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Research on the Influence of the Cutting Speed on the Specific Cutting Force During Turning

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A hypothetical graphical dependence showing the cutting speed influence on the specific cutting force when cutting ductile materials is proposed on the basis of the physical nature. Some hypothetical mathematical models for the approximation of that dependence when changing the cutting speed are shown. Trough experimental study when turning different kinds of processed material and mathematical modelling of the experimental data, new mathematical models approximating the dependence of the specific cutting force and cutting speed have been received. A new, better empiric mathematical model when referred to the structure, adequacy and accuracy is recommended.

Keywords: specific cutting force, thickness of cut, hypothetical models

1 INTRODUCTION

It has been determined by experiments that during the cutting of ductile materials when the cutting speed increases, the tangential specific cutting force decreases. This reduction is more intensive at lower cutting speeds, while at higher ones v_c > 100 to 150 m/min the cutting forces virtually do not change, i.e. the tangential specific cutting force has a constant value.

The influence of the cutting speed on the specific cutting force is most often determined by a correction coefficient, which value is selected from tables or nomograms. The formula to calculate this correction factor is given in [1]:

$$k_v = \left(100/v_c\right)^{n_v}, \tag{1}$$

This means that the specific cutting force is approximated with a mathematical model of the type:

$$k_c = b_0 / v_c^{b_1} . \tag{2}$$

The influence of the cutting speed on the main cutting force is determined in a similar way and also for the specific cutting force for steel according to [2]. For bronze and aluminum this influence is not accounted for.

According to reference data [3] for the specific cutting force the influence of the cutting speed is not taken into consideration for all kinds of cut materials $\left(b_1 = 0\right)$.

In [4], the formulas for the tangential k_t and the radial k_r specific cutting forces $k_{t,r} = f(f, v_c, a_p, a_e)$ are approximated with linear function taking into account the effects of the double influence, where f is feed per tooth, v_c - cutting speed, a_p - axial depth of cut and a_e - radial depth of face milling of aluminum alloy with milling cutter from high speed tool steel. If a_p = const, a_e = const and f = const, then:

$$k_{t,r} = b_{0tr} - b_{1tr} v_c . \tag{3}$$

In this case the approximation has sufficient accuracy because the experimental coefficients vary in very narrow range.

In [5] the dependence of the cutting forces F_c, F_p and F_f on the cutting speed V_c, feeding f, depth of cut a_p and the cutting tool nose radius r_ε in the case of finish turning of 40CrMnMo7 steel are approximated with a second power polynomial. In case we accept that a_p = const, f = const and $r_{\varepsilon = \text{const.}}$ for the main cutting force this dependence is represented as:

$$F_c = b_0' - b_1' V_c + b_2' V_c^2 , \tag{4}$$

and the main specific cutting force dependence:

$$k_c = \frac{F_c}{a_p f} = b_0 - b_1 V_c + b_2 V_c^2 . \tag{5}$$

The hypothesis is proven by experimental research [5], [6] and [8], but this fact has not been categorically expressed. For example, the main specific cutting force has a constant value in the experimental cutting speeds interval of 450 to 600 m/min done with the formula calculations (5) according to the [5] data. In this case the

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deviations are within the multi-criteria experimental plan centre.

It is clear that when selecting a mathematical model for the approximation of the specific cutting force an empirical approach is used. The physical nature of the influence of a certain factor on a given parameter, which is a basic requirement when selecting a mathematical model, especially if the coefficients will vary quite a lot, is not taken into account. This approach can lead to considerable errors when calculating the cutting forces.

The purpose of this research is to present a method for more precise calculation of the cutting forces during turning by using new mathematical models for the specific cutting force, based on the physical nature of the influence of the cutting speed. For this purpose several objectives are reached: physical justification of the hypothetical graphic functions $k_c = f(v_c)$ during the change of the cutting speed in a wide range; solving of the different hypothetical mathematical models for their possible approximation; experimental research of the dependency of the specific cutting force on the cutting speed for different tested materials; obtaining and researching the offered empirical models for this dependency.

2 PHYSICAL EXPLANATION OF THE HYPOTHETICAL MATHEMATICAL MODELS

The specific cutting force is considered as being comprised of two components [7]:

$$k_c = k_{c\gamma} + k_{c\alpha}, \qquad (6)$$

were $k_{c\gamma}$ is the component obtained from the normal force and the friction force on the face, or:

$k_{c\alpha}$ - component obtained from the friction forces on the flank.

The definition of these forces is based on some of the theoretical models for the determination of the cutting forces given in [7].

When the specific cutting force is increased at constant thickness of the cutting material, the component $k_{c\gamma}$ decreases, because the chip reduction ξ decreases due to the reduced plastic deformation in the area of the chip formation and the reduced secondary deformation of the chip from the change of the friction coefficient. At very high cutting speeds the coefficient ξ and the friction coefficient tend to be of constant values ($\xi \rightarrow$ const ≥ 1). Therefore, if $v_c \rightarrow \infty$, $k_{c\gamma} \rightarrow$const. The designation $v_c \rightarrow \infty$ is relative because at extremely high cutting speed other specific physical phenomena are observed, which lead to other objective laws of the cutting forces change and therefore, the specific cutting force.

The designation $v_c \rightarrow \infty$ implies very high cutting speeds where the cutting temperature is close to the melting temperature of the chip contact layer.

It has been determined [8] that the normal force at the flank decreases at smaller coefficients of chip reduction. When the cutting speed is increased, ξ is reduced and therefore, at a given friction coefficient the friction force at the flank also reduces, which leads to the reduction of the specific cutting force $k_{c\alpha}$. At very high cutting speeds $\xi \rightarrow \text{const} \geq 1$, therefore $k_{c\alpha} \rightarrow \text{const}$.

The following condition must be fulfilled: if

$$v_c \rightarrow \infty;\ k_c = k_{c\gamma} + k_{c\alpha} \rightarrow \text{const} = = k_{cv\rightarrow\infty}\,. \qquad (7)$$

At very low cutting speeds the specific cutting force has a certain value which can be estimated to be:

$$v_c = 1\ \text{m/min n}, k_c = k_{c,v=1} = \text{const}. \qquad (8)$$

When cutting at micro speeds where $v_c < 1$ m/min the friction coefficient increases together with the chip shortening [8] and therefore, the specific cutting force changes in a different way in the interval of speeds $v_c = 0$ to 1 m/min.

The hypothetical graphic of the specific cutting force and the cutting speed relating to Eq. and (8) is given on Fig.1. The graphic has the following shape when there is no build-up edge (BUE). New parameters of the specific cutting force are introduced: $k_{cv=1}$ - initial specific force: $k_{cv\rightarrow\infty}$ - boundary specific force. For a given material they are characteristic values, depending on the orthogonal rake and the thickness of the cutting layer, when the cutting tool is sharp.

The empirical mathematical models approximating the formula $k_c = f(v_c)$ for a great range of speed changes must comply with the conditions in (7) and (8).

The mathematical model (2) does not comply with (7) because if $v \rightarrow \infty$ then $k_c \rightarrow 0$, besides if $v = 1$ the values of k_c are unrealistically enormous. The mathematical model (3) complies with (6): if $v = 1$ then $k_{t,r} = b_{0t,r} - b_{1t,r}$, but if $v \to \infty$, $k_{t,r} < 0$.

The mathematical models which can be used to approximate the hypothetical graphic relation between the specific cutting force and the cutting speed and which comply with (7) and (8) are selected from [9] after appropriate structural modification (Table 1).

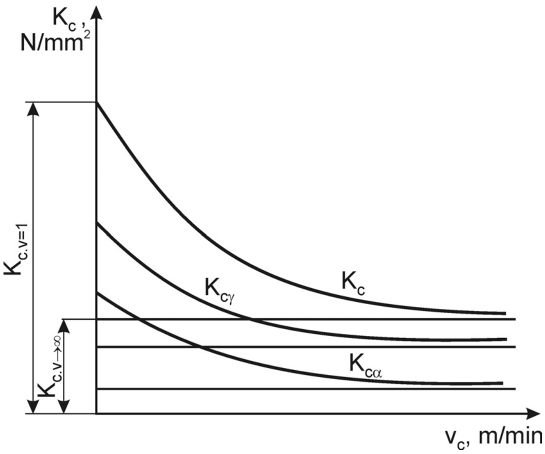


Fig. 1. *Hypothetical graphical dependency of the specific forces Kcγ, Kcα and Kc on the cutting speed*

3 RESEARCH METHODIC

The detailed research methodic is given in [10]. Its basics are presented in this paper.

The specific cutting force for each test is determined by the:

$$k_c = F_c / A\,, \quad \mathrm{N/mm^2}\,, \tag{9}$$

where F_c is the experimentally determined main cutting force, A - the actual area of the cut layer.

The elements of the cut layer section - actual area, width and mean thickness are determined for two most frequently applied turning cutting schemes – the first obtained for the conditions

$$a > r_\varepsilon\left(1-\cos\kappa_r\right),\ f \le 2 r_\varepsilon \sin\kappa_r{}' \tag{10}$$

and the second for the conditions

$$a > r_\varepsilon\left(1-\cos\kappa_r\right),\ f > 2 r_\varepsilon \sin\kappa_r{}'. \tag{11}$$

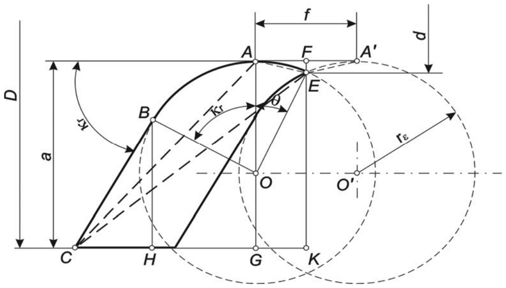
The width of the section is $b_m = AC$ [11], the actual area is $A = f.a - A_{AA'E}$, and the mean thickness is $h_m = A/b_m$.The experimental research is performed on AISI high carbon steel W1-1.0C - 180 HB, CuSn7P0.7 bronze - 93 HB, aluminum alloys AlMn0.5Mg1.6 - 107 HB on universal lathe SU500.

Straight cutting knives with brazed carbide inserts P30 are used having the following geometry parameters $\alpha_0 = 10°$, $\gamma_0 = 10°$, $\kappa_r = 70°$, $\kappa'_r = 20°$ and r_ε = 1.25 to 1.34 mm. A three-component dynamometer with inductive transducers is used to measure the cutting forces. The value of the specific force is determined after three tests.

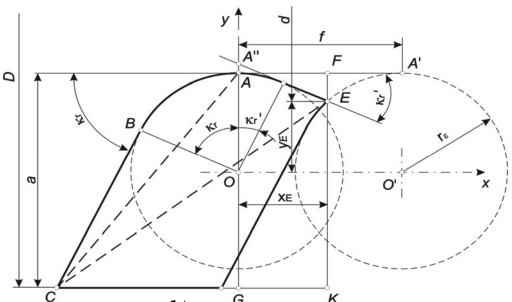
The determination of the coefficients of the mathematical models, which approximate the dependence of the specific cutting force on the cutting speed and the statistical analysis, is done by a specially developed computer program.

Table 1. Mathematical models, used to approximate the hypothetical graphic relation

№	Mathematical model	$k_{c,v=1}$	$k_{c,v\to\infty}$
1.	$k_{c1} = b_0 + \dfrac{b_1}{e^{b_2 v_c}}$	$b_0 + \dfrac{b_1}{e^{b_2}}$	b_0
2.	$k_{c2} = b_0 + \dfrac{b_1}{v_c + b_3} + \dfrac{b_2}{\left(v_c + b_3\right)^2}$	$b_0 + \dfrac{b_1}{1 + b_3} + \dfrac{b_2}{\left(1 + b_3\right)^2}$	b_0
3.	$k_{c3} = b_0 + \dfrac{b_1}{v_c + b_2}$	$b_0 + \dfrac{b_1}{1 + b_2}$	b_0
4.	$k_{c4} = b_0 + \dfrac{b_2}{\left(v_c + b_2\right)^2}$	$b_0 + \dfrac{b_2}{\left(1 + b_2\right)^2}$	b_0



a)



b)

Fig. 2. *Cutting scheme: a) with straight and curved areas of the major cutting edge and with curved areas of the minor cutting edge b) with straight and curved areas of the main and the minor cutting edges*

The Fisher's criteria, the coefficient of correlation R and the absolute value of the maximum relative error $|\Delta k_{c\ max}|$ are used to determine the adequacy, precision and workability of the mathematical models [12].

4 RESULTS FROM THE EXPERIMENTAL RESEARCH

The experiments for the measurement of the main cutting force are carried out with change of the cutting speed from v_c = 4 to 5 m/min up to speeds where there is negligible change of the measured force. The min speed is limited by the lathe capabilities. The experiments were done with constant feed f = 0.289 mm/rev for steel and f = 0.168 mm/rev for bronze and aluminum alloy, at nominal cutting depth of a = 2 mm. The real depth of cut, the real area of the cut layer section and its mean thickness are calculated for each specific test.

The dependency of the specific cutting force on the cutting speed determined on the basis of the parameters mean values for the different cut materials is shown on Fig. 3. It is observed that in the area of low speeds $v_c \leq 50$ m/min the specific force decreases with high intensity for steel and bronze. In the area of high speeds ($v_c \geq$ 100 m/min) the tendency of the decrease of the specific force is not so developed. The influence of the cutting speed on the specific force for aluminum alloy is not so obvious and at high speeds it is almost constant.

By approximating the test results of the dependency of the specific cutting force on the cutting speed the hypothetic mathematical models are obtained and analyzed (Table 1). The models coefficients derived after the processing of the experimental data are given in Table 2.

Table 2. The models coefficients derived after the processing of the experimental data

Mathematical model no.	b_0	b_1	b_2	b_3	R	$\|\Delta k_{c\ max}\|$, (%)
Steel						
1	2215	1275	0.017	-	0.963	7.79
2	2166	2.957E+04	-2.957E+04	15.47	0.994	2.79
3	2167	2.955E+04	16.42	-	0.994	2.82
4	2260	2.852E+04	42.39	-	0.990	3.54
Bronze						
1	1436	1071	0.019	-	0.946	8.1
2	1422	1.710E+04	-5395	9.88	0.998	3.19
3	1422	1.712E+04	10.32	-	0.998	3.19
4	1490	1.198E+04	28.77	-	0.995	4.5
Aluminium alloy						
1	960.0	286.1	0.007	-	0.952	4.44
2	873.3	5.198E+04	-1.051E+06	110.6	0.953	4.44
3	845.0	6.273E+04	156.2	-	0.953	4.54
4	902.7	3.212E+04	303.5	-	0.953	4.54

Table 3. *Recommended mathematical models for different materials*

no.	Cut material	Mathematical model	$k_{c,v=1}$ (N/mm^2)	$k_{c,v\to\infty}$ (N/mm^2)	$k_{c,100}$ (N/mm^2)
1.	Steel	$\hat{k}_c = 2167 + \dfrac{2.955.10^4}{v_c + 16,4}$	3865	2167	2421
2.	Bronze	$\hat{k}_c = 1422 + \dfrac{1.712.10^4}{v_c + 10.32}$	2934	1422	1577
3.	Aluminum alloy	$\hat{k}_c = 845 + \dfrac{6.273.10^4}{v_c + 156.2}$	1244	845	1090

All models comply with the conditions in (7) and (8) and express decreasing functions at $v_c > 0$. According to Fisher's criteria (α = 0.025 to 0.05) all models are adequate. The models assessment is done by the correlation coefficient R and the maximum relative error is $|\Delta k_{c\ max}|$. According to this data the best models for steel and bronze are 2 and 3, and for aluminum alloy all four models are almost equal. The best option is to choose model 3 for the three materials, which has the simplest structure (Table 3).

CONCLUSIONS

The following conclusions are derived on the basis of the conducted tests.

a. On the basis of the physical nature of the influence of the cutting speed on the specific cutting force, boundary conditions are defined for the compliance of the mathematical models for the approximation of this influence in a wide range of cutting speed change.

b. A hypothetical graphical function $k_c = f(v_c)$ for cutting without BUE of plastic materials and hypothetical mathematical models for the approximation of this function are developed, which comply with the defined boundary conditions.

c. New parameters for the specific cutting force are developed – initial specific cutting force at v_c = 1 m/min and boundary specific force at $v_c \to \infty$, which are characteristic for a given cut material when the cutting tool is not worn out and at given cutting depth and rake.

d. Using experimental research and mathematical processing of the test data, new mathematical models which deal with the approximation in a broad range of the dependence of the specific cutting force on the cutting speed in turning of different materials are obtained. A model is recommended on the basis of structure, adequacy and accuracy.

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