EVALUATION OF CUTTING FLUIDS BY A NEW CRATER WEAR MEASURING METHOD

By

I. KALÁSZI

Department of Production Engineering, Technical University, Budapest

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1. Introduction

Evaluation of cutting fluids has long been presenting difficulties to tool engineers. While there is a reliable method for determination of oiliness, the four-ball technique, no satisfactory laboratory process has been developed for cutting fluids' evaluation so far. *Cutting fluids can only be evaluated reliably by cutting procedures*. This is a known fact. The best information on cutting fluids has been achieved through conventional and expensive tool life tests.

All over the world attempts are being made to develop new, efficient cutting fluids. Chemical research is generally time-consuming and expensive. To spare time and cut expenses, short-run tests are preferred to long-time techniques. Some of these attempts are worth mentioning. Plastic deformations taking place in the cutting zone are subject to several effects [1]. One of these is the friction between tool and chip, influencing the chip ratio. In the early fifties MERCHANT proposed to use this parameter [2], which really suits to distinguish between cutting fluids of different activity and effect, when cutting at a given speed. Unfortunately, chip ratio ξ depends on speed and HALL established that the curve $\xi = \Phi(v)$ had two peaks in the range $v = 1$ m/min $- 90$ m/min [3]. Consequently, tool life equations cannot be derived from chip ratio.

Infeed cutting experiments were initiated in several countries simultaneously [4]. Various cutting fluids were applied for a given workpiece and tool material. The cutting fluid permitting most infeeds up to the tool's becoming dull was considered the best one. This method proved more reliable and approaching the optimal procedure testing the cutting phenomena in complexity. Its disadvantage is the considerable dependence on cutting geometry.

Recently, the firm Fletcher-Miller published a new method [5]. They measured the chip length cut from test pieces of certain size by means of a single edge put at 45° to cutting direction on a modified, external broaching machine. In principle, chip deformation is measured, but the oblique position of edge may indicate an excessive deformation. This technique is of the same disadvantage as that of MERCHANT.

In 1963, Author proposed in Hungary the use of a recently developed method for wear measuring (6). The Hungarian firms and institutes which have taken over this method in the meantime gained a lot of practical experience. Using this method not a certain "number" but the *Taylor equation itself* is achieved; its constant and tool life exponent determine the efficiency of cutting fluids to be applied at given cutting conditions. The costs involved — even at the lowest estimate — are reduced to the fifth of the expenses arising at long-time tests. Even, it is practically proved that a reduction to the eighth, and even to the tenth is possible. As a matter of fact, financially this method is not yet as favourable as the four-ball technique used in lubrication tests, but its reliability must be kept in mind.

Following a suggestion from Hungarian side, the competent ISO commission, at present formulating a Standard for Tool Life Tests, adopted a new parameter (width of crater) thus making possible to gather sufficient experience and results on the new method gaining ground in Hungary and its incorporation into the International Standard at a later time (7).

2. Wear and Taylor equation

The well-known Taylor equation is written as

$$v = \frac{C_v}{T^m} . \tag{1}$$

where v is the cutting speed (m/min), T is the tool life (min), C_v is the speed belonging to 1 minute of tool life and m is the so-called Taylor exponent.

The dimensional analysis made by KRONENBERG [8] established that relationship between the following physical quantities is included in the Taylor equation:

Physical quantity	Dimension	Symbol
Temperature at tool	Θ	τ
Tool life	T	T
Chip cross-sectional area	L^2	A
Unit cutting force	$M \cdot L^{-1} \cdot T^{-2}$	F
Cutting speed	$L \cdot T^{-1}$	v
Consolidated heat value (the product of specific gravity, specific heat and heat conductivity)	$M^2 \cdot T^{-5}; \Theta^{-2}$	H

Using the above symbols and dimensions of each quantity in terms of temperature (Θ), time (T), length (L) and mass (M) the temperature equation

$$\tau = \frac{C_\Theta F A^n}{H^{0.5}} v^{(1-2n)} T^{(0.5-2n)} \tag{2}$$

will be obtained, where C_Θ and n are constants; this can be proved experimentally. Transforming this equation and applying $m = \dfrac{0{,}5-2n}{1{,}0-2n}$ the Taylor equation will be

$$v T^m = C_v . \tag{3}$$

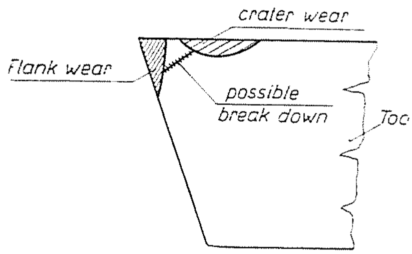

Fig. 1. Effect of the wear simultaneously arising both on the rake face and on the flank controls the break down. The Taylor equation represents this complex relationship

KRONENBERG proved constant n to range from 0 to 0.250. Consequently, when cutting steel and metal, exponent m rangs between 0.5 and 0. (It does not concern ceramics.)

If A and H are constant values in Eq. 2, the cutting fluid applied will influence temperature τ and cutting force F and as a consequence, the values of the temperature equation will be altered. The constant values C_v and m in the Taylor equation derived from the temperature equation will also change.

Thus, the Taylor equation is the mathematical formulation of the complex relationship shown in Fig. 1.

The tool shown in Fig. 1 can be used for cutting up to time T, when the edge — due to the simultaneous wear effect both on the rake face and on the flank — looses its strength and breaks. *In fact, the wear depending on physical quantities is implied in the equation !* Increase of chip cross section A will entail the increase of the force F and temperature τ as per temperature equation (2). So wear will be greater. In order to keep Eq. (2) unchanged, T value must be lower.

Similarly, higher speed will cause higher temperature and wear must be greater, but in turn T lower.

Therefrom it is clear why the Taylor equation has always been determined from wear. In the practice of long-term tool-life tests, one of the dimensions of either the flank wear or crater wear has been measured as a function of time (Fig. 2).

When the dimension of wear scar versus cutting time shows sharp gradient, the period of cutting belonging to this time is considered the tool life. This procedure is approved but not suitable for short-run tests. Namely, for observation of volume borne phenomena, a single parameter is used, for example dimension of flank wear Δ (see Figure 4). Δ depends on the workpiece

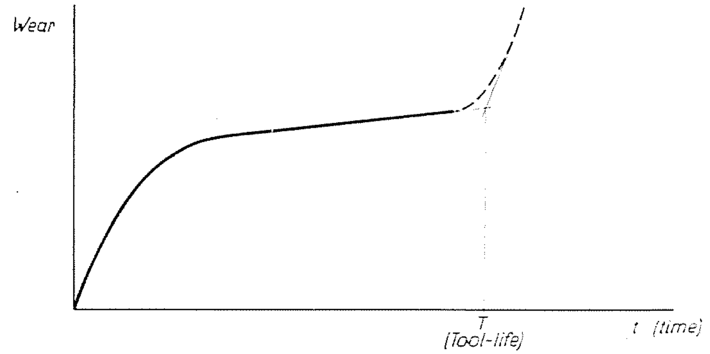

Fig. 2. Conventional method to evaluate the tool life: checking the slope change of the wear curve in the temperature sensitive region

diameter and other geometrical conditions. Wear curves demonstrated in Fig. 3 are known to research workers. Under similar cutting conditions for $t < t^*$ the first tool has more favourable wear features, while for $t > t^*$ the second tool proves better. This fact makes no difficulties when performing long-time tool life tests, but does not permit interpolation. According to Fig. 3 there is an other contradiction, i.e. Δ values measured at $v = 120$ m/min show greater wear up to t^* than those of tool number 1 for $v = 150$ m/min. The possible reason for this contradiction has thoroughly been investigated by the author (9). The results obtained led to the following proposal.

3. Wear cross-section measurement as new technique

The author proposed to observe the *cross-section* of wear at the unit length of edge! It is advisable to consider the changes of A_Δ or A_{kr} areas as a function of time (Fig. 4).

If wear volume is $V = \varphi(t)$, then at the edge of unit length $l = 1$ mm the wear will be $V = A.1$ and we may come to the reliable conclusion that wear ratio is

$$\frac{dV}{dt} \cong \frac{dA}{dt}$$

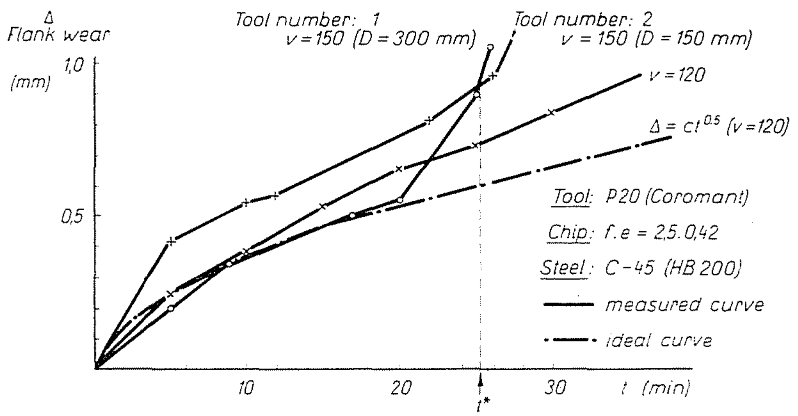

Fig. 3. Contradiction of the Δ flank-wear measurement: Tool No. 1 shows a better wear resistance than tool No. 2 in similar cutting conditions for $t < t^*$, the situation changes for $t^* < t$. The $v = 120$ curve shows less favourable wear features than does curve of $v = 150$; up to a given cutting time, however, it runs longer

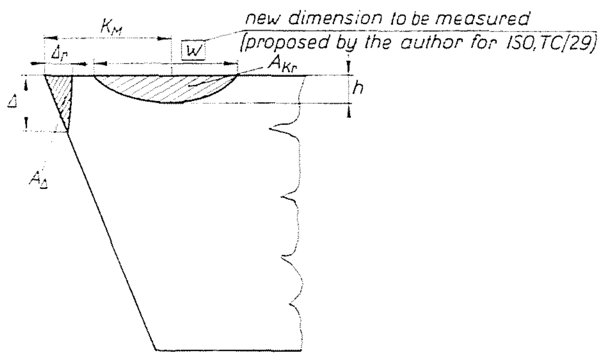

Fig. 4. The usual wear dimensions. Author's proposal is to measure w instead of K_M for the sake of evaluating the area of the crater cross-section $A_{Kr} \cong 2/3\ w.\ h$. On the same principle, $A_\Delta = \Phi(\Delta_r, \Delta)$ is to be used as the area of the flank wear cross-section

Evidently, wear volume comprises the effects of several wears. Qualitatively it may be written according to Takayama and Murata [10]:

$$V = V_A + V_B + V_D + V_I\,, \tag{4}$$

where subscript A refers to abrasive wear, subscript B to fatigue crack, D to the diffusion and I to unknown wears.

Our present knowledge is not sufficient to calculate Eq. 4 in advance, but it can be measured as a function of time. Wear may generally be written by the following formula:

$$V = Ct^n, \tag{5}$$

where C and n may assume different values, depending on conditions. Rate of wear which is characteristic for the wear process is

$$\frac{dV}{dt} = (n-1)\, Ct^{(n-1)}. \tag{6}$$

Along the unit length of edge, for example in case of crater wear:

$$\frac{dA_{kr}}{dt} = (n-1)\, C_{kr}\, t^{(n-1)} \tag{7}$$

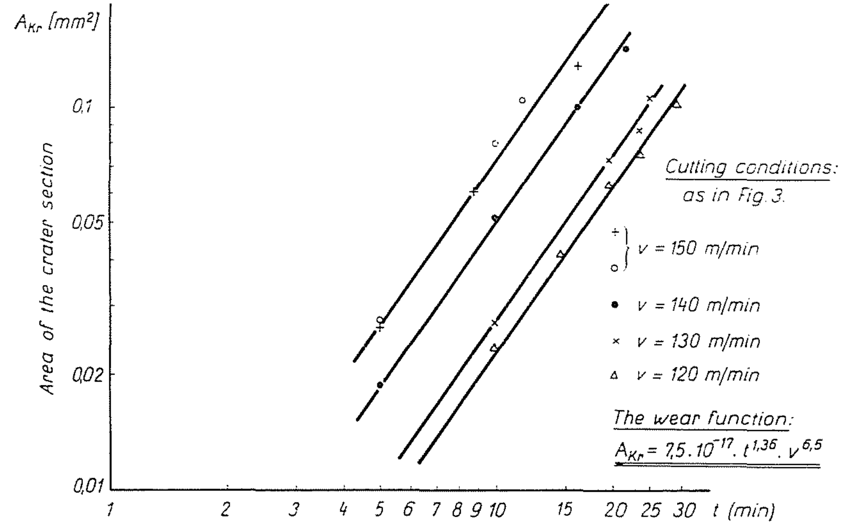

Fig. 5. Area of the crater section versus time, plotted in log-log diagram. When cutting at various speeds it is possible to derive wear function $A_{Kr} = \Phi(t, v)$ numerically or graphically

Because — depending on cutting fluid and other conditions — n may be $\gtreqless 1$, it is expedient to plot log-log diagram of wear to obtain a straight line interpolable for any value of n. $A_{kr} = \Phi(t)$ curves are plotted in Fig. 5, drawn at four different speeds, for the same cutting conditions and tool-tips as in Fig. 3. This conception is used when testing the effects of cutting fluids.

4. Comparison of emulsions by crater cross-section measurement

At the Department of Production Engineering, Technical University, Budapest, investigations are going on according to the method described, for some years. Certain modifications have recently been made, i.e. following the Draft of ISO TC/29 (7) the research workers use the tools and workpieces suggested. Recently, in the course of a large experiment series they had to compare four emulsions mixed from four different soluble oils (11).

Emulsion mixed from oil WE-150 L (12) applied from the beginning of their research work, served as reference. It is to be explained how they obtained the Taylor equation as a result of their experiments made with water based fluid of 5% WE-150 L.

4.1. *Cutting conditions*

a) *Machine-tool:* Centre lathe Type E-500, made in Hungary (With stepless range of speeds.)

b) *Workpiece:* C-45 (Hung. Standard MSZ 6152) carbon steel, normalized.

Composition:

C	Mn	Si	P	S
0.43	0.68	0.23	0.026	0.022

Strength: $\sigma_B = 67.8-70$ kp/mm^2, $\delta_5 = 9\%$

c) *Tool material:* High-speed steel R3 (MSZ 4351-62) (international marking 18-14-1), hardness: 63 HRC $\pm$ 1 HRC

Tool material was used in tip form. Conditions, as suggested by ISO TC/29 were: $\alpha = 6°$, $\gamma = 14°$, $\varkappa = 75°$. During experiments various cutting speed values were taken from $v = 30$ to 38 m/min. Depth of cut was $f = 2.5$ mm, feed $e = 0.4$ mm/rev., as per ISO TC/29, 3rd class.

Wear measurement: In the section perpendicular to the main cutting edge the crater width and depth were examined by Schmaltz light-section technique. Area was determined both by calculation from the two dimensions (depth and width of crater) and by planimetration of the section area photographically registered.

4.2. *Results*

Fig. 6 shows the changes of crater section area versus time at four various speeds. There is no need to measure over $t = 14$ minutes, thus this method presents a ***short-run technique***. At speed 38 m/min, $t = 10$ min the crater wear reached the edge which was considered ***tool life point***, where the crater section area was 0.350 mm^2. At these experiments feed e equalled 0.4 mm, therefore the undeformed chip thickness perpendicular to the edge — for a position angle $\varkappa = 75°$ — was $e_k = 0.38$ mm.

It was experimentally stated that on testing the conditions perpendicular to the edge, changes of depth of cut might be neglected. Changes of e_k at $e = 0.25$, $e = 0.4$ and $e = 0.63$ mm/rev. were, however, observed, while all the other cutting conditions were unchanged. By graphical analysis the wear function

$$A_{kr} = C_{kr}\, t^{0.58}\, v^4\, e_k^{2.6} \tag{8}$$

was obtained. Tool life equation can be derived from this equation. Using the related points A_{kr}, t, v, e_k of the measurings, the value of C_{kr} wear constant may be computed: $C_{kr} = 5.464 \cdot 10^{-7}$.

5. Deriving T-v equation from crater wear function

According to the results obtained in dimensional analysis referred to in chapter 2, the wear function leads to the Taylor equation when solving for cutting speed v.

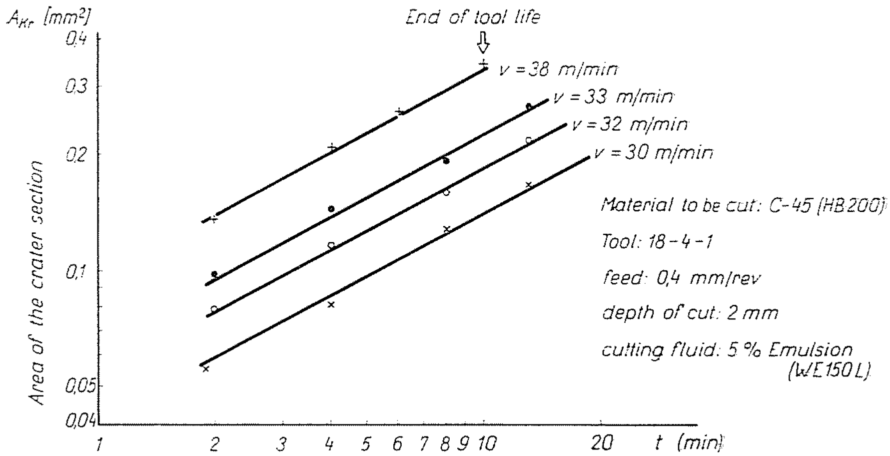

Fig. 6. Area of the crater section versus time when cutting with emulsion, at four cutting speeds. The four tests run during $t \leq 12$ min only. Log-log diagrams lend themselves to interpolation

Considering the real value of C_{kr} measured at the experiment mentioned in chapter 4 and solving equation 8 for v we have:

$$v = \left[\frac{A_{kr}}{5.464 \cdot 10^{-7}}\right]^{1/4} \cdot \frac{1}{t^{0{,}58/4} e_k^{2.6/4}} \cdot \tag{9}$$

Practically, the Taylor equation is obtained.

The first term in brackets presents C_v value, tool life exponent is $m = \dfrac{0{,}58}{4} = 0.14$ and exponent e_k is $y = \dfrac{2.6}{4} = 0.65$. For calculation of C_v value one tool life point must be known. At $v = 38$ m/min. its occurrence was stated at $A_{kr} = 0.350$ mm² (see Fig. 6). Substituting this value into the first term of Eq. (9) the constant will be

$$C_v = \left[\frac{0.350}{5.464 \cdot 10^{-7}} \right]^{1/4} = 29.06$$

and the Taylor equation yields:

$$v = \frac{29.06}{T^{0.14}\, e_k^{0.65}}\,. \tag{10}$$

To set an example, let us examine the speed at $T = 60$ min. given by the Standard Data adopted by the Hungarian Ministry for Metallurgy and Machine Industry (13). Conditions: $f = 2.5$; $e_k = 0.38$ ($e = 0.55$, for $\varkappa = 45°$) and $\sigma_{Bsteel} = 75$ kp/mm^2. In the tables $v = 28.5$ m/min. indicated for not defined normal cooling for tool material 18-4-1. In this special instance, using Eq. (10), speed

$$v = \frac{29.06}{60^{0.14}\, 0.38^{0.65}} = 31\text{m/min}$$

is permissible. That means that the emulsion applied in the experiment allows 10% increase in speed for the same tool life, or improves tool life for a speed 28.5 m/min given by Standard Data as follows:

$$\left[\frac{v_2}{v_1} \right]^{1/0.14} = \left[\frac{31}{28.5} \right]^{7.1} = (1.085)^{7.1} = 1.78\,.$$

Thus, the results are superior to those of Standard Data using the above given cutting fluid.

6. Conclusions

1. Efficiency of cutting fluids may be evaluated from a cutting process only.

2. Even in our days, long-time cutting tests incorporate the most reliable techniques, leading to the Taylor equation. Their disadvantage lies in their time-consuming and expensive nature.

3. When observing volumetric wear phenomena of cutting tool, one wear parameter is not sufficient for correct evaluation and no short-run method can be performed.

4. Both wear on the flank and crater wear is well characterized by the wear section area which can be measured or calculated in the section perpendicular to the edge and its interpolation in log-log diagram is possible for any type of wear. This, requires the knowledge of at least two wear parameters.

5. Observation of crater section area versus time presents a simple evaluation and may be expressed as a wear function derived graphically or numerically. This may be transformed into a tool life equation, enabling evaluation under both wet and dry cutting conditions.

Summary

A new and less expensive short-run crater wear test for evaluation of cutting fluids is presented. The results obtained by this method make possible to set up wear functions in mathematical form which lead to the Taylor equation when solving for cutting speed. Its use in Hungary for high speed or carbide tool life test has recently been introduced. The application of this method to evaluate water based fluids is shown through an example.

References

1. Rice, W. B.—Salmon, R.—Advani, A. G.: Effects of cooling and heating workpiece and too on chip formation in metal cutting. Int. J. of Machine Tool Design and Research **6,** 143—152 (1966).
2. Merchant, M. E.: The action of cutting fluids in machining. Iron and Steel Engineer. 1950. No. 11.
3. Hall: Ein Beitrag zur Abgrenzung der Wirkungen von Kühlung und Schmierung eines Kühlschmiermittels auf die Zerspanung von Stahl. Werkstattstechnik, 1959. No. 5.
4. Kunowski, F.: Kühl- und Schneidflüssigkeiten für die Metallbearbeitung. TZ für praktische Metallbearbeitung, **54,** 583—594 (1960).
5. Properties and Utilization of Cutting Fluids. Fletcher-Miller Ltd., 1963.
6. Kalászi, I.: Investigation of wear phenomena in metal cutting. Dissertation, presented at the Hungarian Academy of Sciences, Budapest, 1963.
7. Merchant, M. E.: Tool-life test. Draft Proposal for ISO TC/29. Paris, 1968.
8. Kronenberg, M.: Ultra high speed and other metal cutting phenomena explored by dimensional analysis. ASTME paper **61,** 331 (1961).
9. Kalászi, I.: A corrected method for the determination of flank wear on the single point cutting tool on turning steel. Acta Technica Academiae Scientiarum Hungaricae **53,** 73—89 (1966).
10. Takeyama, H.—Murata, R.: Basic investigation of tool wear. ASME paper, No. 61—WA—92. New York, 1962.
11. Research report. No. 4—1968. BME Gépgyártástechnológia Tanszék, Budapest.
12. Emulsol WE—150 Lf. Firma GEROVE, Cottbus, German Democratic Republic.
13. Standard Data for turning with single point tool. Published by KGM, 1950, Budapest.

Prof. Dr. István Kalászi, Budapest, XI., Stoczek u. 2—4, Hungary