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CUTTING FORCE MODEL FOR TOOL WEAR ESTIMATION

by

TSU-REN KO, Research Assistant
YORAM KOREN, Professor

Department of Mechanical Engineering and Applied Mechanics
The University of Michigan
Ann Arbor, MI 48109

ABSTRACT. Model-based indirect tool wear measuring techniques are most suitable for on-line tool wear assessment. A comprehensive physical model that relates the clearance wear to the change of the cutting force is proposed. This model takes the tool geometry of a practical turning operation into consideration. The model was tested and the experimental results support the proposed theory.

Traditional Methods

On-line tool wear information is essential for modern manufacturing. Since tool wear has a direct influence on the part dimensions, on-line tool wear information is indispensable in precision machining [1]. In adaptive controlled (AC) machines, the constraints and the performance index are usually functions of tool wear, and only when real-time tool wear information is obtained, the AC algorithm can achieve their optimal performance [2,3]. Some types of tool breakage may be predicted by tool wear measurement, therefore on-line tool wear information can be used to assure safe cutting operations [4]. This information is also important in deciding when tools should be changed to avoid cutting with excessive tool wear. It is, therefore, no wonder that in unmanned factories, tool wear knowledge plays a central role in the process diagnostic system [5]. Despite the attempts of many researchers, however, there is no satisfactory way to acquire on-line tool wear information by direct measurements.

Direct measurements of tool wear may be divided into off-line and on-line methods. Off-line measurements may be performed by a person (e.g. with a microscope) or automatically by sensors that measure either the tool geometry or the amount of tool particle in chips [6,7]. Since off-line methods introduce a time delay in tool wear measurements, they are not suitable for the on-line applications discussed above.

Direct on-line tool wear sensing methods include the electrical resistance [7,8], the radiometric [9], and the optical scanning techniques [10,11]. The electrical resistance techniques and the radiometric technique require special preparations of the tools, which is costly and inconvenient. In addition, the radiometric technique has a potential danger of radioactivity. The practical usage of the optical scanning techniques is limited because of the inaccessibility of the wear zone and the production environment (coolant, chips, etc.) [12].

The two remaining alternatives to acquire tool wear information are either by estimation based on models obtained through off-line measurements or by indirect on-line measuring techniques.

Tool life algebraic equations have been widely used for off-line wear estimation for more than eighty years [13]. Taylor's tool life equation is the most known example of this type of equations [14]. This equation predicts the period of time during which the cutting tool, under certain cutting condition, will develop a predefined amount of wear. The equations, however, are based only on the final state of the tool wear, and do not describe the state of the tool wear during cutting. This limitation prevents their usage in on-line applications such as dimensional compensation, tool breakage prediction, and adaptive control, and they are useful only in the pre-process calculation of the tool changing times.

Modern Methods

Tool wear may be described by differential equations that are also derived by off-line measurements [15-19]. These tool wear state equations formulate the wear process based on the insight of its mechanisms, thereby provide tool wear estimation during the whole cutting process. The accuracy of these estimation, however, depends on the completeness and the correctness of the process formulations, which, in turn, are very hard to obtain because of the lack of knowledge on the complicated cutting process and its large scatter. In addition, extensive off-line measurements are required to make them applicable in a wide range of cutting conditions, and these measurements are very costly and time consuming. These drawbacks are the reasons for the development of indirect measuring techniques for tool wear.

The indirect measuring techniques measure accessible process variables which are related to tool wear, and then retrace the state of the tool wear from these measurements. The measurable variables used in these techniques include cutting force [20-23], torque [12], tool vibration [24-26], workpiece dimension [27], cutting temperature [28], and acoustic emission [29]. In order to retrace the state of the tool wear, mathematical formulations of the relationship between tool wear and the measured signals are needed. These formulations may be based on either empirical analyses or physical models. The empirical approaches are limited by their nature, applicable only in some specific conditions. By contrast, the model-based methods are applicable in a wider range, but they are restricted by the difficulties in formulating accurate models. However, because of the readiness of the measurements, the indirect measuring techniques are most suitable for real-time implementations and are therefore still under extensive research.

A more advanced approach for tool wear estimation combines the tool wear state equations with the model-based indirect measuring techniques by using the observer concept from control theory [30]. This approach utilizes the output measurements (e.g. cutting force) to correct the estimation of the state equations. The quality of the result of this approach depends both on the reliability of the indirect measurement and the accuracy of the state equations. The main problem associated with a successful implementation of this observer-based approach is the lack of reliable models of the output measurements.

As a result, to acquire on-line tool wear information, a reliable model-based indirect measurement method is of major concern, which may be used to estimate tool wear by its own formulation as well to combine with the existing tool wear state equations for advanced approaches. Accordingly, the objective of this article is to introduce a new comprehensive model between the cutting force, i.e., the measured process variable, and the clearance wear (which includes the flank wear and the nose wear); based on this model the clearance wear may be estimated directly or by the observer approach. The reasons to choose the cutting force as the measured signal are the availability of commercial dynamometers with high sensitivity and reliability, providing nearly noise free measurement, and the dependence of the cutting force on the tool wear, which makes possible to construct a physical model.

Force-Wear Relationship

The relationship between the cutting force and the flank wear has been studied by several researchers [15,20,31]. Their works were mainly based on the investigations of either orthogonal cutting or oblique cutting. Basically, they assumed certain pressure distributions and constant friction coefficient on the flank wear surface. Usually in both orthogonal and oblique cutting, the width of the flank wear, W_f, develops uniformly and the change of the cutting force , $\Delta\vec{F}$, may be modeled as

$$\Delta\vec{F} = \vec{F}_p + \vec{F}_f \tag{1}$$

where $\vec{F}_p$ and $\vec{F}_f$ are two perpendicular components given by

$$\vec{F}_p = P_{av} W_f b \tag{2}$$

and

$$\vec{F}_f = \mu P_{av} W_f b \tag{3}$$

where P_{av} is the average pressure on the flank wear surface, b is the width of cut (or the depth of cut in turning), and μ is the friction coefficient. Note that $\vec{F}_p$ acts normal inward to the flank wear surface and $\vec{F}_f$ acts along the direction of the cutting speed.

In the case of real turning applications, the tool engagement is more complex, since the insert nose is also involved in the cutting operations. We can, however, extend the flank wear model to the nose surface and obtain a comprehensive wear model that describes the clearance wear effect on the cutting force.

Let us define s as the coordinate along the projection of the actual cutting edge on the plane perpendicular to the cutting speed, with the starting point corresponding to the initial cutting point on the flank edge and the ending point to the end cutting point on the nose edge, as shown in Fig. 1. The cutting force change due to the pressure on the clearance wear surface can be written as

$$\vec{F}_p = \int_0^{s_2}\int_0^{W(s)} p(s,w)\,\vec{n}(s)\,dw\,ds \tag{4}$$

where $W(s)$ is the local wear at point s, $p(s,w)$ is the pressure distribution on the clearance wear surface, $\vec{n}(s)$ is the unit normal vector pointing inward on the clearance wear surface, and s_2 is the value of the ending point in the s coordinate. Note that since we analyze a general turning case in which the tool is tilted with respect to the workpiece, the wear, W, is measured along the direction of the cutting speed, not necessarily perpendicular to the cutting edge. $\vec{F}_p$ in Eq. (4) represents a force that its direction varies with $\vec{n}$ along s. Also note that Eq. (2) is a particular case of the comprehensive model of Eq. (4), in which $W(s)$ becomes a constant, W_f, and s is a straight line of a length b.

The general expression of the force change due to the friction force on the clearance wear surface may be written as

$$\vec{F}_f = \int_0^{s_2}\int_0^{W(s)} \mu(s,w)\,p(s,w)\,\vec{v}\,dw\,ds \tag{5}$$

where $\mu(s,w)$ is the friction coefficient on the clearance wear surface and $\vec{v}$ is the unit tangent vector in the direction of the cutting speed. The sum of these two forces represents the total clearance wear effect on the cutting force.

To evaluate Eqs. (4) and (5), the following functions should be known

1. $p(s,w)$
2. $\mu(s,w)$
3. $\vec{n}(s)$
4. $W(s)$

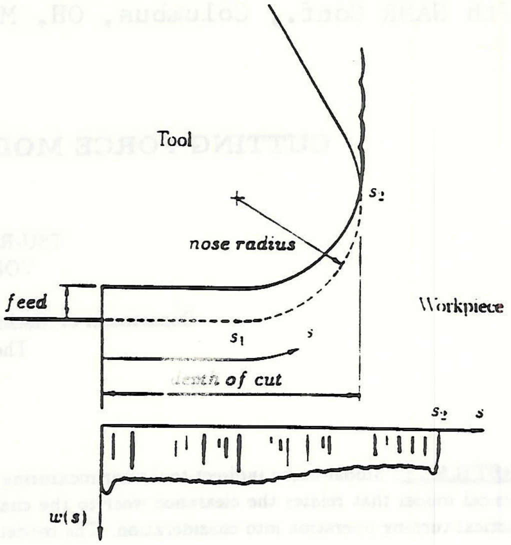

Fig.1 Schematic drawing of the clearance wear in turning operation.

To know the exact structure of these functions is very complex in machining. However, as a first approximation, we can make assumptions regarding the above four functions to simplify the model.

By assuming that the average pressure on the clearance wear surface is constant [31], we have

$$\left[\int_0^{W(s)} p(s,w)\,dw\right]/W(s) = P_{av}(s) = P_{av} = constant \tag{6}$$

By assuming that the friction coefficient on the clearance wear surface remains unchanged, we have

$$\mu(s,w) = \mu = constant \tag{7}$$

By assuming that the clearance wear does not change the original shape of the cutting edge (viewed from the direction of the cutting speed), we obtain

$$\vec{n}(s) = \vec{n}_o(s) \tag{8}$$

where $\vec{n}_o$ is the unit vector normal to the cutting speed pointing inward to the cutting edge of an unworn tool. Finally, we assume that the clearance wear may be written in an approximate linear form (see Fig. 2) as

$$W(s) = \begin{cases} W_f & 0 < s < s_1 \\ ((s-s_2)/(s_1-s_2))\,W_f + ((s-s_1)/(s_2-s_1))\,W_n & s_1 < s < s_2 \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

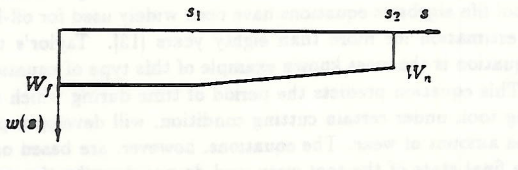

Fig.2 Graphical representation of the linear clearance wear model.

where W_f is the average flank wear on the flank edge, W_n is the nose wear at the end point s_2, and s_1 is either the s value of the tangent point connecting the flank edge and the nose edge when greater than zero, or is zero otherwise.

By substituting Eqs. (6-9) into Eqs. (4) and (5), the following simplified model for the change in the cutting force is obtained.

$$\vec{F}_p = P_{av} \int_0^{s_2} W(s)\,\vec{n}(s)\,ds \tag{10}$$

$$\vec{F}_f = \frac{1}{2}\mu P_{av} [W_n(s_2 - s_1) + W_f(s_2 + s_1)]\,\vec{v} \tag{11}$$

Note that $\vec{F}_p$ actually consists of a component in the radial cutting force direction and a component in the feed cutting force direction, and $\vec{F}_f$ is almost in the normal cutting force direction (with a negligible amount in the feed cutting force direction).

If we denote $\Delta\vec{F}_r$, $\Delta\vec{F}_d$, and $\Delta\vec{F}_n$ as the radial, the feed, and the normal components which constitute the total cutting force change due to the clearance wear, the relationships between them and $\vec{F}_p$ and $\vec{F}_f$ may be written as

$$\vec{F}_p = \Delta\vec{F}_r + \Delta\vec{F}_d \tag{12}$$

and

$$\vec{F}_f = \Delta\vec{F}_n \tag{13}$$

Note that these equations are vector equations.

When compared with Eqs. (10) and (11), the magnitude of these three components may be expressed as

$$|\Delta\vec{F}_r| = P_{av}\,\mathcal{F}_r(s) \tag{14}$$

$$|\Delta\vec{F}_d| = P_{av}\,\mathcal{F}_d(s) \tag{15}$$

and

$$|\Delta\vec{F}_n| = \frac{1}{2}\mu P_{av}\,\mathcal{F}_n(s) \tag{16}$$

where $\mathcal{F}_r(s)$ and $\mathcal{F}_d(s)$ are the radial and the feed components of the integral in Eq. (10), and $\mathcal{F}_n(s)$ is the function to the right of P_{av} in Eq. (11). These $\mathcal{F}$ functions can be evaluated for a specific cutting tool geometry and cutting conditions, and therefore may be considered as known values.

Experiments were conducted to test the simplified model given in Eqs. (10) and (11). Since the crater wear is not considered in this model, it is desired to cut with inserts that have only clearance wear. Tools with artificial flank wear were used by a few researchers for this purpose [31,32]. However, we have found that it is almost impossible to grind an insert to have a clearance wear with natural wear shape when the insert nose is also involved in the cutting. As an alternative, by assuming that the crater wear develops slower than the clearance wear [33] and has a negligible effect on the cutting force at the initial period of cutting, we can examine the cutting force behavior at this period for testing the model. An insert with a relief angle of 11 degrees was chosen for the cutting operation in order to avoid the possible rubbing of the insert nose against the finished workpiece (which is not considered in the model).

Three experiments were conducted. The cutting conditions are listed in Table 1. Notice that experiments #2 and #3 are identical. The measured cutting forces of the first two experiments are shown in Figs. 3 and 4. The first cutting periods are used to verify the simplified model. The measured W_f and W_n after the first cut in each experiment are listed in Table 2.

In order to calculate the force-component changes based on the simplified model, P_{av} and μ should be given. These values, however, are not known. Nonetheless, the ratio of the radial cutting force component change, $|\Delta\vec{F}_r|$, to the feed component change, $|\Delta\vec{F}_d|$, may be computed by deviding Eq. (14) by Eq. (15) which cancels the unknown P_{av}. To verify the model, the calculated ratio is compared with the actual measured value (given in Table 2) for the three experiments. As one may see, the predicted values are close to the measured values, but always a little bit higher. (The speculated reason is that the chip is thicker on the flank cutting edge and causes more residual pressure on the flank wear surface than on the nose wear surface [34]. Therefore, the feed component of the cutting force increases more than the predicted value and drives the measured ratio down.)

Table 1: The cutting conditions of the three experiments.

Exp. No.	Insert Type	Depth of Cut (in)	Feed (in/rev)	Cutting Speed (ft/min)
1	TPG 434 G370	0.1	0.006	800
2			0.004	1200
3				

Table 2: The measured clearance wears, the ratios of the radial cutting force component change to the feed component change, and the estimated friction coefficients.

Exp. No.	W_n (in)	W_f (in)	Predicted Ratio	Measured Ratio	Estimated μ
1	0.002	0.002	0.65	0.48	0.44
2	0.002	0.003	0.53	0.45	0.42
3	0.002	0.0035	0.50	0.41	0.42

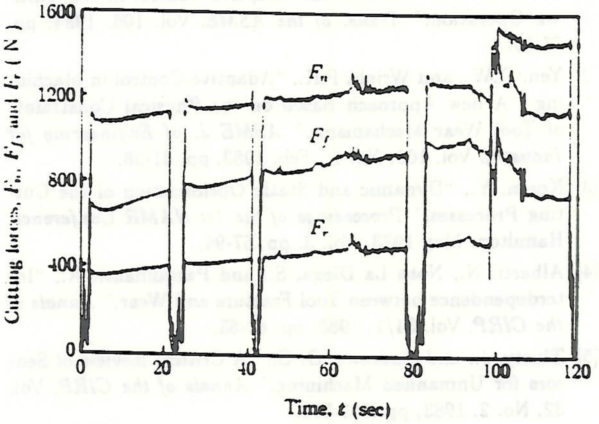

Fig.3 The measured force components of the 1st Experiment : the normal component, F_n, the feed component, F_f, and the radial component, F_r.

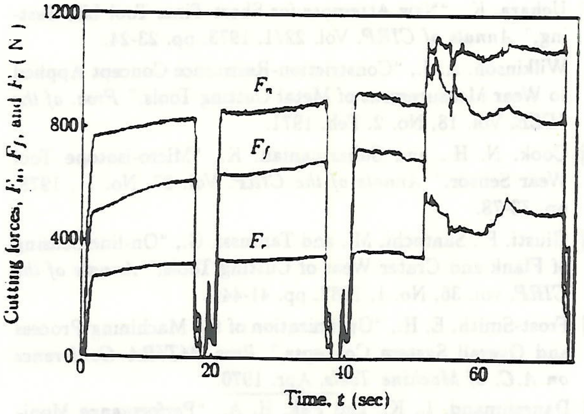

Fig.4 The measured force components of the 2nd Experiment : the normal component, F_n, the feed component, F_f, and the radial component, F_r.

If the pressure distribution is taken as a constant, the friction coefficient may be computed from Eqs. (16) and (14) (or (15)). The calculated average values of μ are also listed in Table 2, and they appear to be reasonable and consistent in all our three experiments. The results of the ratio of the force changes and μ show that the model development is reasonable.

Conclusion

A comprehensive model that relates the clearance wear to the change in the cutting force was proposed and tested. This model considers the practical turning case and can be used for tool wear estimation when the crater wear effect is negligible (or be combined with the crater wear model when the crater wear effect is influential). It can also serve as the output equation in the observer-based approach. However, further research regarding the pressure distribution on the clearance surface and the crater wear model are needed for the study of a complete tool wear estimation based on the cutting force signal.

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