AN EXPERIMENTAL STUDY OF UNIT POWER LOADING OF CURVILINEAR CUTTING EDGES

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INTRODUCTION

As a result of the cutting process, the mechanical energy is expended in deforming the chip and overcoming friction between the tool and the workpiece. A series of experiments [8] estimate that the energy that is not converted to thermal energy is only between 1 and 3 percent of the total cutting energy. This thermal energy yields high temperature in the deformation zone and surrounding regions of the chip, tool and workpiece.

Among the geometric parameters of the cutting tool so far considered having a significant influence on cutting energy should be mentioned the side rake angle γ, the main relief angle α and the angle of inclination λ [8].

Considering the major influence of the round shape of cutting edges on face milling cutting process [6], [7], [8] it has been decided to investigate it's action on mechanical energy transferred through the cutting tool.

1. UNIT POWER LOADING

As a measure of the mechanical energy transferred through the cutting tool, the Romanian school of cutting utilises the unit power loading, defined as the power consumed by the unit on length of the cutting edge [2]:

$$u_e = \frac{F_c \cdot v}{l_e} \quad [(\text{daN}\cdot\text{mm})/(\text{min}\cdot\text{mm})], \tag{1}$$

where F_c [daN] is the main cutting force, v [m/min] is the cutting speed and l_e [mm] is the effective length of contact between the cutting tool and workpiece (measured in the rake face of the tooth).

As shown in figures 1 and 2 and described in reference paper [8], in case of the partial curvilinear cutting edge the effective (real) length of contact between the cutting tool and workpiece is given by the simplified relation (2):

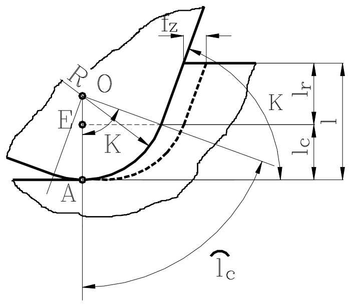

Figure 1. View of partial curvilinear cutting edge in the rake face of the tooth.

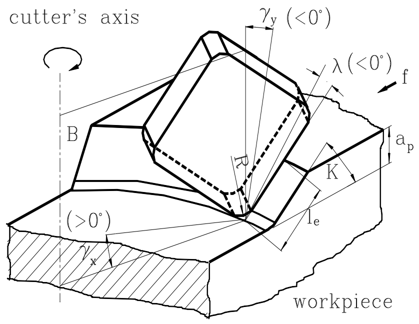

Figure 2. Cutting variables and angular orientation of the curvilinear cutting edges in face milling.

$$l_e = R \cdot K + \frac{a_p - R(1 - \cos K)}{\sin K \cdot \cos \lambda} \tag{2}$$

or by a more accurate one:

$$l_e = R \cdot \arccos\frac{A}{R} + \frac{a_p - R(1 - \cos K)}{\sin K \cdot \cos \lambda} \tag{3}$$

where R is the nose radius, a_p is the axial depth of cut, K is the entry angle, λ is the angle of inclination and A is computed as:

$$A = R[\sin\gamma_x \cdot tg\gamma_y \cdot \cos(\arcsin\frac{\cos\gamma_y \sin K \cdot \cos\lambda + \cos K - 1}{\sin K \cdot \cos\lambda \cdot \cos\gamma_x}) + \frac{\sin^2\gamma_y(\cos\gamma_y \cdot \sin K \cdot \cos\lambda + \cos K - 1)}{\sin K \cdot \cos\lambda \cdot \cos\gamma_x}] \tag{4}$$

According to the RSM methodology [5] and considering specific aspects of the cutting processes [8] the following mathematical model was utilised and validated:

$$u_e = C_u \cdot e^{\sum_{i=1}^{n} \alpha_i \cdot x_i}, \qquad (5)$$

where: C_u is a constant, e is the base of natural logarithm (2,7182…), x_i are the independent variables considered (representing the cutting speed, feed per tooth, angle of engagement, nose radius and the axial depth of cut) and α_i are coefficients considered as function depending on the n independent variables which can be expressed as linear combination of x_i.

In order to evaluate the coefficients α_i the following model was utilized:

$$u^*_e = a_0 + \sum_{i=1}^{n} a_i \cdot x_i + \sum_{i=1}^{n} a_{ii} \cdot x_i^2 + \sum_{\substack{i=1 \\ j>1}}^{\substack{i=n-1 \\ j=n}} a_{ij} \cdot x_i x_j, \qquad (6)$$

where a_0, a_i, a_{ii} and a_{ij} are constants and represent estimations of the regression cofficients of the considered homologous theoretical function.

2. RESULTS AND DISCUSSION

Five levels for each factor have been selected and coded as is shown in table 1.

In order to determine the coefficients of the relation (6), a central rotatable experiment [5] of a 2^{6-1} type, has been utilised, consisting of:

- 16 experiments, that represent half of the factorial programme 2^5;
- 10 additional experiments have been performed at the extremities of ranges of variables values;
- 6 experiments have been carried out in the core of the experimental domain to determine the experimental error.

The tests have been applied on a universal milling machine of the FU 32 type in the following conditions: face up milling, with normal orientation of a cutter equipped with cemented carbide inserts, grade P30, uncoated, without chipbreakers, having a diameter D=165 mm, z=6 teeth, main relief angle α_N=12°, side rake angle γ_N=9°30', angle of inclination of the main cutting edge λ=11° and entering angle K=62°. The workpiece was a rectangular block of constructional steel OLC 45 (DIN 10503) with t=100 mm.

The responses of the target function have been calculated by relation (1) and the values of F_c were measured by means of a data acquisition system composed of a tensometer transducer, an amplifier, an analogue-digital converter and a personal computer. The regression coefficients and the t-tests of these models have been calculated as given in table 2.

After having reached the transition in natural co-ordinates of the variables and a suitable grouping of the terms, the mathematical model of

Table 1. Coding of milling parameters

Parameter	Symbol	-2	-1	0	1	2
Cuttting speed, v [m/min]		49,244	77,754	121,38	194,38	311,01
	x_1=lg$v$	1,6923	1,8907	2,0857	2,2886	2,4927
Feed, f_z [mm/edge]	x_2	0,05	0,1	0,15	0,2	0,25
Angle of engagement, ε [rad]	x_3	0,2443	0,5148	0,7853	1,0559	1,3264
Nose radius, R [mm]	x_4	1	1,5	2	2,5	3
Axial depth of cut, B [mm]	x_5	1	1,5	2	2,5	3

Table 2. Regression coefficients and the t distribution in coded coordinates

Coeff.	Value	t^* distrib	Coeff.	Value	t^* distrib	Coeff.	t^* distrib	Value
a_0	6,09948	-	a_{13}	0,047810	3,08	a_{35}	-0,039057	2,52
a_1	0,411681	6,64	a_{14}	0,053935	3,48	a_{45}	-0,029047	1,87
a_2	0,275193	4,44	a_{15}	0,034660	2,23	a_{11}	-0,030542	2,02
a_3	-0,021229	3,42	a_{23}	0,048423	3,12	a_{22}	-0,070800	4,68
a_4	-0,117948	1,9	a_{24}	0,027592	1,78	a_{33}	-0,014485	0,958
a_5	0,042517	0,68	a_{25}	0,048579	3,13	a_{44}	-0,008120	0,53
a_{12}	-0,034787	2,24	a_{34}	-0,032091	2,07	a_{55}	-0,040092	2,65

the unit power loading becomes:

$$u_e = e^{\alpha_1 \cdot lgV + \alpha_2 \cdot f_z + \alpha_3 \cdot \varepsilon + \alpha_4 \cdot R + \alpha_5 \cdot B}, \qquad (7)$$

where:

$$\alpha_1 = 1{,}52394 - 0{,}153329 \cdot lg\,v - 1{,}55889 \cdot f_z +$$
$$+ 0{,}395985 \cdot \varepsilon + 0{,}241693 \cdot R + 0{,}15532 \cdot B$$
$$\alpha_2 = 12{,}581 - 28{,}3201 \cdot f_z + 3{,}57993 \cdot \varepsilon +$$
$$+ 1{,}10368 \cdot R + 1{,}9432 \cdot B$$
$$\alpha_3 = -1{,}15428 - 0{,}197928 \cdot \varepsilon - 0{,}23725 \cdot R -$$
$$- 0{,}28875 \cdot B$$
$$\alpha_4 = -1{,}01353 - 0{,}032483 \cdot R - 0{,}11619 \cdot B$$
$$\alpha_4 = 0{,}148272 - 0{,}16037 \cdot B$$

In order to visualise the bidimensional section, in relation (7) the values of three out of five variables have been maintained successively constant at the levels corresponding to the core of the experimental domain (see table 1). According to this procedure the bidimensional sections of all the possible combinations of the five independent variables have been visualised (figure 3). Also the equal contour lines have been visualised, obtained by slicing the response surfaces on various horizontal levels (figure 4).

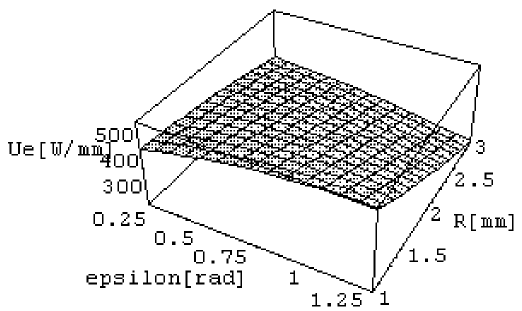

Figure 3. The bidimensional section of u_e depending on ε and R.

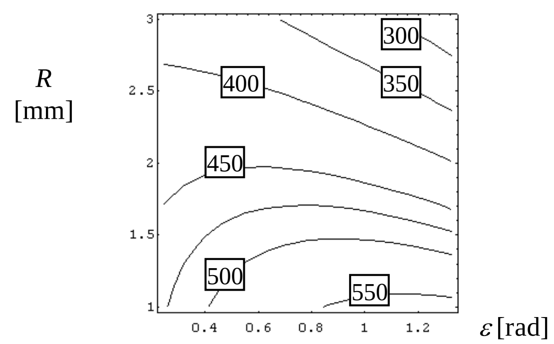

Figure 4. The equal contour line of the bidimensional section presented in figure 3.

3. CONCLUSIONS

The RSM technique has made it possible to describe a complex process through experimental results. The cutting condition and tool geometry determine the unit power loading. The examination of the bidimensional sections leads to the conclusions mentioned below:

- the cutting speed and feed have the greatest influence on unit power loading;
- in certain conditions, the increase of nose radius *R* is able to cause a significant modification (in the sense of increasing or decreasing the power loading); in this sense, as is shown in figure 4, the rise of nose radius from 1 mm to 3 mm produces a decrease with 54 percent of unit power loading.

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