which occurs under these circumstances. We showed elsewhere [10] that the formation of either a built-off edge or a lamellar chip might result in a vibration in the workpiece-machine-tool elastic system due to the fact that the tool makes a periodic motion in the direction of the cutting speed. This vibration may be sufficiently modelled by the function

$$v=v_0+\Delta v\cdot\sin\omega t \quad (10)$$

in which Δv can even increase during cutting in a harmful, so-called resonance process. Here we assume a lamellar chip formation process, a quasi-stationary state where v=const. If we substitute this into the wear equation devised previously, we obtain the results shown by Figure 6. Angular natural frequency $\omega=3$ min^{-1} is included in this figure only to model the nature of the process, wear curve $\omega=10^4$ min^{-1} is more realistic, the wear curve appears as a continuous line then. Wear rate and the failure of the tool are considerably higher in periodically changing speed. Cutting force increases in significant wear, which further increases wear, the tool gets fractured or chipped, then breaks. This is the typical consequence of resonance.

This modelling of the effect of the rapidly fluctuating cutting speed can only be regarded as a qualitative method as we ignored the specific characteristics of the transient change of temperature, which we already discussed before elsewhere [11]. Figure only demonstrates that, on the one hand, the complex wear equation can also be used under such technological circumstances and, on the other hand; it shows one of the possible reasons for scatter in tool life.

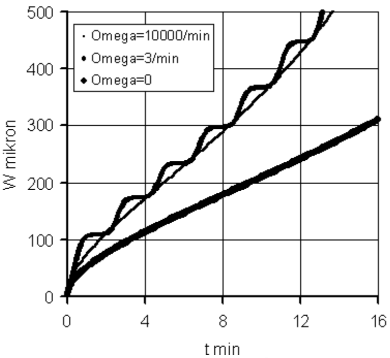

Figure 6 – Wear curve in vibrating cutting speed (v_o=160m/min, Δv=150 m/min)

SUMMARY

Having reviewed the literature on cutting and based on the optical, electron-optical and morphological examinations of wear processes we have reached the conclusion that it is possible to describe the abrasive, adhesive and thermally activated diffusion, oxidation processes in a single mathematical model. This model is a non-linear autonomous differential equation that takes the length of work cut and the interaction of the temperature and wear on the tool flank into consideration in all the related processes. The wear curves calculated by the wear equation closely correlate with flank wear measurement results in cutting examinations. The model can even be used with changing technological parameters as the data necessary for the constants of the wear equation may as well be determined even by measurements performed on the tool during factory manufacturing. If we have this data, we can calculate the activation energy of the process determining the nature of the wear process. The adverse effect of the tool's vibration, which accelerates wear, can also be described by this equation.

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References: **1** Schallbroch, H., H. Bethmann, **Kurzprüfvervaren der Zerspannbarkeit**, 1950. Teubner Verlaggesellschaft Leipzig. **2** Finnie, I., **Review of the Metal-Cutting Analyses of the Past Hundred Years**. Mechanical Engineering, 1956. Aug. 715-721. **3** Colding, B., W. König, **Validity of the Taylor Equation in Metal Cutting**, Annals of the CIRP Vol. XVIV (1971) 793-812. **4** Koren, Y., **Flank Wear Model of Cutting Tools Using Control Theory**, Trans. of the ASME, Journ. of Engineering for Industry Vol. 100. Febr. 1978. 103-109. **5** Usui, E., T. Shirakashi, **Analytical prediction of cutting tool wear**, Wear 1000 (1984) 129. **6** Mathew, P., **Use of predicted cutting temperatures in determining tool performance**, Int. Journ. Mach. Tools Manufact. Vol. 29 (1989) No. 4. 481-497. **7** Luo, X., K. Cheng, R. Holt, X. Liu, Modeling flank wear of carbide tool insert in metal cutting, Wear, 259 (2005) 1235-1240. **8** Schaller, E., **Einfluss der Diffusion auf den Verschleiß von Hartmetallwerkzeugen bei der Zerspanung von Stahl**, Industrie Anzeiger 87 (1965) No.9. 29. Jan. **9** Müller, E., **Der Verschleiß von Hartmetallwerkzeugen und seine kurzzeitige Ermittlung.** Eidgenössischen Technischen Hochschule in Zürich, 1962. **10** Pálmai, Z. G. Csernák, Chip formation as an oscillator during the turning process, Journal of Sound and Vibration 326 (2009) 809-820. **11** Pálmai, Z., Cutting temperature in intermittent cutting, Int. Journ. Mach. Tools Manufact. Vol. 27. No. 2 1987. 261-274.

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