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RESEARCHES ABOUT THE CUTTING EDGE TEMPERATURE IN HIGH SPEED TURNING OF QUALITY STEEL

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Abstract: *The determination of the temperature distribution and its maximum along the rake face of the cutting tool is important because, through its control, the conditions of the cutting process as well as the quality of the machined surface will be improved. This paper is the result of the author's previous investigations on the temperature at the edge of the tool, at the turning of the quality steel, depending on the cutting conditions, with the object of simulating the cutting process in HSC conditions. For the determination of the temperature values there was used an experimental setup with natural thermocouple. The mathematical model obtained through regression method was analyzed for emphasizing the influence of the cutting parameters on the temperature.*

Key words: *edge temperature, calibration, natural thermocouple, turning.*

1. INTRODUCTION

Cutting is one of the most important and common manufacturing processes in industry. Machining is not an easy process to study and to model, due to the inherent difficulty to know exactly what happens in the region around the tool tip. The heat generated during cutting has been studied by a large number of researchers using experimental techniques [1, 2, 3]. The determination of the maximum temperature and temperature distribution along the rake face of the cutting tool is of particular importance because of its controlled influence on tool life, as well as on the quality of the machined part and on the production costs, that become lower.

This article is the result of the author's investigations on the determination of the temperature at the edge of the cutting tool during the turning of the quality steel in high speed cutting conditions using a tool with coated carbide insert. The purpose of this project was to investigate the influence of the cutting parameters on the temperature at the edge of the cutting tool.

The progress of the experiments as well as the processing of the results have been done using the modern method of the response surfaces. The temperature has been measured experimentally using a montage with natural thermocouple. The data acquisition has been accomplished using the LabVIEW instrumentation. The model, as well as the temperature profiles have been obtained through analytical calculus using the MATHLAB program and the mathematic regression method.

2. THEORETICAL ASPECTS

The researches that have been fulfilled have shown that the mechanical work of the cutting process turns almost completely into heat. Just a little part of it (0,5…1%) remains stored as tensions in the chips as well as in the superficial layer from the level of the generated surface. Therefore, with precision, the quantity of the emitted heat can be determined using the following formula:

$$Q_c = \frac{L_c}{E}\alpha_0, \tag{1}$$

where: Q_c – the quantity of heat in a specified time period (the heat flow) [cal/s]; L_c – the unitary mechanical work at the cutting (the cutting power) [Nm/s]; E – the equivalent of the calorie (E = 4.27 J/cal); α_0 – the coefficient which takes account of the quantity of the mechanical work at the cutting that turns into heat (α_0 = 0.99…0.995%).

Firstly, this is produced (Fig. 1) in the primary cutting plane (Q_1), which is found at the Φ angle from the cutting edge and, secondly, in the rubbing areas between the chip - the rake face of the tool (Q_2) and the flank face of the tool - the machined surface (Q_3) [4].

According to the accomplished studies, with a certain approximation, it is considered that 75 % of the heat generated by the cutting comes from the distortion and the detachment from the cutting edge, and 25 % from the rubbing process. From these areas, the heat is transmitted in the areas with lower temperature, being distributed between the chip, the tool, the workpiece and the environment. The share of distributions changes depending on the processing procedure.

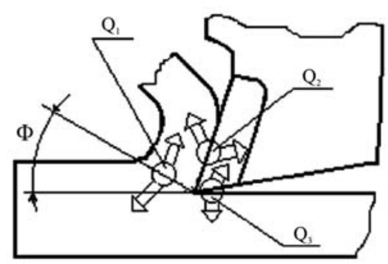

Fig. 1. Mechanic works transforming in heat.

The factor that influences the most the economy of the cutting process is the quantity of heat, which is taken over by the tool, because it determines the wear condition of the tool due to the thermal loading.

The quantity of heat generated during the cutting process, depending on the cutting parameters, can be determined using a mathematical model based on the equation of the thermal balance between the chip, the tool, the workpiece and the environment.

According to this balance, the general function of the temperature can be determined using the following formula [5]:

$$\theta = C_\theta \times e^{\Sigma}\ [°C];\ \Sigma = \frac{x_a}{m} a^m + \frac{y_f}{n} f^n + \frac{z_v}{q} v_c^q, \quad (2)$$

where x_a, y_f, z_v are variables dependent on the parameters of the cutting process a, f and v_c, C_θ - constant which expresses the conditions of the heat transfer in still thermal conditions, dependent as value on the thermophysical properties of the material of the workpiece, on the geometry of the active part of the tool and on the wear grade of the edge of the cutting tool.

Particularly, x_a, y_f, z_v being independent variables on a, f and v_c there are the relations: $m = n = q$; $x_a = x_\theta$, $y_f = y_\theta$, $z_v = z_\theta$.

Therefore the relation (2) becomes:

$$\theta = C_\theta \cdot v_c^{z_\theta} \cdot f^{y_\theta} \cdot a^{x_\theta},\ [°C]. \quad (3)$$

The experimental data for the constants and the exponents is few, incomplete and therefore it can hardly be used.

The measurement of the temperature is realized using a variety of instruments, devices and montage schemes, whose choice is imposed by the actual conditions of experimenting and by the range of the temperature.

3. EXPERIMENTAL SETUP AND PROCEDURE

The experimental investigations have been accomplished in the laboratories from the Engineering and Management of the Technological Systems from the University "Politehnica" of Bucharest. The experimental setup is presented in Fig. 2.

Experimental conditions:

- Machine-tool: SN 400x1000 lathe;
- Cutting tool (pos. 2): PDJNL 2525M 15 with DNMG 15 06 04-PM cutting insert;

Fig. 2. Experimental setup.

- Workpiece (pos. 1): Ck 45 rectified bar ($\varnothing_{ext}$ = 98 mm) according to the DIN 17200 norm.;
- The data acquisition (pos. 3 and 4): Measurement and Automation Software National Instruments LabVIEW with Multifunction DAQ PCI-6024E;
- The signal for measurement of the temperature of the cutting edge: natural thermocouple;
- Settings for the measurement lines:
  - channel 2 (natural thermocouple): number of scans/sec.: 5; number of acquisitions: 20; measurement range: 0 … −10V; measurement without scale; factor of amplification of the operational amplifier: 250;
  - channel 1 (artificial thermocouple CuCt (pos. 6): conditioner 5B47; measurement range (0 – 200)°C.

The calibration of the measurement line with natural thermocouple (Fig. 3) has been realized by heating a Ck 45 steel bar, using an electric resistor on ceramic support, whose temperature had been measured with a FeCt artificial thermocouple which has been modified depending on the temperature of the cold junction (the temperature of the environment in the laboratory) [6].

The acquisition of the values for the electro-motive tension of the natural thermocouple has been accomplished during the cooling phase of the steel bar, in order to remove the influences of the electric field, produced by the electric resistor during the heating phase.

The calibration diagram is presented in Fig. 4.

The linear dependence of the temperature/electro-motive tension of the natural thermocouple is given by the following relation:

$$\theta = 41.185\,x + 39.681,\ [°C]. \quad (4)$$

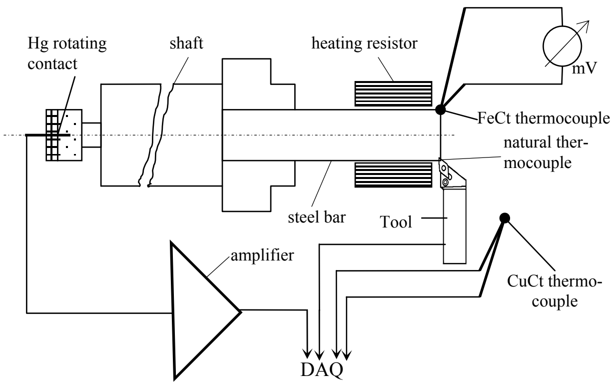

Fig. 3. Scheme for the calibration of the natural thermocouple.

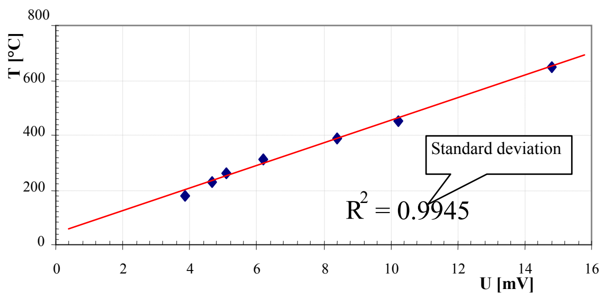

Fig. 4. The calibration diagram for the natural thermocouple.

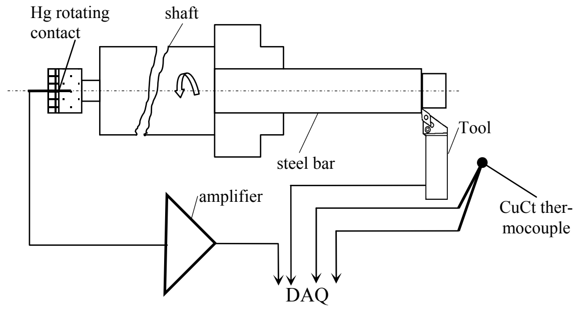

Fig. 5. Measurement scheme.

4. EXPERIMENTAL RESEARCH

For the determination of the analytic model of the temperature at the cutting edge, depending on the cutting speed (v_c), of the rotation feed (f) and of the cutting depth (a), defined by the equation (4), there has been organized a factorial experimental program, in which, for every variable, there have been chosen three values, taking account of the technological limits imposed by the work conditions and of the recommendations of the cutting inserts' producer. The scheme of the working stand is presented in Fig. 5.

For a model of first order with three variables (Table 1) [7], the whole factorial program contains $2^3 = 8$ experiences.

In order to respect the orthogonal conditions, for each variable were taken values in geometric progression (Table 2).

The processing of the experimental data:

- number of determinations for the same cutting conditions: 3;
- the results from DAQ were divided by 250;
- for each determination there have been calculated: the linear tendency equation of the measured data and the standard deviation;
- for each cutting conditions there has been calculated the arithmetic mean of the electro-motive tension, that had been calculated, and the tendency equation for $t = 0$. During the data analysis there has been observed a decreasing tendency of the values of the electromotive tension during the cutting process, due to the appearance of a new natural thermocouple, this time of contrary sense, between the cutting insert and the shank of the cutting tool;
- the effective calculation of the coefficients of the equation (3) has been accomplished with the relations:

$$C_\theta = \exp\left(b_0 - \sum_{i=1}^{3} b_i \frac{\ln\left(x_{i\max} \cdot x_{i\min}\right)}{\ln\left(x_{i\max} / x_{i\min}\right)} \right), \qquad (5)$$

$$x_\theta = \frac{2 \cdot b_3}{\ln\left(x_{3\max} / x_{3\min}\right)}, \qquad (6)$$

$$y_\theta = \frac{2 \cdot b_2}{\ln\left(x_{2\max} / x_{2\min}\right)}, \qquad (7)$$

$$z_\theta = \frac{2 \cdot b_1}{\ln\left(x_{1\max} / x_{1\min}\right)}, \qquad (8)$$

where: x_i has been defined in Table 2 and:

$$b_0 = \frac{1}{8}\ln\left(T_1 \cdot T_2 \cdot \ldots \cdot T_8\right), \qquad (9)$$

$$b_1 = \frac{1}{8}\ln\frac{T_2 \cdot T_4 \cdot T_6 \cdot T_8}{T_1 \cdot T_3 \cdot T_5 \cdot T_7}, \qquad (10)$$

$$b_2 = \frac{1}{8}\ln\frac{T_3 \cdot T_4 \cdot T_7 \cdot T_8}{T_1 \cdot T_2 \cdot T_5 \cdot T_6}, \qquad (11)$$

$$b_3 = \frac{1}{8}\ln\frac{T_5 \cdot T_6 \cdot T_7 \cdot T_8}{T_1 \cdot T_2 \cdot T_3 \cdot T_4}. \qquad (12)$$

Table 1

The organization of the experiments

Experiment	Variable levels			Results
	v_c	f	a	
1	-1	-1	-1	T_1
2	1	-1	-1	T_2
3	-1	1	-1	T_3
4	1	1	-1	T_4
5	-1	-1	1	T_5
6	1	-1	1	T_6
7	-1	1	1	T_7
8	1	1	1	T_8

Table 2

The values of the cutting parameters

Nivel	v_c (x_1)[m/min]	f (x_2)[mm/rot]	a (x_3)[mm]
–1	235.4	0.06	0.5
0	293.9	0.12	1
1	369.3	0.24	2

5. RESULTS AND DISCUSSION

The results of the experiments are centralized in Table 3. The model of the cutting edge temperature depending of the cutting process parameters is:

$$\theta = 243{,}283 \cdot v_c^{0{,}242} \cdot f^{\,0{,}078} \cdot a^{0{,}021}. \qquad (13)$$

From the comparison between the measured values and the calculated values (see last three columns in Table 3) it can be observed that the determined model describes correctly the temperature variation for cutting quality steel with coated carbide types.

In order to check the determined model, there were accomplished many experiences with lower values of the parameters of the cutting conditions and higher than the values used to determinate the model (Fig. 6).

The dependence of the temperature with the cutting speed (Fig. 7) reveals an important increase of the temperature at the same time with the cutting speed.

Table 3

The measured and calculated values of the temperature at the cutting edge

Exp.	v_c	f	a	T_m	T_c	$\varepsilon = (T_c - T_m)/T_c$ [%]
1	235.4	0.06	0.5	704.0	721.9	2.47%
2	369.3	0.06	0.5	803.9	805.0	0.14%
3	235.4	0.24	0.5	802.8	804.3	0.18%
4	369.3	0.24	0.5	884.1	896.9	1.43%
5	235.4	0.06	2	741.0	743.2	0.30%
6	369.3	0.06	2	817.8	828.8	1.33%
7	235.4	0.24	2	818.1	828.1	1.20%
8	369.3	0.24	2	911.8	923.4	1.26%

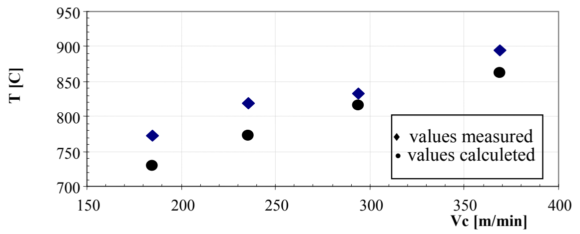

Fig. 6. Comparison between values measured and values calculated of the temperature.

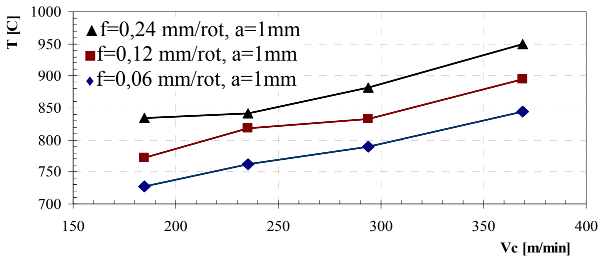

Fig. 7. The variation of the temperature with the cutting speed.

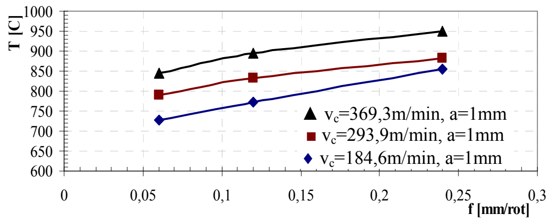

Fig. 8. The variation of the temperature with the feed.

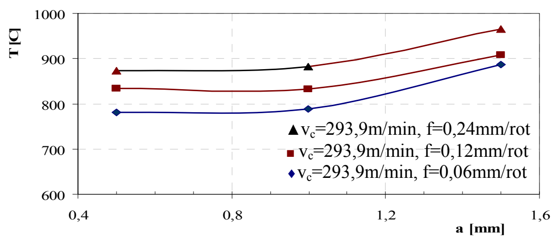

Fig. 9. The variation of the temperature with the depth.

For an increase of the cutting speed from 184.6 to 369.3 m/min, representing dubbing the speed, the increase of the temperature was 122 °C (from 773 to 895°C). For a constant speed v_c = 293.9m/min (Fig. 8) an increase of the feed from 0.5 mm to 2mm (at four time), the cutting temperature increased with 93 °C.

It comes out that the influence of the cutting depth on the cutting temperature (Fig. 9) may be considered as insignificant. The increase of cutting depth from 0.5 to 1 mm, yields to an insignificant temperature variation. That can be explained by the influence of the cutting edges rayon (r_ε = 0.4 mm), whose value is comparable with the minimum cutting depth.

6. CONCLUSIONS

The temperature of the cutting edge measured with the natural thermocouple represents the real temperature of the cutting edge during the cutting process, without any approximation or simplifying hypothesis.

The measurement of this temperature by other measurement means is not possible without considering certain work hypotheses. The successful checking of the determined model for other cutting conditions, too (Fig. 6), has shown the validity of the applied theory, the one of the response surfaces and the accuracy of the accomplished experiments.

The results have emphasized the major influence of the cutting speed. The cutting feed and cutting depth have smaller influence on the cutting temperature according to their exponents in the determined model (13). Some researchers find statistically insignificant the influence of the cutting depth [7].

The temperature of the cutting edge can reach high values even for conventional cutting conditions or for the inferior limit of the HSC. It is simple to see that the HSC domain is approachable only with tools that withstand at high temperatures and that have high wear resistance.

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