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Semi-Analytical Prediction of Flank Tool Wear in Orthogonal Cutting of Aluminum

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ABSTRACT

This study aims to model the flank wear prediction equation in metal cutting, depending on the workpiece material properties and almost cutting conditions. A new method of energy transferred solution between the cutting tool and workpiece was introduced through the flow stress of chip formation by using the Johnson-Cook model. To investigate this model, an orthogonal cutting test coupled with finite element analysis was carried out to solve this model and finding a wear coefficient of cutting 6061-T6 aluminum and the given carbide tool.
Keywords: flank wear, orthogonal cutting, wear coefficient

التنبؤ شبه التحليلي بالبلي الجانبي اثناء عملية قطع متعامدة للألمنيوم

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الخلاصة

تهدف هذه الدراسة الى صياغة معادلة للتنبؤ بالبلي الجانبي للعدد المستخدمة في عملية قطع المعادن، بالاعتماد على الخصائص المعدنية للمشغولة واغلب ظروف القطع. تم تقديم هذا الطريقة بالاعتماد على الطاقة المنتقلة بين عدة القطع والمشغولة، من خلال الاجهادات المسالة اثناء تكون الرايش وباستخدام نموذج جونسون – كوك. وللتحقق، تم اجراء عملية قطع متعامدة بصورة عملية، مصحوبة بمحاكاة معتمدة على طريقة العناصر المحددة لحل هذا النموذج وإيجاد معامل جديد للبلي الجانبي اثناء قطع مسبوكة الالمنيوم بعدة الكربيد المستخدمتين في هذه الدراسة.
الكلمات الرئيسية: بلي جانبي، قطع متعامد، معامل البلي.

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1. INTRODUCTION

Tool wear in metal cutting is a serious problem that causes a poor surface finish of the workpiece, degradation of dimensional accuracy, lower productivity of the process, etc. **(Young, 1996)**. The tool wear is the primary parameter that definite its lifetime. Besides, the replacing cost of the tools is the major cost of machining **(Lim et al., 1993**). There are different types of wear at the cutting edge of the tool such as flank wear, crater wear, nose wear, etc. in practice, the flank wear is often used to determine the tool life **(Kalpakjian et al., 2008)**. There are two main related aspects of studies to improve the tool life; the first one is by prolonging the tool cutter performance by depositing a single or multi-layer of hard material coating on cutting tool substrate. The development of coated tools technology had a significant advance, such as **(Aziz *et al.*, 2017)** research presents a new approach of electroless nickel deposition on cutting tools as to enhance tool performance. The second one is by studying the tool wear associated with cutting conditions, which is the point of interest in this paper.
Well known Taylor's equation was the earlier model for tool life. A simple relation between cutting speed V and tool life T is considered, which is $VT^n = C$, where C and n are constants. Then, it was extended to include the parameters of feed, depth of cut, work material hardness, to comprehensive tool life relation with the cutting condition that is obviously enhanced. However, to analyze the tool life properly as an analytical model, it is necessary to detect the progress of tool wear in practical conditions **(Usui et al., 1984)**.
High strain rate and friction phenomena outline the materials thermo-mechanical behavior, which characterized the mechanism of chip segmentation in metal cutting. To describe this mechanism, it is essential to understand the complicated flow stress, which depends on the strain, strain rate, and temperature that occurred in the chip formation **(List et al., 2012)**. Obviously, the tool wear itself also yields under this entire mechanism. In previous studies, this relation between tool wear and material behavior does not take more attention somehow.
This study aims to find the factors that affect on the flank wear of the cutting tool in orthogonal type, by relating the energy dissipating in tool wear with the total energy required to orthogonal cutting in the workpiece, by introducing the effective strain energy stored in the workpiece including the energy from the plastic deformation and thermal condition.
As a result, a new model to predict flank wear that complementing the previous models in the literature was proposed in this paper.

2. THEORY

(Usui et al., 1984) introduced an Archard type equation as follows:

$$\mathrm{d}W = \frac{\sigma_t}{H}\frac{c}{b} Z\,\mathrm{d}L \tag{1}$$

Where $\mathrm{d}W$ is the wear volume, σ_t is the normal stress at the contact surface, H is the hardness of the metal asperities, $\mathrm{d}L$ is the sliding distance, c is the height of the postulated plate, b is the mean spacing of the asperities, and Z is Holm's probability. By combining cZ/b into a coefficient k_1, Eq. (2) can be obtained as follows:

$$\mathrm{d}W = k_1 \frac{\sigma_t\,\mathrm{d}L}{H} \tag{2}$$

According to **(Shaw, 1984)** analysis, the volume of wear can be converted to the flank wear land V_B with the assumption that the rake angle of the cutting tool is equal to zero as follows:

$$W = \frac{1}{2} w\, V_B^2 \tan(\theta) \tag{3}$$

where w is the cutting width, and θ is the relief angle as illustrated in **Fig. 1**

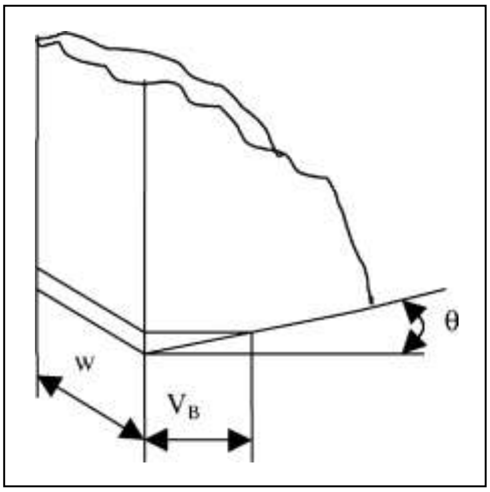

Figure 1. Cutting tool with zero rake angle scheme.

To represent the thrust force F_t in cutting, area of tool-work interface and the normal stress at the flank face are assumed as:

$$A = wV_B \tag{4}$$

$$\sigma_t = \frac{F_t}{A} = \frac{F_t}{wV_B} \tag{5}$$

Now by substituting Eq. (3) and (5) into Eq. (2), to predict the flank wear as presented by **(Zhao et al., 2002)**, a flank wear equation is given as follows:

$$V_B = K\left(\frac{2}{w^2 \tan\theta}\right)^{1/3}\left(\frac{F_t L}{H}\right)^{1/3} \tag{6}$$

Where the coefficient $K = {k_1}^{1/3}$ which can be determined by experiment, L is the cutting length, and H is the hardness of the cutting tool.

The energy-based computational solutions to describe the viscoplastic behavior of the materials is widely used in literature, **(Yan et al., 2019)** applied the Johnson-Cook model to quantify energy dissipating mechanisms during orthogonal cutting of composite materials. A detailed energy analysis based on finite element calculations was presented by **(Reiner et al., 2016)** in order to investigate damage modes in hybrid titanium-composite materials subjected to impact. In this paper, the empirical equation by **(Johnson, 1983)** to describe a thermo-viscoplastic behavior of workpiece material was considered in this study, as follows:

$$\bar{\sigma} = (A + B\bar{\varepsilon}^n)\left(1 + Cln\left(\frac{\dot{\varepsilon}_{eff.}}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right) \tag{7}$$

Here $\bar{\sigma}$ is the effective flow stress of the material, $\bar{\varepsilon}$ is the cumulative plastic strain, $\dot{\varepsilon}_{eff.}$ the effective plastic strain rate, $\dot{\varepsilon}_0$ the reference plastic strain rate of 1 s^{-1}, T_0 the room temperature and T_m the melting temperature. A, B, C, n and m are material constants that are material constant that experimentally calculated, which can found in literature for specific material.

In this study, an energy transferred solution is proposed to relate the effective flow stress of Eq. (7) with flank wear equations. The work done per unit volume is presented as follows **(Bayoumi, 2018)**:

$$\frac{dW_P}{vol.} = \bar{\sigma} d\bar{\varepsilon} \tag{8}$$

$$W_P = \left(\int_0^{\bar{\varepsilon}} \bar{\sigma} d\bar{\varepsilon}\right) vol. = \left(\int_0^{\bar{\varepsilon}} \bar{\sigma} d\bar{\varepsilon}\right)\ w. t_1. L \tag{9}$$

Where vol. is equal to the volume of the removed chip at specific slide distance, L or orthogonal cutting length, and t1 is undeformed chip thickness.

To authorize this solution, **(Merchant, 1945)** model in Eq. (10), **(Lee, 1951)** model in Eq. (11) are used to represent effective stress through the resultant force in flank wear equation, as follows:

$$\phi = tan^{-1}\left(\frac{(t_1/t_2)cos\alpha}{1-(t_1/t_2)sin\alpha}\right) \tag{10}$$

$$\beta = \frac{\pi}{4} - \phi + \alpha \tag{11}$$

$$F_t L = R_s \sin(\beta - \alpha) L = W_P \tag{12}$$

Where ϕ is the shear angle, t_2 is the deformed chip thickness, and β is friction angle the tool-chip interface.

Now, by combining Eq. (6), (9) and (12) the Flank wear equations are given as follows:

$$V_B = K\left[\frac{2t_1 L\sin(\beta-\alpha)}{w\tan(\theta)} \frac{(\int_0^{\bar{\varepsilon}} \bar{\sigma} d\bar{\varepsilon})}{H}\right]^{1/3} \tag{13}$$

$$K = V_B\left[\frac{2t_1 L\sin(\beta-\alpha)}{w\tan(\theta)} \frac{\left(\int_0^{\bar{\varepsilon}} \bar{\sigma} d\bar{\varepsilon}\right)}{H}\right]^{-1/3} \tag{14}$$

3. METHODS AND MATERIALS

Orthogonal tests over a tube with different diameters are carried out. Employed material is 6061-T6 Aluminum machined using a horizontal lathe with uncoated P15 DCMA110402 tool inserts, which have a rake angle of zero and a clearness angle of +7 and SDJCR161611 tool holder, as shown in **Fig. 2**. Testing was carried out with four different cutting speeds V of 460, 408, 374, and 323 mm/s, with a depth of cut and feed rate of 2 (mm) and 0.2 (mm/rev), respectively, in the form of dry machining. Set up and conditions above were considered to achieving plain strain configuration.

In this study, the effect of cutting speed was considered the main parameter. Therefore, the sliding distance fixed to be equal to $8 \times 10^5\ mm$. After that, the aluminum workpiece was machined with the above-defined cutting condition. Carbide tools were collected to examine the flank wear land using a microscope. Samples with excessive debris in areas rather than flank wear were extracted. The wear land of selected samples was measured using five equidistant locations then take the average, as shown in **Fig. 3**.

Accordingly, the experiments above are employed to investigate the flank wear on the tool inserts in an orthogonal setup of machining with plain strain configuration. Consequently, the V_B flank wear land data are collected with constants of w cutting width, t_1 undeformed chip thickness, and L sliding distance for each of the four cutting speeds. Also, the hardness test was also conducted on the tool insert. All of that will make Eq. (14) find the coefficients K, except the data of $\bar{\varepsilon}$ the cumulative plastic strain, $\dot{\varepsilon}_{eff.}$ the effective plastic strain rate, t_2 deformed chip thikness and temperature which will be achieved using the finite element analysis that will be explained in the next section. This procedure allows later to predict and validate the flank wear with the same cutting condition and workpiece material by depending on FEA or viscoplacticity analysis.

Figure 2. The tool insert and the tool holder.

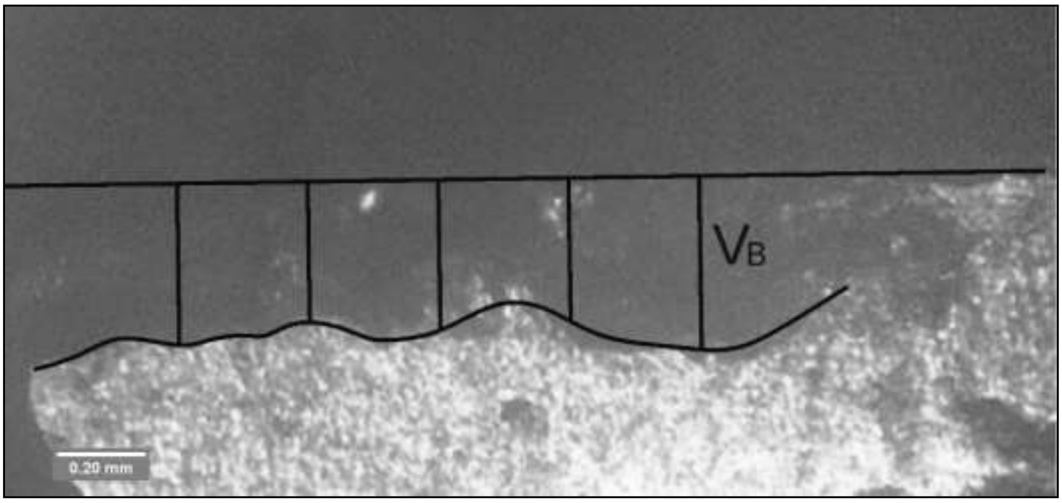

Figure 3. Flank wear measurement.

4. FINITE ELEMENT MODEL

ABAQUS/Explicit package for Finite Element analysis has been employed. A 2D orthogonal model has been built for the estimation of Eq. (7) variables in the primary shear zone of chip formation. **Fig. 4** shows the geometry of the model, built using square elements and Arbitrary Lagrangian-Eulerian (ALE) formulation step that regulates the topology of the mesh in the cutting clearance to avoid excessive mesh distortion. The tool is considered as an elastic rigid body, and the workpiece material follows a thermo-viscoplastic behavior described by the Johnson-Cook's law **(Johnson, 1983)** as the same model as in Eq. (7), which is interesting in this situation to validate the simulation model and get comparable analysis. The parameter of this empirical equation was calibrated by **(Dabboussi and Nemes, 2005)** to represent the response of 6061-T6 Al, as detailed in **Table 1.**

Table 1 parameters of Johnson cook model.

A (MPa)	B (MPa)	C	n	m
335	85	0.11	0.012	1

A damage criterion was also applied to the element of the workpiece by following the Johnson and Cook's damage law **(R. Johnson and H. Cook, 1985)**. The general expression for the strain at fracture is:

$$\varepsilon_f = (D_1 + D_2 e^{(D_3\sigma*)})(1 + D_4 ln\varepsilon)(1 + D_5 T^*) \qquad (15)$$

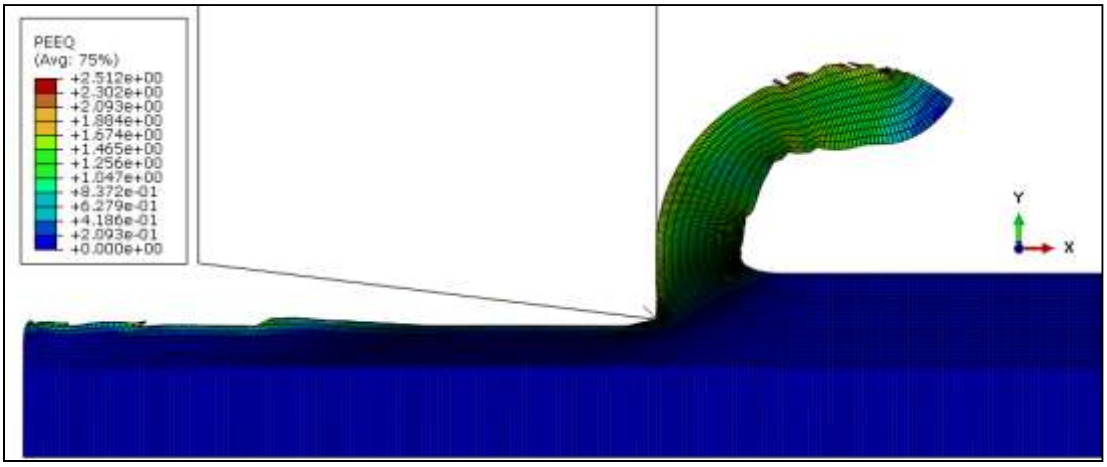

Figure 4. The geometry of the FEM simulation.

where σ^* is the mean stress normalized by the effective stress, and T^* is the homologous temperature. The parameters *D1*, *D2*, *D3*, *D4*, and *D5*, are material constants were obtained from **(Corbett, 2006)** for 6061-T6 Al, as detailed in **Table. 2.**

Table 2 parameters of Johnson-cook damage model.

D_1	D_2	D_3	D_4	D_5
-0.77	1.45	-0.47	0	1.6

5. RESULTS AND DISCUSSION

Effective strain rates and temperatures of the simulation model were taken at the primary shear zone near the tooltip, which is maximum values in this region, as detailed in **Table 3.** At this point of maximum strain rate, the cumulative plastic strain was taken here to calculate. However, the plastic strain continually increased, especially when entering the secondary shear zone, which is out of interest in this study. FEM is used only to provide cutting signals for the wear model while could also using Visioplasticity techniques for that purpose.

The samples of carbide tools collected were chosen to be at acceptable values of land wear V_B in industrial practice, which is usually beyond these limitations when the carbide tools have to be replaced. Sliding distance L had chosen to be high enough instead of high cutting speed to ensure a steady-state of wear particle debris.

Table 3. summary of the results.

V (mm/s)	t_2 (mm)	$\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{eff.}}\ (\boldsymbol{s^{-1}})$	$\bar{\boldsymbol{\varepsilon}}$	T °C	$V_{B\ (mm)}$	K
323	0.31	2.75×10^4	1.152	93.2	0.168	2.8×10^{-3}
374	0.303	2.81×10^4	1.208	96.5	0.275	4.4×10^{-3}
408	0.295	3.24×10^4	1.176	107.7	0.294	4.7×10^{-3}
459	0.285	3.76×10^4	1.227	114.6	0.361	5.6×10^{-3}

6. CONCLUSIONS

In this study, the flank wear proposed model is depending on the workpiece material properties and almost cutting conditions. A method of energy transferred solution between the cutting tool and workpiece was introduced, which could also be in other forms for metal cutting wear analysis in future work.

As a result, a new wear coefficient of flank wear for 6061-T6 aluminum was also introduced, which was fitted as shown in **Fig. 5**. It was observed that the coefficient of wear (K) was increasing with the velocity of cutting v at a different rate. From the speed of cutting 300 – 400 mm/s, the increase in the coefficient of wear is very high, which means that the effect of friction in tool wear is more pronounced than the thermal condition. While when the speed increased to 470, the rate of increase in K becomes low, and the thermal factor is more effective than dynamic friction. Until the value of 500 mm/s of the cutting speed was reached, the value of K became more stable.

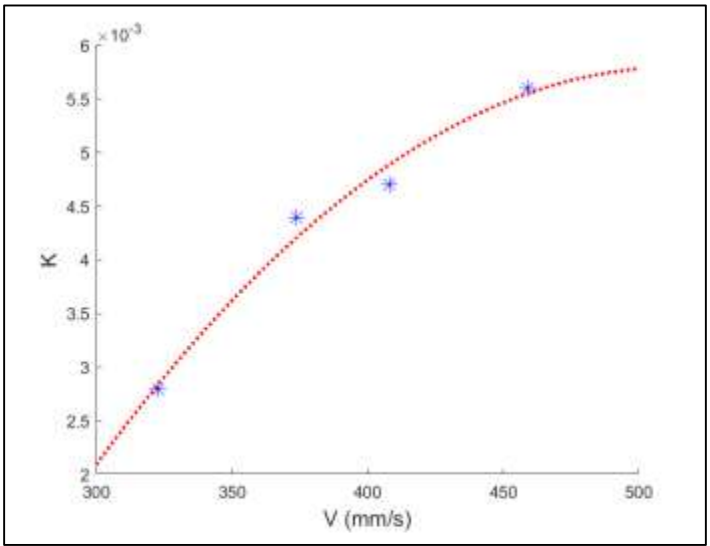

Figure 5. fitting of wear coefficient.

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