RELATION BETWEEN CUTTING FORCE AND TOOL FORM IN TURNING OF ALUMINIUM ALLOY

By

Á. Kardos

Department of Technology of Machine Production, Polytechnical University,
Budapest

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1. Introduction

To estimate the cutting characteristics and machinability of a given material, in addition to the tool life attainable under the given conditions, cutting force and/or cutting performance are employed.

Machinability will always express the interaction between work and tool. It is, therefore, readily understandable why research workers studied, even in the earliest stages of cutting experiments, what tool formation would best promote the achievement of optimum cutting conditions. Time [1] dealt with this problem already in 1870 in a paper, and Taylor [2] developed a tool having a special form for economic cutting purposes.

In the course of the last 50 years various experiments were carried out in the field of the relation between cutting force and tool form (*e.g.* [3], [4], [5], [6], [7] and [8]). In the course of these experiments, generally the main cutting force was measured. This measurement method is easily understandable as, with respect to tool load and cutting power requirements, the magnitude of the main cutting force may be considered as the most significant of all cutting force components.

In order to measure the main cutting force when turning, the Department of Machine Production Technology elaborated dynamometer types operating on mechanical [9], hydraulic [10], pneumatic [11], plastic deformation [12], and electric [13] principles, respectively. The present paper deals with the experiments conducted by means of an apparatus [14] operating on elastic deformation principles and equipped with strain gauges.

2. Experimental

The purpose of the experiments was the determination of the relation between tool form and main cutting force on an experimental aluminium alloy (2.8% Cu, $\sigma_B = 24$ kp/mm^2, $HB = 61$ kp/mm^2). The tests covered the determination of the effects exerted on the main cutting force by relief angle (α), rake angle (γ), main cutting edge entering angle ($\varkappa$), end cutting edge angle (τ), and nose radius (r).

For experimental purposes, informatory data had been supplied by measurements performed in the course of tool life studies [15] and different dynamometer investigations [11]. These data have been completed by preliminary measurements made in order to promote the preparation of the detailed program of present force measurement tests.

In accordance with the aforementioned conditions, the experiments were conducted by employing a cutting speed of $v = 280$ m/min. For the individual measurements, speed deviation amounted to 10 m/min-max, as compared to the above value. The relief angle of the secondary cutting edge was, in each case, $\alpha' = 10°$, the cutting edge inclination being $\lambda = 0°$. Tool grinding has been effected by means of tool edging machine using a grinding wheel of 80 degree fineness. According to the control measurements performed with a shop microscope, tool angle deviation as compared to the given values amounted to maximum $\pm 0.5°$. The experimental set-up is illustrated in Table 1. Evaluation of the measurement results were accomplished partly by graphic and partly by semi-graphic techniques.

Table 1

$f_{(mm)}$	$e_{(mm/rev)}$	$\alpha_{(o)}$	$\gamma_{(o)}$	$\varkappa_{(o)}$	$\tau_{(o)}$	$r_{(mm)}$
1. 1—3	0.1—0.487	6—15	30	45	15	0.5
2. 1—3	0.1—0.475	10	20—40	45	15	0.5
3. 3.5	0.1—0.475	10	30	45—90	15	0.5
4. 3	0.2—0.69	10	30	45	5—35	0.5
5. 3	0.2—0.69	10	30	45	15	0.5—3

1. Results of the experiments performed to determine the influence of relief angle exerted on the main cutting force are presented in Figures 1 and 2. Fig. 1 shows the measurement results obtained with cut depths of $f = 1$ mm and $f = 2$ mm, respectively, whereas those for a cut depth of $f = 3$ mm are shown in Fig. 2.

Investigations conducted with a cut depth of $f = 1$ mm did not show a unequivocal relation due to the scatter of the measurement points. According to the curves plotted, cutting force does not decrease significantly with an increased relief as compared with the experimental results obtained with cut depths of $f = 2$ mm and $f = 3$ mm. This might be attributed to the fact that in course of investigations performed with a small depth of cut, cutting has to a considerable extent been made by the rounded-off part of the tool and in this part, the influence of the secondary cutting edge relief angle was con-

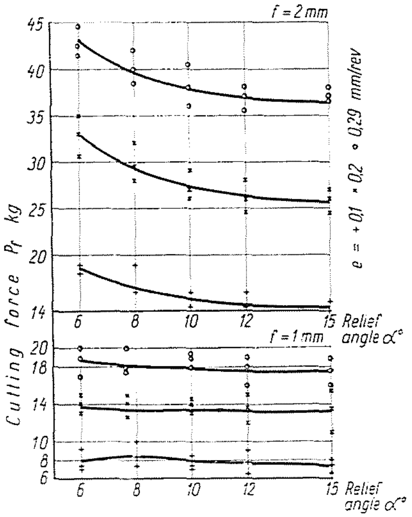

Fig. 1

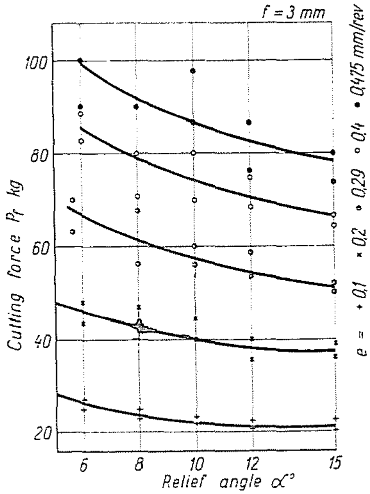

Fig. 2

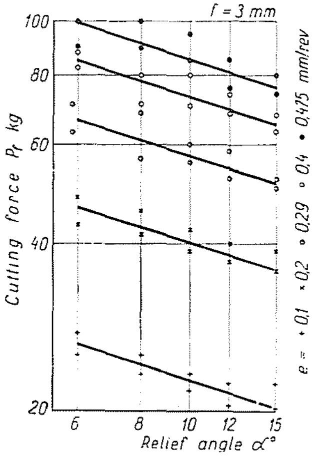

Fig. 3

stantly maintained during experiments and manifested itself to a significant degree.

According to the investigations performed with cut depths of $f = 2$ mm and $f = 3$ mm, cutting force decreased significantly with a relief angle increased to $a = 12°$. This is due to a twofold reason: the friction of the back section against the cutting surface is reduced by the increased relief angle and, on the other hand, the quantity of the particles adhering to the back section from the material which is cut is similarly reduced.

When determining the relation of relief angle to cutting force, measurement results were illustrated by means of a double logarithmic chart as well

(Fig. 3, $f = 3$ mm). According to the calculations, the relation of cutting force to relief as under the experimental conditions may be expressed by the following formula:

$$P_f = \frac{C_a}{a^{0,3}}.$$

On the basis of the investigations so far completed it may be stated that, for the experimental and similar aluminium alloys, and taking tool strength and tool life also into consideration, a relief angle of $a = 10 - 12^\circ$ could be suggested.

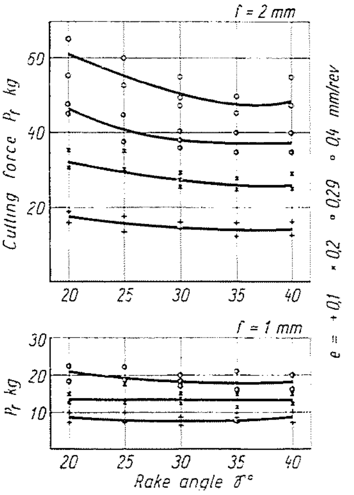

Fig. 4

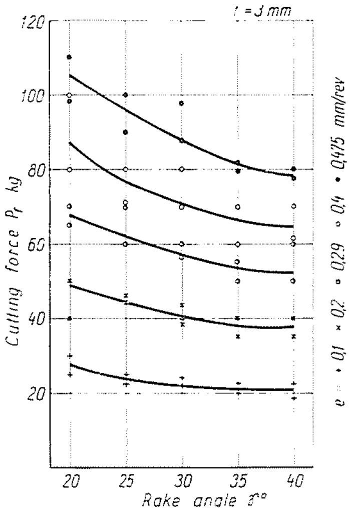

Fig. 5

2. Investigations on the rake angle effect were similarly performed with cut depths of $f = 1$, 2, and 3 mm, respectively. The measurement results are presented in Figures 4 and 5.

Measurements made with a cut depth of $f = 1$ mm did not it possible to discover a definite relation in this case, either. Such a development in the measurement results is due to the nose radius effect. These experiments, therefore, supported the fact, that the effects of the cutting angle on cutting force should be studied preferably with extended cut depths only, as compared to nose radii.

As shown by measurements made with the cut depths of $f = 2$ mm and $f = 3$ mm, respectively, cutting force will decrease with an increased rake angle. This well-known relation may well be explained by the influence of the directional angle increasing proportionally to the reduction of the true cutting angle ($\delta = 90 - \gamma$). Cutting force reduction is significant up to $\gamma = 35^\circ$. Results obtained with $\gamma = 40^\circ$ may be also explained by some factor affecting the measurement process itself. However, it seems possible that a so-called "jamming" phenomenon is encountered as soon as at this rake angle value observed like those found in certain research activities.

For demonstration purposes, the measurement results suitable to determine the relation between cutting force and rake angle have been illustrated by means of the graph shown in Fig. 6. According to the calculations, the phase $\gamma = 20 - 35°$ may be characterized by the following equation:

$$P_f = \frac{C_\gamma}{\gamma^{0,4}}$$

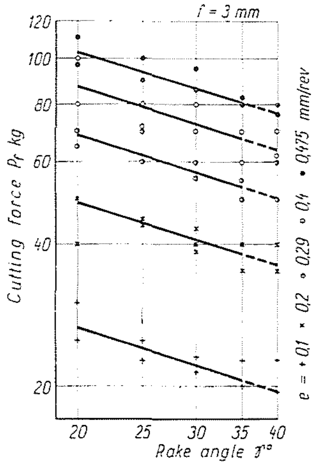

Fig. 6

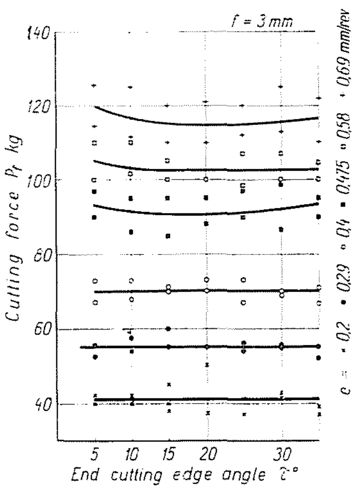

Fig. 7

From the graphs it can be seen that in the measurement range tested, the employment of a rake angle of $\gamma = 30 - 35°$ might be suggested.

3. The results of experiments conducted with a cut depths of $f = 3$ mm for testing the influence of the end cutting edge angle are presented in Fig. 7.

As is seen from this Figure, in case of a small-size feed the end cutting edge angle practically does not modify the main cutting force. With higher feed values, tha main cutting force will decrease up to about $\tau = 15°$ but will increase somewhat where greater angles are involved.

The fact according to which the influence of the end cutting edge angle is, for small feeds, negligible seems quite natural, if one is remember that the formation of the machined surface is accomplished, in such cases, mainly by the rounded part of the tool.

The secondary cutting edge effects are, however, greatly emphasized with larger feeds. Here, by using higher τ values, the edge length involved in cutting, as well as the actual chip area decrease. The reduction of either of these factors should reduce cutting force. However, measurement results, partly contradict this theoretical consideration. This contradiction (and the shape of the curves) may in the present case be explained by the chip removal process.

With a small τ employed ($\tau = 5-10°$), particles have been worked off the chips and forced in between the back section of the secondary cutting edge and the machined surface [16]. Through this process friction, and consequently, cutting force was increased. By increasing the end cutting edge angle, the number of friction particles and the cutting force have both been reduced. In the situation of $\tau > 15°$, the edge of the chip and the machined surface developed more unevenly due to the increasing inclination of the secondary cutting edge.

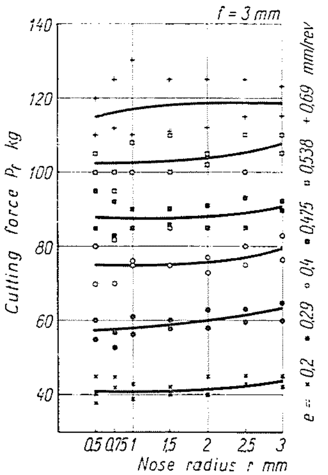

Fig. 8

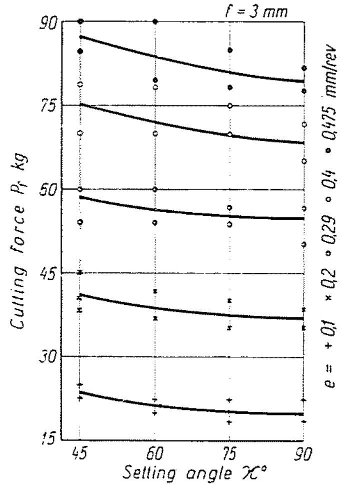

Fig. 9

This may be attributed to the fact that cutting force did not decrease any further but, in some cases, increased.

No unequivocal mathematic relation could be established, on grounds of the measurement results, between the main cutting force and the end cutting edge angle. It might be stated, however, that the magnitude of this angle in the case of the given material is best selected as $\tau = 15°$.

4. For investigating the nose radius effects, cut depth and feed values were used similar to those adopted previously. Measurement results are presented in the graph of Fig. 8.

According to the theoretical considerations and the results of the experiments completed so far, increasing the nose radius will increase cutting force as well. This could be attributed to the fact that by increasing the nose radius the edge length involved in cutting as well as the magnitude of the chip deformation factor will similarly increase.

The measurement results obtained have qualitatively and generally shown the relationship referred to above. As can be seen from the Figure quoted, cutting force will increase monotonously with an increased nose radius in case of a small feed size employed however, showing a less unequivocal modification when a larger feed size was adopted.

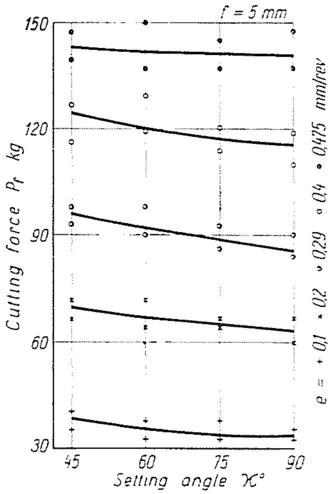

Fig. 10

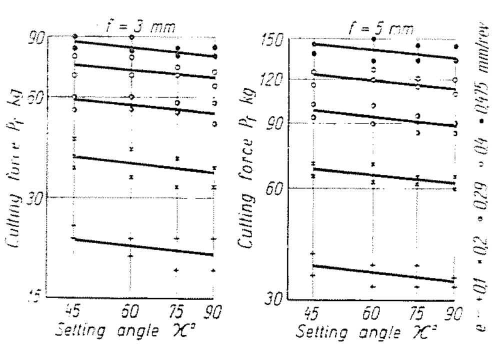

Fig. 11

As far as the nose radius is concerned, force measurements made possible the establishment of only a qualitative relationship: the general rule which seems reasonable, with respect to cutting force, is to perform cutting with a tool having the smallest possible nose radius, also applies in this case.

5. The results of experiments conducted to study the setting angle of the main cutting edge are shown in Figures 9, 10 and 11. Figure 9 presents the experimental results obtained with a cut depth of $f = 3$ mm, while Fig. 10 illustrates those given by the $f = 5$ mm depth of cut, both in a linear co-ordinate system. Fig. 11 summarizes the results in graphs of logarithmic axial scale.

As for the setting angle effects exerted on cutting force, contradictory statements are to be found in the literature. According to one point of view, increasing the setting angle from 30° to 90° will reduce cutting force. However, according to the other point of view, the force reduction is experienced only to a certain degree when the cutting force is again subsequently increasing. Both statements are supported as well as refuted by arguments in the literature. Thus, for example, RICHTER [17] reports on grounds of tests performed with steel samples that by increasing the setting angle from 40° to 90° the main cutting force will similarly increase, if fixed cutting is performed. This author explains the increase with the action of the secondary cutting edge. HORNUNG [18] at the 1st Hungarian Machine Tool Congress represented the other opinion. On the same occasion KAZINCZY [19] theoretically, proved, having selected the phenomena taking place in the chip root as a basis, that increasing the setting angle would reduce cutting force.

As the Figures show, in course of the experiments referred to above cutting force decreased with the increase of the setting angle. Calculations made by making use of the results obtained reveal that there is a similar relation between setting angle and cutting force to that found between the theoretical medium chip thickness (as calculated by means of the edge length involved in cutting) and specific cutting force. This fact explains the experimental results obtained and, simultaneously, supports the opinion represented by Hungarian research workers at the 1st Machine Tool Congress.

The numerical relation between cutting force and setting angle can be determined by utilizing the graph presented in Fig. 11. Accordingly,

$$P_f = \frac{C_\varkappa}{\varkappa^{0,13}}$$

In practice, setting angle effects are usually taken into account through correction factors. In the present case these are:

$\varkappa°$	45	60	75	90
$K_\varkappa$	1	0.97	0.94	0.92

For comparison salve, it will be noted here that Kashirin's correction factors [20] are, as calculated for steel samples and for the above setting angles, as follows: 1, 0.98, 1.03, 1.08.

Conclusions

In determining the relationship between cutting force and tool form, the following statements may be made as a summary on grounds of the experiments performed with test samples.

The relief angle effect exerted on cutting force may be considered as given by the relation

$$P_f = \frac{C_\alpha}{\alpha^{0,3}}.$$

For the material types tested and for those similar to the tested types, the magnitude of the relief angle should preferably be selected as 10° min.

By increasing rake angle, cutting force will decrease up to about $\gamma = 35°$. For this phase, the relation

$$P_j = \frac{C_\gamma}{\gamma^{0,4}}$$

applies. According to experimental results, no rake angles exceeding the value $\gamma = 35°$ are suitable for cutting the material tested, as far as cutting force is concerned.

As for end cutting edge angle and nose radius effects, a qualitative relations can be established. According to the test results, the selection of a $\tau = 15°$ end cutting edge angle is recommended. If the reduction of the cutting force is aimed at, the smallest possible nose radius should be selected.

The influence of the setting angle of the main cutting edge as exerted on cutting force may be expressed by the relation

$$P_j = \frac{C_\varkappa}{\varkappa^{0,13}}.$$

According to the investigations, there is always a lower force pertaining to greater setting angles. Force variations are explained by the variations of medium chip thickness as well as by that of the specific cutting force.

The experimental results partly supplement and, on the other hand, confirm the data found in the literature concerning steel samples.

Summary

The present paper deals with the experimental investigation on the relation of cutting force to the geometry of tools by discussing the effects of relief angle, rake angle, main cutting edge setting angle, end cutting edge angle, and nose radius variations exerted on the main cutting force for experimental aluminium alloy.

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Árpád Kardos, Budapest XI. Sztoczek u. 2—4. Hungary