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Sensors of Tool Life for Optimization of Machining*

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Several types of sensor for detecting tool wear of both on-line and semi-on-line performances are reported. As for a parameter for an on-line sensor, variation of cutting force and relative displacement of machined surface due to flank wear have been experimentally proved to be adequate. The proportionality constants of the relations between cutting forces and wear lands have a close and simple correlation with the physical properties of the work materials. The continuous measurements of flank wear by way of the relative displacement of the machined surface are also highly reliable for an optimizing control of a lathe in view of tool life. In order to obtain more direct information of tool wear, an electro-optical measuring device has been also developed.

1. Introduction

A numerically controlled machinability test lathe, in which tool life tests can be conducted in a fully automatic manner except loading and unloading the work materials, and the cutting speeds are controlled within 0.5 percent in surface speed, has been developed by the Government Mechanical Laboratory in cooperation with Okuma Machinery Works. The block diagram is shown in Fig. 1. By utilizing this, a new project of self-optimizing control of the lathe referring to tool life has started since 1966. The scheme is diagrammatically shown in Fig. 2, in which speed or feed is controlled automatically to achieve the computed optimum tool life.

One of the most essential problems encountered in developing such a self-optimizing machine tool is to find out highly effective and reliable sensors, as the previous workers⁽¹⁾ tried.

Here in this paper, several sen-

Fig. 1 Block diagram of speed control in numerically controlled lathe

Fig. 2 Block diagram of optimum control of cutting process in view of cutting speed

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sors for detecting tool wear of both on-line and semi-on-line performances are described. As for a parameter for an on-line sensor, variation of cutting force and relative displacement of machined surface due to flank wear have been experimentally proved to be quite adequate. Cutting forces have an excellent linear correlation with the wear rate of tool for various work materials such as plain carbon steels, alloy steel, brass, aluminium, etc. Furthermore, the proportionality constant of the cutting force with regard to the wear land has a close and rather simple correlation with the physical properties of the work material. This characteristic is extremely worthwhile for reducing the number of the controlling parameters. The continuous measurement of flank wear by way of the relative displacement of the machined surface is a highly reliable method if the major disturbance due to the temperature rise is properly eliminated as described later.

In order to obtain more direct informations of tool wear, an electro-optical measuring device has been also developed.

2. Cutting force

If the cutting forces increase as the wear land increases, as pointed out by the previous workers⁽²⁾, the rate of increase of cutting force can be an input for the on-line control of the system. The problems are (1) what the characteristic of the relationship between the cutting force and the wear land is, (2) how great its reliability is and (3) whether the relationship is valid or not for varied work materials and cutting conditions.

Here, the three components of a cutting force are measured in reference to the cutting time or the wear land when turning 0.45 percent carbon steel, 0.15 percent carbon steel, Ni-Cr-Mo alloy steel, cast iron, brass and aluminium alloy with P20 and P30 carbide tools at various cutting conditions.

2.1 Relationship between cutting force and wear land

Figures 3, 4 and 5 show the relationships of wear land with principal, feed and radial forces, respectively, when turning 0.45 percent carbon steel with P20 carbide tools at the speeds of 100, 150 and 200 m/min. Assuming the relationships to be linear, and carrying out the regression analyses the coefficients of correlation become larger than 0.90 in most cases.

On the other hand the linearity is supported by the following simple analysis. In a two-dimensional cutting with a worn tool of zero rake angle as shown in Fig. 6, denoting the tangential and normal forces on the rake face by T_1 and N_1 , respectively, the tangential and normal forces on the wear land, of which width is V_B , by T_2 and N_2 , respectively, and the width of cut by d , the force components parallel and normal to the cutting direction F_c and F_r are expressed as follows, respectively,

$$F_c = N_1 + T_2 \quad \dots \dots \dots (1)$$

$$F_r = T_1 + N_2 \quad \dots \dots \dots (2)$$

Assuming that the stress situation on the rake face is not altered by the increase of wear land ΔV_B , the increase of F_r , which is denoted by ΔF_r ,

Fig. 6 Schematic model of two-dimensional machining

is equal to the increase of N_2 , i.e., ΔN_2 ,

$$\Delta F_r = \Delta N_2 \dots \dots \dots (3)$$

or

$$\frac{\Delta F_r}{\Delta V_B} = \frac{\Delta N_2}{\Delta V_B} \dots \dots \dots (4)$$

If the work material in contact with the wear land is assumed to be yielding, and the yield stress σ is constant,

Fig. 7 Schematic model of three-dimensional machining

Material cut: 0.15 % carbon steel; Other conditions same as in Fig. 3

Fig. 8 Relation of radial force with flank wear for low carbon steel

Material cut: Ni-Cr-Mo alloy steel; Other conditions same as in Fig. 3

Fig. 9 Relation of radial force with flank wear for Ni-Cr-Mo alloy steel

Material cut: brass, aluminium
Tool: P 30 carbide (0, 0, 6, 45, 45, 0.5)
Other conditions same as in Fig. 3

Fig. 10 Relation of radial force with flank wear for brass and aluminium

$$\frac{\Delta F_r}{\Delta V_B d} = \sigma \dots \dots \dots (5)$$

This seems to verify the validity of the linear relationship between the cutting force and the wear land.

Even in a three-dimensional cutting as illustrated in Fig. 7, the chip formation in the plane normal to the side cutting edge can be regarded as two-dimensional. Then the feed force F_f and the radial force F_r can be expressed as follows.

$$F_f = T_1 \cos \theta + N_2 \cos \theta \dots \dots \dots (6)$$

$$F_r = T_1 \sin \theta + N_2 \sin \theta \dots \dots \dots (7)$$

where T_1 , N_1 , T_2 and N_2 denote the corresponding forces specified in Fig. 7. Then similarly,

$$\frac{\Delta F_r}{\Delta V_B} = \frac{\Delta N_2 \sin \theta}{\Delta V_B d} = \sigma \dots \dots \dots (8)$$

where θ is the side cutting edge angle, d the depth of cut, and the nose radius is assumed to be zero.

Now let us examine whether the linear relation between the force and the wear land is valid for other materials, and if so, the proportionality constants are governed by the yield stresses or other mechanical properties.

Material cut: Ni-Cr-Mo alloy steel, 0.45 % carbon steel, 0.15 % carbon steel, brass, aluminium
Cutting speed: 200 m/min
Other conditions same as in Fig. 3

Fig. 11 Relation of elastic limit of work material with $\Delta F_r / \Delta V_B d$

Fig. 12 Relation of Brinell hardness of work material with $\Delta F_r / \Delta V_B d$

Figures 8, 9 and 10 show the relationships between the radial forces and the wear lands for 0.15 percent carbon steel, Ni-Cr-Mo alloy steel, brass and aluminium. Taking a relatively large number of observed points, an excellent linearity can be revealed, and especially in the case of Ni-Cr-Mo steel the coefficient of correlation is 0.98.

Now plotting $\Delta F_r / \Delta V_B d$ vs. elastic limit and Brinell hardness in place of yield stress, the relations become as shown in Figs. 11 and 12, respectively. The illustrations show fair correlations between the normal stress on the wear land and the mechanical properties of material cut as predicted in Eqs. (5) and (8), although a quantitative agreement cannot be expected because of the assumptions.

However, there is an exception. That is, in the case of cast iron the value of $\Delta F_r / \Delta V_B d$ increases at a larger wear land, although there still exists linearity in the range of wear land smaller than approximately 0.1 mm, as seen in Fig. 13. The deviation from the linearity will be attributed to the fact that the larger the wear land, the more work-hardened the machined surface.

2.2 Effects of cutting conditions

For the present purpose it is desirable that the value of $\Delta F_r / \Delta V_B d$ for a definite work material is constant regardless of the cutting conditions such as speed, feed, tool shape, etc. As seen in Figs. 5 and 9, the value of $\Delta F_r / \Delta V_B d$ a little differs according to the cutting speeds. This is probably due to the shape of wear land, and to built-up-edge when the

Material cut: Meehanite cast iron
Tool: P20 carbide (0, 0, 6, 6, 45, 45, 0.5)
Feed: 0.2 mm/rev, Depth of cut: 1 mm

Fig. 13 Relation of radial force with flank wear for cast iron

Cutting conditions same as in Fig. 3 except varied feeds and cutting speed 150 m/min

Fig. 14 Relation of radial force with flank wear for varied feeds

cutting speed is extremely low. The situation is almost the same with the feed as shown in Fig. 14. The measured normal force on the wear land can be regarded as the integrated value of the stresses on the wear land regardless of the shape of wear land, so that the variation of force will represent with fidelity the overall variation caused by the variation of wear land. However, if there is an appreciable built-up-edge, it will cause an inevitable error.

As to the rake angle the value of $\Delta F_r / \Delta V_B$ is practically constant as seen in Fig. 15. The situation is completely different with the depth of cut as predicted by Eq. (8). Figure 16 shows the experimental result, in which the larger the depth of cut, the larger slope is obtained. However, if $\Delta F_r / \Delta V_B$ is divided by d , or the stress is taken, it becomes almost constant regardless of the depth of cut as predicted by Eq. (8). In order to obtain a better sensitivity with a definite sensor, it is advisable to choose a larger depth of cut.

3. Automatic sensing of tool wear

A direct on-line measurement of tool wear has been a dream in the field of metal cutting engineering. Various physical quantities such as cutting force, cutting temperature^{(1) (3)}, etc. which have been attempted to utilize as measuring parameters for the tool life, unfortunately necessitate a correctly known relation with the tool wear. A rather simple device using an electric feeler micrometer made it

Cutting conditions same as in Fig. 3 except varied rake angles and cutting speed 150 m/min

Fig. 15 Relation of radial force with flank wear for varied rake angles

Cutting conditions same as in Fig. 3 except varied depths of cut and cutting speed 150 m/min

Fig. 16 Relation of radial force with flank wear for varied depths of cut

possible to measure the tool wear in a direct manner.

3.1 Principle

The feeler of an electric micrometer head is mounted on the tool post in contact with the work surface immediately after being machined by the side cutting edge as shown in Fig. 17. As the flank wear increases the machined surface relatively shifts towards the tool axis, this resulting in the same displacement of the feeler or the corresponding electric output to $V_B \tan \gamma$, where V_B is the width of wear land, γ is the side relief angle, and both the side rake angle and the side cutting edge angle are zero.

A distinct advantage of this attempt will be that the sensor measures the displacement of the surface machined by the side cutting edge instead of that by the end cutting edge, otherwise the extraordinary geometrical irregularities due to feed marks will result in an extreme confusion.

However, there are still inherent disturbances which hamper the automatic measurement of the tool wear: (1) the thermal expansion of the tool, (2) the deflection of the tool due to the cutting force, (3) the deflection or vibration of the work material (4) insufficient accuracy of the machine tool, and

(5) the irregularities of the machined surface which the sensor feeler contacts.

The vibratory disturbances of rather high frequencies can be smoothed out electrically by an appropriate low-pass filter. Figure 18 shows an example in which the higher harmonics originated by the work material are eliminated by a low-pass filter.

The external disturbances due to insufficient accuracy of the machine tool and the lack of rigidity of the work material can be minimized as far as an average numerically controlled machine is utilized and the test setup is properly arranged such that, for example, the sensing point may locate as close as possible to the cutting tool and the entering angle of the tool is 90 degrees. The 90 degree entering angle is also effective to eliminate the disturbance due to the thermal expansion of the tool in the direction of the tool axis.

The fluctuations caused by the irregularities of the wear land, consequently, of the machined surface are not so serious usually, because they can be averaged out as described later. However, as far as the excessive fluctuations caused by the built-up-edges or weldings at the cutting edge are concerned, some special on-line treatments of the signals will be necessary.

Consequently, the most serious and fundamental disturbances to be compensated are those originated by the thermal expansion of the tool and the deflection of the tool due to the cutting force. It must be noticed that both disturbances are unfortunately of the same order as the displacement to be sensed.

After all the following relation holds,

$$\delta_w = \delta_s - \delta_\theta + \delta_f \quad (9)$$

where δ_w is the displacement of the side cutting edge due to the flank wear, δ_s the observed displacement of the machined surface, δ_θ the displacement due to the thermal expansion of the tool, and δ_f the deflection of the tool due to the feed force.

The thermal displacement δ_θ is determined by the cutting temperature θ_w for definite tool and work piece. That is,

$$\delta_\theta = K_\theta \theta_w \quad (10)$$

where K_θ is a constant to be determined experimentally.

Similarly δ_f is expressed as follows,

$$\delta_f = K_f F_f \quad (11)$$

where F_f is the feed force and K_f is a constant to be experimentally determined.

Substituting Eqs. (10) and (11) into (9), the following expression for flank wear is obtained,

$$\delta_w = \delta_s - K_\theta \theta_w + K_f F_f \quad (12)$$

3.2 Measuring circuit

Figure 19 illustrates the block diagram for measuring the tool wear. The primary detector to measure

Fig. 17 Setup of detector

(a) Low-pass filter circuit

(b) Example of recording
Fig. 18 Electric smoothing-out

the relative displacement of the machined surface δ_s is an electric micrometer head of a differential transformer type as shown in Fig. 20. The feeler point is a sintered carbide sphere of 1 mm diameter which would never wear appreciably even after an extremely long run.

The feed force and the cutting temperature can be measured by a tool dynamometer of wire strain gauge type and tool-work thermocouple method, respectively, and after passing through the low-pass filter, both outputs are multiplied by K_f and K_θ , respectively, by means of a potentiometer. $K_\theta \delta_w$, $K_f F_f$ and δ_s , thus obtained, are given to an analog summing circuit to obtain δ_w ($=V_B \tan \gamma$) using Eq. (12).

For a sensor of on-line performance, however, it is desirable to cancel out the two terms of disturbances automatically instead of obtaining the constants involved in Eq. (12). The setup for this is shown in Fig. 21, in which the feeler of a compensating detector is supported in contact with the free surface of the tool tip immediately behind the

Fig. 19 Block diagram for compensation

Fig. 20 Structural view of detector

Fig. 21 Setup of detector

active cutting edge. It is assumed that the thermal displacement at the compensating detector δ_θ' is proportional to that at the active cutting edge δ_θ , as

$$\delta_\theta = k \delta_\theta' \quad (13)$$

where k is a proportionality constant.

On the other hand, the deflection due to the feed force can be minimized by utilizing a tool holder of high rigidity, and furthermore it can be almost compensated automatically by the compensating detector except for the vibratory displacements of rather high frequencies. In order to avoid the transient disturbance caused by the initial deflection of the tool, an electric signal is generated to start the measurement and at the same time to set the zero point of the output to be sensed.

Thus, the displacement merely due to the flank wear δ_w can be obtained from Eqs. (9) and (13), neglecting the term of cutting force.

$$\delta_w = \delta_s - k \delta_\theta' \quad (\delta_f = 0) \quad (14)$$

where δ_s is the output by the primary detector.

For determining the constant k a specially designed experiment where the work material (0.45% carbon free cutting steel), the tool (P10 sintered carbide) and the cutting conditions (cutting speed 100 m/min, feed 0.1 mm/rev) were chosen so as to produce only a negligible tool wear was conducted. Figure 22 shows the result in which the displacement by the primary detector δ_s and that by the compensating detector δ_s' are plotted with regard to the cutting time, and the relation between δ_s and δ_s' is illustrated in Fig. 23. Assuming that the tool wear is negligible at least until the cutting temperature around the active cutting edge reaches the stationary state, the output sensed by the primary detector δ_s should be nearly equal to the thermal displacement at the active cutting edge δ_θ . Consequently,

$$\delta_s = \delta_\theta = k \delta_\theta' \quad (\delta_w = 0, \delta_f = 0) \quad (15)$$

where

$$\delta_s' = \delta_\theta' \quad (\delta_f = 0) \quad (16)$$

Material cut: 0.45% carbon free cutting steel (S45CF)
Tool: P10 carbide (0, 0, 6, 6, 15, 0, 0.5)
Cutting speed: 100 m/min, Feed: 0.1 mm/rev
Depth of cut: 2.5 mm

Fig. 22 Output by primary and compensating detectors when tool wear is negligible

According to the result shown in Fig. 23, δ_s is approximately equal to δ_s' . Therefore, k can be regarded as nearly unity, so that, from Eq. (14),

$$\left. \begin{aligned} \delta_w &\approx \delta_s - \delta_s' \\ \text{or } \delta_w &\approx \delta_s - \delta_s' \end{aligned} \right\} \dots\dots\dots (17)$$

This means that the deflection of the tool due to both the thermal expansion and the cutting force can be satisfactorily compensated by mounting the compensating detector as long as its location is close enough to the active cutting edge. Here, of course, it is essentially important for the detectors not to be bothered by the chip disposal, this being accomplished by utilizing an adequate chip guards.

Figure 24 shows a recorded example of the displacement originated by the tool wear δ_w which was obtained by means of the approximate compensation based upon Eq. (13). The comparisons of thus obtained displacement due to the tool wear with that measured by the conventional off-line method are illustrated in Fig. 25, which will verify a satisfactory agreement and validity.

3.3 Data processing

As seen in Fig. 24, the output signal of the tool wear contains various noises originated by the irregularities of the worn surface of the tool, the weldings at the cutting edge, etc., of which frequency is usually too low to be filtered out electrically. The authors' attempted remedy is to sample out the signals with a certain period and store the data, then

Fig. 23 Comparison of output by primary and compensating detectors when tool wear is negligible

Fig. 24 Example of recorded displacement due to tool wear

to carry out the regression analysis by a digital computer, and finally to obtain the regression curve with a certain confidence limit. Thus the tool life is predictable, which is one of the important parameters involved in the performance index for the optimizing control of the machine tool.

4. Electro-optical method

An off-line performance sensor is also investigated for the accomplishment of more direct measurements of the tool wear. It will be useful not only for the sampling examination of the validity of the data obtained by the aforementioned on-line type of sensors but also for the on-line sensing of the tool wear in an intermittent cutting process such as milling.

The electro-optical device developed by the authors consists of a microscope furnished with a vidicon followed by a delaying trigger circuit, a gate circuit, a high speed pulse counter or an integrator, as shown in Fig. 26. The image of the properly illuminated flank wear is magnified by the microscope and transmitted to the vidicon screen as seen in Fig. 27. The output of the vidicon is proportional to every brightness along the line scanning the magnified image of the flank wear, as shown in Fig. 28. A single scanning line produces a rectangular shape of which width corresponds to the width of the flank wear. In order to pick up a single scanning line out of the numerous, a synchronized signal produced by the first scanning line makes a trigger signal delayed by the delaying circuit, which opens the gate connected with the vidicon output, as shown in Fig. 29. By properly choosing the duration of the gate opening, the out-

Fig. 25 Relation between sensed displacement and optically measured width of flank wear

put of the single line, or two, three or more lines, if necessary, can be deduced.

In case where the shape of the wear land is irregular, it is advisable to average out the outputs from several scanning lines.

5. Conclusion

For the optimization control of a lathe referring to tool life, three types of sensor have been developed. The variation of cutting force is proportional to the width of flank wear, and the proportionality constant has a close relation with the elastic limit or hardness of the work material. This characteristic is extremely valuable for reducing the number of the controlling parameters. The continuous and semi-direct measurements of the flank wear by way of the relative displacement of the surface

machined by the side cutting edge have led to a highly reliable sensor for the on-line performance. The major disturbances due to the temperature rise and the cutting force can be satisfactorily eliminated by utilizing the primary and compensating detectors. The electro-optical sensor, which gives more direct information on tool wear, is applicable as a semi-on-line performance sensor or a checking sensor.

References

- (1) R. M. Centner and J. M. Idelsohn: *Application of Adaptive Control to Manufacturing Processes*, 3rd I.F.A.C. Conference, Session 27, Paper 27 C, (1966-6).
- (2) G. F. Micheletti and R. Levi: *Relationship between Cutting Forces and Tool Wear in Steel Turning*, Contributed at 7th International Machine Tool Design and Research Conference, (1966-9).
- (3) H. Takeyama and R. Murata: *Trans. ASME, Ser. B*, Vol. 85, No. 1 (1963), p. 33.

Fig. 26 Block diagram of electro-optical sensor

Fig. 27 Magnified image of wear land in scanning plane

Fig. 28 Output of vidicon

Fig. 29 Processing of scanning lines of vidicon

Discussion

I. YOSHIMOTO: (1) In the first method, in which the flank wear is estimated through the cutting force, the variation of cutting force is significant. In order to figure out the accuracy of estimation of flank wear, a more expanded scale of the ordinate will be desirable. Also in the second method, the sensing accuracy can be estimated from Fig. 25. So, it will be necessary to examine quantitatively to what extent the sensing accuracy in both methods influences upon the whole system to be controlled.

S. INABA: The final problems to be approached for a substantial improvement of accuracy in numerically controlled machine tools are those of tool wear and tool deflection. From this point of view this paper is highly appreciated. However, the discussor has two questions;

(2) Isn't there any influence of feed rate upon the results of measurement?

(3) Is there any means to improve the machining accuracy by sensing the tool wear?

Authors' closure

(1) For an off-line regression analysis the ordinate should be expanded as the discussor points out, although it does not matter for the on-line control.

The measuring error of tool wear, $\Delta V_B/V_B$, will be expressed in relation to A and B in the tool-wear characteristic equation $V_B = At^B$ as follows:

$$\frac{\Delta B}{B} \doteq \frac{\Delta V_B}{V_B}, \quad \frac{\Delta A}{A} \doteq \frac{\Delta V_B}{V_B}$$

where V_B is the width of flank wear, t is time, A the function of cutting speed and B a constant. At the present stage the object to be controlled is cutting speed. According to the experimental results cutting speed is approximately proportional to $A^{1/1.51}$. Therefore, the effect of measuring error of V_B will

be minor (less than 10 percent), so that there will be no fear of miscontrol.

(2) If there is a quick change of feed rate, there must be an undesirable effect since there is a phase difference between the primary and compensating sensors, as pointed out by the discussor. However, it will be possible to control the system by avoiding the transition time. Furthermore, since the parameter to be controlled is only cutting speed at the present stage there will be no problem.

(3) Machining accuracy will be also considered in connection with the performance index or constraints. Conceivable approaches are feed-back control by on-line measurement of a work piece dimension and indirect compensation by a computer after sensing cutting force, temperature, tool wear, etc.

Errata (Vol. 11, No. 48, December, 1968)

Author	Page	Column	Line	For	Read
K. SATO	1029	left	2 from bottom	deflection	deflection
	1030	Eq. (21)		$d\left(\frac{F}{\beta^{1/2}}\right) \dots$	$d\left(\frac{\dot{F}}{\beta^{1/2}}\right) \dots$
	"	Eq. (22)'		$\left(\left \sqrt{\frac{\beta}{\alpha}}\right \frac{F}{\sqrt{\beta}}\right)^2 =$	$\left(\left \sqrt{\frac{\beta}{\alpha}}\right \frac{\dot{F}}{\sqrt{\beta}}\right)^2 =$
	1034	left	10 from bottom	$f_1 \ (i=0, \dots$	$\dot{f}_1 \ (i=0, \dots$
	"	Eq. (41)		$\dots \left\{ \frac{1}{2} \frac{a^2}{r^2} \frac{f_0 f_2}{f_3} + \frac{f_1}{f_3} - \frac{f_2}{f_3} \frac{P_0 l^2}{EI} \right\}^{1/2},$	$\dots \left\{ \frac{1}{2} \frac{a^2}{r^2} \frac{\dot{f}_0 \dot{f}_2}{\dot{f}_3} + \frac{\dot{f}_1}{\dot{f}_3} - \frac{\dot{f}_2}{\dot{f}_3} \frac{P_0 l^2}{EI} \right\}^{1/2},$
"	"	left	2 from bottom	by f_i	by $\dot{f}_i$
K. KASAI	1070	left	5	mass	weight
T. KUSUI	1085	Fig. 2, Scale of a vertical axis		Uniform scale	Scale of error integral function, only positions of 0.1 and 0.9 are correct
	1090	References (7)		Цяцко Технической Москав	Цяцко технической Москва
T. MAEDA	1102	right	2 from bottom	throughout	throughout
	1103	Fig. 3		Alminum	Aluminum
	1106	left	3	∂_0/u_0	v_0/u_0
	1110	Eq. (60)		$\phi_0 = B\eta_0^{1/m}$	$\phi_0 = B\eta_0^{1/m}$
	1111	Eq. (72)		$\dots / [1 + (v_0/u_0)\phi_0^2]$	$\dots / [1 + (v_0/u_0)\phi_0^2] d\eta_0$
I. TANISHITA et al.	1168	left	13	for	far