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MODELING OF TOOL WEAR IN HARD TURNING – A LITERATURE REVIEW

Tool wear has a huge influence on tool life and thus the cost of machining; therefore, it is important to identify cutting parameters and how they are affected by the wear processes. During hard turning abrasive, adhesive and diffusive wear mechanisms occur. Which will be the dominant mechanism mainly depends on cutting conditions and cutting temperature. With help of wear models the single wear mechanisms can be described separately or, using the combined models, we can describe the combination of these wear processes. These models have importance from the point of view of finite element (FEM) simulations since simulation software uses one or more of them.

Keywords: hard turning, tool wear, wear rate

1. INTRODUCTION

With hard turning we are machining hardened parts with high hardness (>50 HRC). As a result the tool is exposed to an increased load, thus higher demands are made on the tool. CBN materials, owing to their great thermal strength, wear resistance, high hardness at low and high temperatures, high thermal conductivity and low coefficient of thermal expansion, correspond to these strict requirements [1]. Hard turning is used typically as finish machining, therefore it has to meet strict requirements of economy and it has to provide parts with the determined quality standards.

If we want to evaluate a machining process from the point of view of economy, then we take into account those costs which are related to a given process, and compare them with a basic process. In hard turning the tool cost amounts to a significant proportion of the total machining cost. According to [2] the tool cost related to the machining of one part range between 9-39% of the total machining cost depending on whether the tool material is coated or uncoated.

The tool cost related to one machined part can be decreased by utilizing the tool life up to its maximum. The determination of tool life is based in advance on fixed tool life criteria: for example the permissible tool flank wear [3]. In the [4] article the authors determined the tool life of CBN tools on the whole range of cutting speed based on the flank wear measurement. This is often the appearance of any form of wear (flank or crater wear) in a given quantity. Therefore it is necessary to carry out an exact determination and quantification of wear processes. In the following sections we show the specific wear mechanism of CBN tool and the mathematical models used to describe them.

2. WEAR PROCESS OF CBN TOOLS AND ITS MATHEMATICAL MODEL

During metal cutting we can observe three main wear mechanisms: abrasion, adhesion and diffusion [5-7]. During cutting all three wear mechanisms appear at the same time, and depend on the cutting conditions one or another will be dominant. Adhesion and diffusion are thermally activated processes and thus are determinative at greater cutting temperatures (over 700-800°C) while at lower temperatures abrasion is the stronger mechanism [8, 9].

The existing wear models can be classified into two groups: one is based on the cutting parameters–tool life relation another is the process variables–wear rate relation [10]. The tool wear models, determine the ratio of volume wear loss–which occurs on the contact surfaces of the tool (flank and face surfaces)–related to unit area and unit time. To apply the wear models we need to know the wear mechanism, the coupled tool–workpiece material and the ranges of cutting parameters [11]. In the following we show the process variables–wear rate models for different single wear mechanisms and for combined wear mechanisms.

2.1. SINGLE WEAR MODELS

2.1.1. Abrasive Wear

Abrasive wear is caused by the scratching effect of hard particles between the tool and the workpiece [12], and the hard asperities of the workpiece. In the case of abrasive wear we distinguish between two-body and three-body wear processes based on the free abrasive particles, which come mainly from the material of workpiece [13].

With low CBN content tools several abrasive scratches can be seen at 150 m/min cutting speed and continuous surface cutting. So the main wear mechanism is abrasion [1]. Abrasive wear was first examined by Archard, who determined Eq. (1) related to wear rate (volume wear loss per unit area per unit time) [14]:

$$\dot{w}^{I} = K\frac{\sigma_n \cdot v_s}{H_a} \tag{1}$$

where: K – constant, depending on the coupled tool-workpiece materials; v_s – relative sliding velocity on tool-chip interface; H_a – asperity hardness on tool-chip interface; σ_n – normal stress on tool-chip interface.

Equation (1) determines the abrasive wear rate as a function of normal stress, relative sliding velocity and the asperity hardness.

In 1978 Usui et al., using FDM (finite difference method) methodology, determined the flank and crater wear with their wear equation (Eq. (2)), which was developed to describe adhesive wear [15]. Maekawa et al. in [16, 17] show that this model is suitable for describing the flank wear caused by abrasion.

$$\dot{w} = C \cdot v_s \cdot \sigma_f \cdot e^{\left(\frac{-\lambda}{\Theta_f}\right)} \tag{2}$$

where: $\dot{w}$ wear rate; v_s – relative sliding velocity on tool-workpiece interface; σ_f – normal stress; Θ_f – absolute temperature; C, λ – constants, depending on the coupled tool-workpiece materials.

Rabinovicz et al. developed a mathematical model to determine the abrasive volume wear loss in that case when there are free abrasive particles between the two sliding surfaces [18]. This was extended by Huang and Liang for metal cutting [13] and they defined the following relation:

$$V_{abrasion} = \frac{v_c \cdot w \cdot VB \cdot \bar{\sigma} \cdot p_{abrasion}\%}{2} \cdot K \cdot \left(\frac{P_a^{n-1}}{P_t^n} \right) \cdot tg\,\Theta \cdot \Delta t \tag{3}$$

where: $V_{abrasion}$ – tool volume loss due to abrasion within time interval; P_a – hardness of the abrasive particle; P_t – tool hardness; Θ – the average roughness angle of the abrasive particle; K, n – constants, known function of P_t/P_a [19]; $\bar{\sigma}$ – average normal stress; w – width of cut; ($p_{abrasion}\%$) – percentage of the total normal force supported by abrasive particles; VB – flank wear length or wear land; v_c – cutting velocity; Δt – time interval.

2.1.2. Adhesive Wear

Adhesive wear is caused by the welding and breaking of asperities [12]. The contact area between the tool and workpiece is made up of asperities. Under high temperature and pressure these asperities are deformed plastically and welded, which causes microwelding between the tool and the workpiece. Due to the relative movement of the tool and workpiece these microwelds break away, which causes adhesive wear [13].

Usui et al. originally developed the mathematical model in Eq. (2) to describe adhesive wear. Huang and Liang suggest the following model for adhesive wear [13]:

$$V_{adhesion} = \frac{1}{b} \cdot p_0 \cdot K_0 \cdot (1 - p_{adhesion}\%) \cdot \bar{\sigma} \cdot e^{aT} \cdot v_c \cdot w \cdot \Delta t \tag{4}$$

where: $V_{adhesion}$ – tool volume loss due to adhesion within time interval; p_0 – probability of forming a sizeable wear particle from the harder material; $p_{adhesion}\%$ – percentage of the total normal force supported by adhesive particles; v_c – cutting velocity; Δt – time interval; w – width of cut; $\bar{\sigma}$ – average normal stress; K_0 – constant; T – average temperature; a, b – hardness constants.

It can be seen from Eq. (4) that, the volume wear loss due to adhesion is independent of the flank wear (VB) but depends on the sliding distance [13].

2.1.3. Diffusive Wear

The high temperature caused by the cutting speed that occurs on the edge of tool causes diffusion between tool and chip. In the case of diffusive wear the atoms diffuse from the tool material into the chip and are removed with it [20]. Takeyama and Murata [8] showed that at high temperatures diffusive wear is the dominant wear mechanism. It can be described by modified the Takeyama-Murata model:

$$\dot{w} = D \cdot e^{\left(\frac{-E}{R \cdot T}\right)} \tag{5}$$

where: D – coefficient of diffusion; E – activation energy; R – gas constant T – local temperature.

It can be seen from Eq. (5) that the efficiency of the model strongly depends on the distribution of temperature in the tool material [21].

The CBN particles in the tool material are chemically stable, but under the usual cutting conditions, the binder material is relatively instable. During hard turning the diffusion of binder material causes the diffusive volume wear loss of the tool [13]. In the published diffusive wear model in [13], the authors suppose that the distribution of temperature on the tool-workpiece interface is homogenous and the concentration of the diffusing species (C_0) is constant. Furthermore, the velocity of diffusion is constant on the tool–workpiece interface and the concentration gradient $dc/dy_{y=0}$ at any point of interface does not change with time [22]. The volume wear loss caused by diffusion is:

$$V_{diffusion} = K_{diffusion} \cdot \sqrt{v_c \cdot VB} \cdot e^{-(K_Q/T+273)} \cdot w \cdot \Delta t \tag{6}$$

where: $V_{diffusion}$ – tool volume wear loss due to diffusion within time interval; D – coefficient of diffusion; K_Q – constant related with activation energy for diffusion; $K_{diffusion}$ – process-related diffusive wear coefficient.

The value of the $K_{diffusion}$ coefficient is constant for a given tool-workpiece combination, and independent of cutting conditions and tool edge geometry.

2.2. COMBINED WEAR MODELS

In the previous section we showed the mathematical models of different wear mechanisms. Nevertheless we know that these wear processes occur not individually but together. Therefore, for the more accurate description of wear mechanisms these models have to be combined. Here we show some combined models.

2.2.1. Takeyama–Murata Abrasive-Diffusive Wear Model

Takeyama and Murata [8] take into account the abrasive and diffusive wear mechanisms determining the wear rate in Eq. (7):

$$\frac{dW}{dt} = G(v, f) + D \cdot e^{\left(\frac{-E}{R \cdot T}\right)} \tag{7}$$

where: dW/dt – wear rate; G(v,f) – abrasive term; v – cutting speed; f – feed rate; E – activation energy; R – universal gas constant; T – cutting temperature; D – coefficient of diffusion.

2.2.2. Coupled Abrasive-Diffusive Model

The modified Takeyama–Murata wear model describes diffusive wear, while the Usui model describes abrasive wear. The coupled abrasive-diffusive model – which is introduced in [23] – is the combination of the following wear models:

$$\begin{aligned} &\frac{\partial W}{\partial t}=\frac{\partial W_a}{\partial t}=A\cdot p\cdot v_s\cdot e^{-B/T} && T<T_{act} \\ &\frac{\partial W}{\partial t}=\frac{\partial W_a}{\partial t}+\frac{\partial W_d}{\partial t}=A\cdot p\cdot v_s\cdot e^{-B/T}+D(T)\cdot e^{-E/RT} && T>T_{act} \end{aligned} \qquad (8)$$

where: $\frac{\partial W}{\partial t}$ – tool wear rate; $\frac{\partial W_a}{\partial t}$ – tool wear rate calculated according to the abrasive model; $\frac{\partial W_d}{\partial t}$ – tool wear rate calculated according to the diffusive model; E – activation energy; R – gas constant; p – contact pressure at the interface between tool and chip; v_s – sliding velocity at the interface between tool and chip; T – tool temperature at the interface between tool and chip; T_{act} – activation temperature of the diffusive phenomenon.

This coupled abrasive-diffusive model is suitable to determine the wear in the case of non-orthogonal cutting, both in the initial transient phase of wear – when the abrasive wear mechanism is dominant – and in the steady state phase of wear, when diffusion is the dominant wear mechanism [23].

Unlike the Takeyama– Murata model in Eq. (7), the model in Eq. (8) takes into account the fact that at low cutting temperatures abrasive wear dominates, while at high cutting temperatures diffusive wear plays the major role.

3. SUMMARY

In this article we provided a short review about different wear models. It can be seen that the tool wear is a fairly complex process; the models contain several parameters which can be determined by experiments or measurements. The models shown are suitable for describing the wear mechanisms separately, but with the help of coupled or combined models we obtain models that determine the real processes more accurately. The wear models shown are used widely in FEM simulation.

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