RESEARCHES ABOUT THE TEMPERATURE OF THE CUTTING EDGE IN TURNING OF UNALLOYED STEEL

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Lucrarea prezintă rezultatele cercetărilor autorilor asupra temperaturii muchiei aşchietoare a sculei la prelucrarea oţelurilor de calitate, în funcţie de parametrii procesului de aşchiere cu valori convenţionale. Pentru determinarea valorilor de temperatură ale muchiei aşchietoare s-au utilizat montaje experimentale cu termocupluri naturale şi artificiale, cameră de luat vederi în infraroşu şi pirometru optic. Pentru analiza influenţei variaţei parametrilor de aşchiere asupra temperaturii muchiei aşchietoare s-a utilizat o relaţie analitică determinată prin metoda planelor simetrice de măsurare şi a regresiei matematice.

This paper is the result of the authors' investigations on the temperature at the edge of the tool, during turning of unalloyed steel, depending on the parameters of the cutting process with conventional values. For the determination of the temperature values of the cutting edge an experimental setup with natural and artificial thermo-couples, infrared camera and optical pyrometer was used. To analyze the influence of the variation of the cutting parameters on the temperature of the cutting edge an analytical relation, determined through the method of symmetrical measurement plans and through mathematical regression was used.

Key words: Edge temperature, calibration, natural thermocouple, virtual instrumentation, thermography

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 due to its controlled influence on tool life, as well as on the quality of the machined part and on the production costs.

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This paper is the result of the authors' investigations on the determination of the temperature at the edge of the cutting tool during the turning of an unalloyed 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 progresses 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 using an experimental setup with natural thermocouple. The data acquisition has been accomplished using the LabVIEW instrumentation. The temperatures, as well as the temperature profiles have been obtained through analytical calculus using the MATLAB program and the mathematic regression method.

2. Theoretical aspects

The researches that have been undertaken 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 stresses 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 into account the quantity of the mechanical work at the cutting that turns into heat (α_0 = 0,99…0,995).

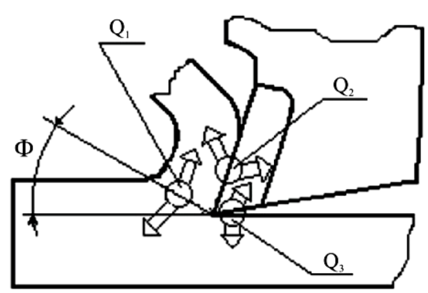


Fig. 1. Mechanic works transforming in heat.

First, this is produced (Fig. 1) in the primary shear plane (Q_1), which is found at the Φ angle from the cutting direction and, second, 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 machining procedure.

The factor that mostly influences the economy of the cutting process is the quantity of heat, 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]:

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

where x_a, y_f, z_v are variables depending on the parameters of the cutting process a, f and v_c and C_θ is a constant which expresses the conditions of the heat transfer in steady thermal conditions, depending on the thermal 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 the following relations occur: $m=n=q$; $x_a=x_\theta$, $y_f=y_\theta$, $z_v=z_\theta$. Therefore, relation (2) becomes:

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

The experimental data for the constants and the exponents are scarce, incomplete and therefore they can hardly be used.

The measurement of the temperature is realized using a variety of instruments, devices and mounting schemes, whose choice is required by the actual conditions of experimenting and by the range of the temperature to be measured.

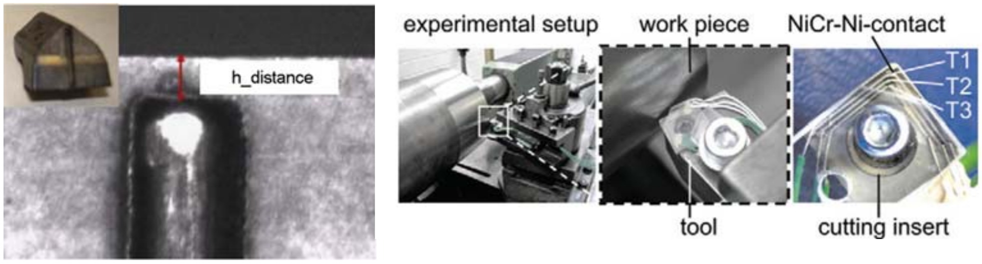
3. Methods of measuring the temperature

There are a lot of methods of determining the average temperature of the cutting edge. In the specialized literature the measurement methods are divided in the following principal groups:

- measurements with contact;
- measurements without contact;
- measurements after ending the cutting process.

The measurements with contact (during the cutting process) are realized with one or more thermocouples placed in the cutting tool. The thermocouple represents a device of measuring the temperature, widely used due to their advantages, in comparison to other means of measuring the temperature: simple construction, low cost, wide range of measurement (-200^{o}C ... + 3000^{o}C). Thermocouples can be connected to different indicators, recorders, signal and commanding devices. For measurement with contact, three types of thermocouples are used:

- *the artificial thermocouple* - in the active part of the cutting tool there are installed (Fig. 2) one or more thermo-elements each formed out of two wires (copper/constantan, iron/constantan, cromel/alumel, cromel/constantan etc.), each having their terminations welded together and isolated from the active part of the tool [6, 7]. The hole in which the thermocouple is placed represents a perturbation factor and it can significantly modify the distribution of the measured thermal field. Therefore, it is very small and very close to the active parts of the tool. The gradients of temperature are very important in this area. A variation of hundreds of degrees per mm can be observed. A change of position of the thermocouple can generate very important differences of temperature. Moreover, the presence of the thermo-couple perturbs the thermal field and can sometimes show values that are different from the real ones. The measurements made in these configurations are difficult to discuss. In order to correct the results of the primary measurements from the cutting area, it is necessary to make the calibration of the measurements line, which is a difficult operation, taking into consideration the fact that the temperature distribution (the temperature measured by the artificial thermo-couple) depends also on time.
- *the semi-artificial thermocouple* – the thermo-element is formed of the metal of the active part of the tool (Fig. 3) and one constantan wire driven out to the layout or rake face, through an eyelet with a small diameter and stuck to the body of the tool.
- *the natural thermocouple* – is the most simple and easy to be realized, being formed of the active part of the cutting tool and the workpiece to be machined (Fig. 4.a) [8]. The contact T_1 between the tool and the chip encompasses the hot junction, and the point T_a represents the cold junction, being at the temperature of the environment. If the temperature of these points is significantly different from the temperature of the environment, special procedures of compensation are imposed. The linking conductors are generally made of copper and have no influence on the generated thermo electromotive tension, because



a) **b)**

Fig. 2. The Measurement of the temperature with artificial thermocouple.
a – Chromel/Alumel thermocouple (K type) with a diameter of 0.5mm was properly forced into the tool [6]
b - Embedded thermocouple arrangement used to measure rake face temperatures in dry cutting of cast iron GG25 [7].

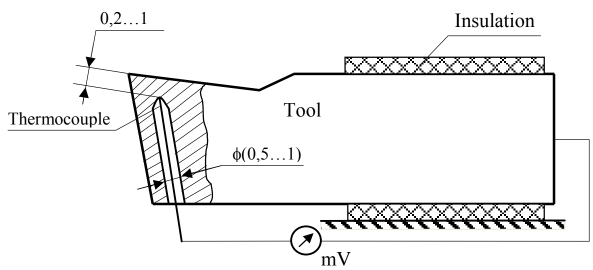
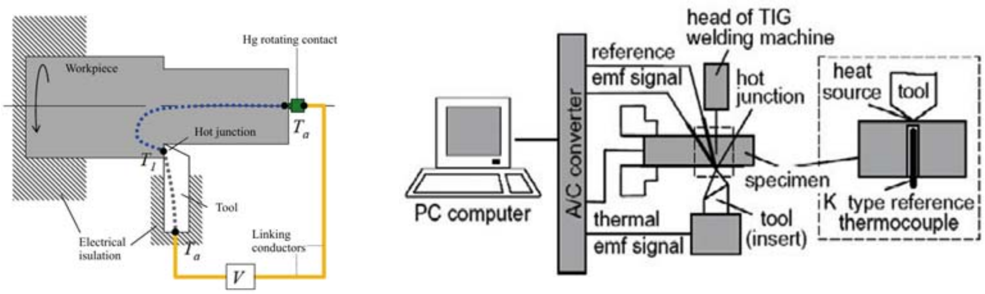


Fig. 3 The semi-artificial thermocouple

their terminations have the same temperature. The tool and the work-piece have elements through which they are electrically isolated one from another. The connection of the conductor with the work-piece is realized through a rotary contact with mercury. The measured temperature can be different from the real average temperature of the tool, taking into consideration the presence of the thermal resistance of sliding contact at the level of the tool-workpiece interface.

Therefore, it is imposed to make a calibration of the measuring line in conditions as close as possible to the real ones. In Fig. 4.b the calibration scheme in the researches concerning the analysis of the fragmentation of the chip at turning steels, [9], is presented.

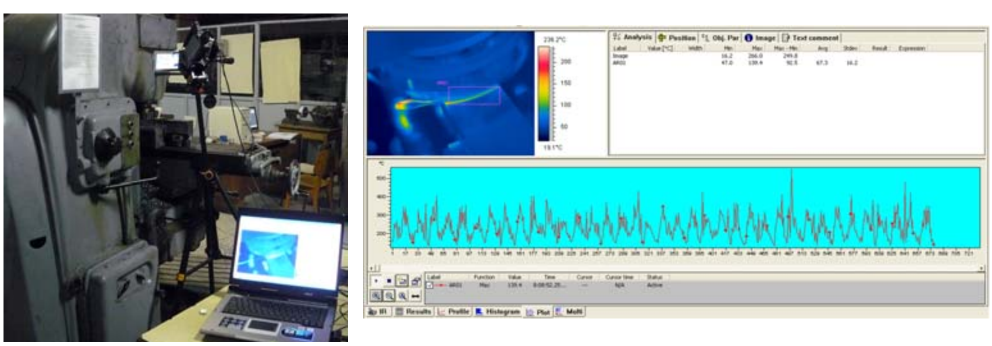
The measurements without contact are realized by infrared thermography, with infrared camera or with CCD/IR camera (Fig. 5), which allows working in a wide range of waves, close to the visible spectrum or with the help of a pyrometer (Fig. 6). These methods have some disadvantages. First, due to their metallic nature, the used materials lead to multiple reflections that perturb the measurements on all the surfaces. The transmission of the surfaces is unknown and varies depending on the temperature and their orientation, as well as on the the wave length. The measurement of the temperature through thermography



a) b)

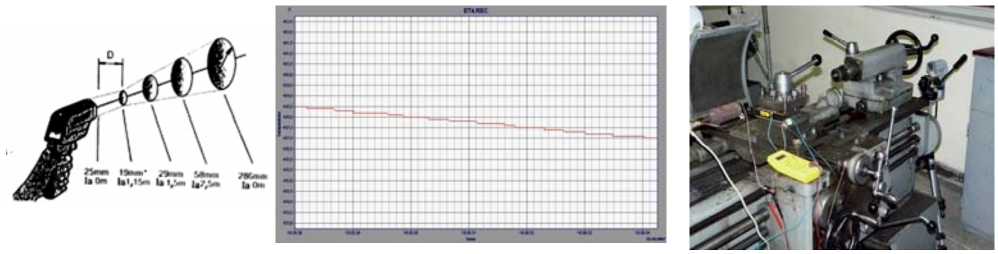
Fig.4. Typical natural (tool-chip) thermocouple set-up [8].
(a – The principal scheme for experimental measurements,
b. – Experimental stand for calibration [9].)

or infrared can only be used in particular configurations (orthogonal cutting) and does not provide absolute values of the temperature of the cutting edge of the tool. These measurements are important from the qualitative point of view because they allow a global view of the thermal field in the cutting area. Nevertheless, even in the case of orthogonal cutting, the chip emits an important infrared ray (depending on its temperature), which perturbs the measurements of the temperature in the cutting area. From another point of view, the temperature that we want to know is the one of the cutting edge, which is covered by the chip that rubs over the tool during the cutting process. In Fig. 5 and 6 there are presented two experimental set-ups used by the authors, during the researches done in order to determine the temperature during the cutting process. The obtained results have been used as guide values for evaluating the subsequent measurements that were carried out with the natural thermocouple.



a) b)

Fig. 5. Measurements with the Thermo-vision Camera in Infrared ThermaCAM SC 640
(a –Experimental set-up, b – Thermo graphic Image)



a) b) c)

Fig. 6. Measurements with the RAYNGER MX4 pyrometer produced by Raytek.
(a – Measurement scheme, b – Temperature/Time Diagram, c – Experimental setup for determining the emissivity coefficient)

The subsequent measurements (after the cutting process) are realized through two methods:

- *With the help of thermo sensitive paints.* The principle of these materials is to change color at a fixed temperature, adjustable depending on their chemical composition.
- *With the help of micro structural analysis of the materials*. Knowing the phase changes and the metallurgical transformations of the machined material, or of the tool, one can determine the isotherms after the cutting operation.

4. Experimental setup and procedure

The experimental investigations have been carried out in the laboratories of the Faculty of Engineering and Management of Technological Systems from the University Politehnica of Bucharest. The experimental setup is presented in Fig. 7.

Experimental conditions:

- Machine-tool: SN 400x1000 lathe;
- Cutting tool (pos. 2): PDJNL 2525M 15 with DNMG 15 06 04-PM indexable insert;
- Workpiece (pos. 1):Ck 45 rectified bar ($Ø_{ext}$=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. 8) 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 [11].

Fig. 7. Experimental setup.

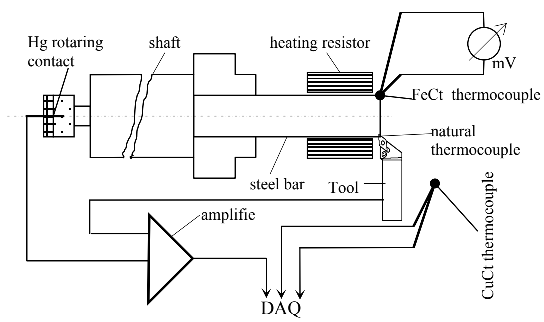


Fig. 8. Scheme for the calibration of the natural thermocouple.

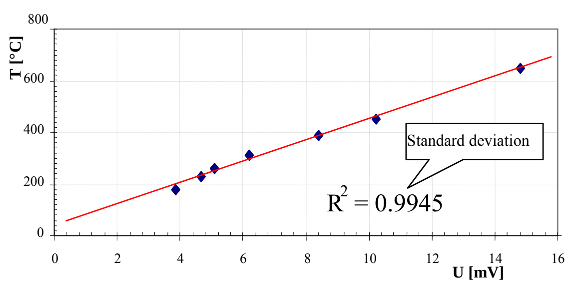


Fig. 9.The calibration diagram for the natural thermocouple.

The acquisition of the values for the electromotive 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. 9. The linear dependence of the temperature/electromotive tension of the natural thermocouple is given by the following relation:

$$\theta = 41.185 \cdot x + 39.681 \text{ [°C]}. \quad (4)$$

where: θ - calculated temperature, x – the value of the measured thermo-electromotive tension.

5. Experimental research

In order to obtain the analytical model of the temperature at the cutting edge, depending on the cutting speed (v_c), the rotation feed (f) and the cutting depth (a), defined by the equation (3), an experimental program has been organized, in which, for each variable, three values were chosen, taking into account the technological limits imposed by the working conditions and the recommendations of the cutting inserts' producer. The scheme of the experimental set-up is presented in Fig. 10.

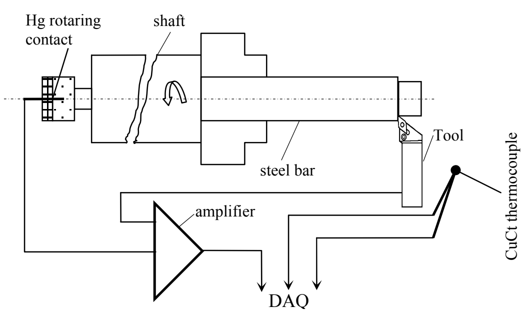


Fig. 10. Measurement scheme.

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

For a model of first order with three variables, the whole factorial program contains 2^3=8 experiments (Table 1) [12].

In order to respect the orthogonal conditions, values were taken in geometric progression for each variable (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, the value of the amplification coefficient;
- for each determination: the equation of the trendline for the measured data and the standard deviation have been calculated;
- for each cutting conditions the arithmetic mean of electro-motive tension and the trendline equation for t=0 were calculated. During data analysis a decreasing tendency of the values of the electromotive tension during the cutting process was observed, 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 coefficients of the equation (3) were obtained with the relations:

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

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

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

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

where: x_i has been defined in Table 2 and:

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

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

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

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

6. Results and discussion

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

$$\theta = 243.283 \cdot v_c^{0.242} \cdot f^{0.078} \cdot a^{0.021} [°C]. \quad (13)$$

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%

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

In order to check the determined model, many experiments with lower values of the parameters of the cutting conditions and higher than the values used to determinate the model (Fig. 11.) were undertaken.

The dependence of the temperature with the cutting speed (Fig. 12) reveals an important increase of the temperature with the cutting speed. For an increase of the cutting speed from 184.6 to 369.3 m/min,

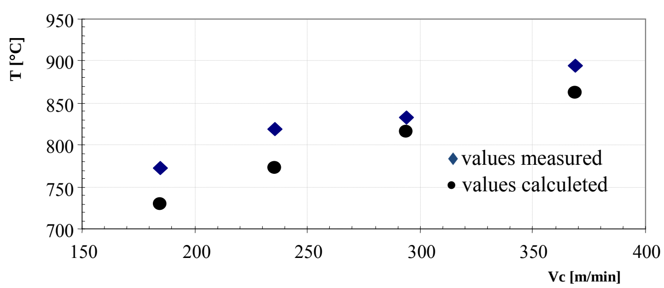


Fig. 11. Comparison between values measured and values calculated of the temperature.

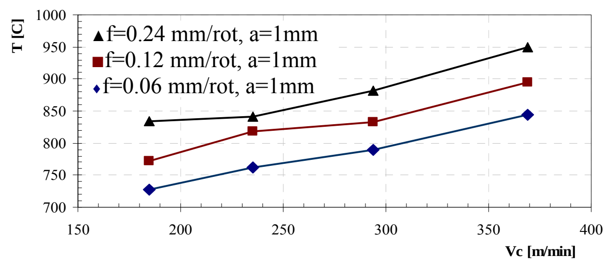


Fig. 12**.** The variation of the temperature with the cutting speed.

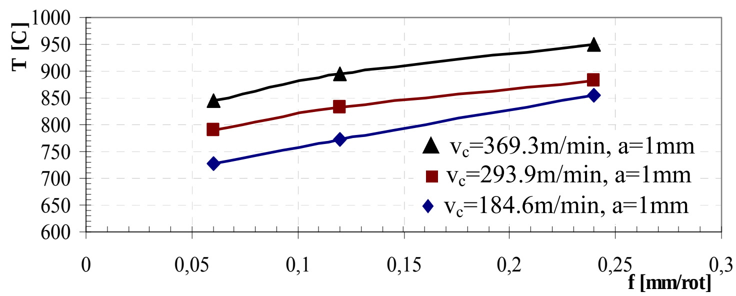


Fig. 13**.** The variation of the temperature with the feed.

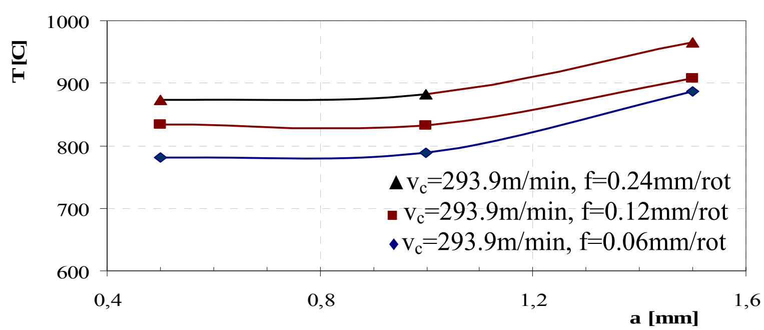


Fig. 14**.** The variation of the temperature with the cutting depth.

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. 13) an increase of the feed from 0.5mm to 2mm (four times), the cutting temperature increased with 93 °C.

It comes out that the influence of the cutting depth on the cutting temperature (Fig. 14) 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 radius (r_ε=0.4mm), whose value is comparable with the minimum cutting depth.

7. 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 hypotheses.

The measurement of this temperature by other measurement means is not possible without considering certain work hypotheses.

The successful check of the determined model for other cutting conditions (see Fig. 6), has shown the validity of the applied theory, the one of the response surfaces and the accuracy of the accomplished experiments, too.

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 the influence of the cutting depth as statistically insignificant [12].

The temperature of the cutting edge can reach high values even for conventional cutting conditions or for the lower 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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