CALCULATION OF TEMPERATURE FIELDS DURING LATHE MACHINING WITH THERMOELECTRICAL COOLING BY USING THE FINITE ELEMENT METHOD

by

Radovan H. NIKOLIĆ [a]***, Miroslav V. LUČIĆ*** [b]***, Bogdan P. NEDIĆ*** [c*]***,***
and Miroslav R. RADOVANOVIĆ [d]

[a] Technical College od Applied Studies in Mechanical Engineering, Trstenik, Serbia
[b] Technical College of Applied Studies, Cacak, Serbia
[c] Faculty of Engineering, University of Kragujevac, Kragujevac, Serbia
[d] Faculty of Mechanical Engineering, University of Nis, Nis, Serbia

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The aim of this work is to explore the possibilities of the implementation of systems based on a thermoelectric module for cooling the cutting tool. This cooling becomes significant when it is not possible to use conventional coolants and lubricants. Starting from existing mathematical models for the calculation of the temperature field of the cutting tool, a mathematical model is developed that takes into account the cooling based on the thermoelectric module. The use of the finite element method determines temperature field when dry lathe machining in the cooling conditions based on the thermoelectric module. The Software package, PAK-T, is used for the calculations and was developed at the Department of Applied Mechanics, Faculty of Engineering in Kragujevac, Serbia. The system for cooling the cutting tool based on the thermoelectric module was realized under laboratory conditions on a prototype model, which consists of a cutting tool and a thermoelectric module. Verification of the obtained results was carried out on the basis of a mathematical model by experimental research of the temperature field of the cutting tool in terms of cooling based on a thermoelectric module.

Key words: *dry machining, cutting tool, heat sources, heat sinks, temperature field, cooling, thermoelectric module, finite element method, cutting tool life*

Introduction

In the machining process by cutting a part of mechanical energy used to remove material from the workpiece is transformed into thermal developing heat sources which cause heating of the elements of the machining system (tools and workpiece). The major quantity of thus generated heat goes away with chips, while a minor part is retained within the workpiece and the cutting tool. From the practical aspect, the heat transferred to the tool and workpiece is of special importance. This is primarily reflected in machineability of the workpiece, that is, the accuracy of shapes and dimensions, quality of the machined surface and tool wear. The heat sources on the tool are located on the cutting wedge. Knowledge of the temperature fields in chips, workpiece an, before all, the tool makes it possible to adjust better the cooling conditions and therefore to reduce unfavourable influences of thermic actions [1]. Lowering of the temperature in the cutting tool is of special importance for reduction of wear and improvement of

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[*] Corresponding author, e-mail: nedic@kg.ac.rs

accuracy of machining. In case of increased requirements for the quality of the machined surface high-speed machining is more increasingly used where it is not possible to apply classical means for cooling and lubrication [2]. In such cases the only economically justified process is dry machining with no cooling [3]. Such conditions of machining increase heating of the cutting tools which leads to its more intensive wear as well [4].

Thermoelectric modules (TEM) in the cooling system in industry find very broad and diversified use. In order to solve the problem of cooling in dry machining the idea has developed to try with application of thermoelectric cooling of cutting tools. The central topic of this paper is theoretical and practical investigation of the possibility of applying thermoelectric cooling of cutting tools [5]. Using the known mathematical models of temperature fields in the tools as a base a mathematic model was developed which takes into consideration cooling by thermoelectric module [6, 7]. In terms of defining boundary conditions this model was suited to the available software package PAK-T [8].

Calculation of temperature fields by using finite element method

In order to investigate the possibility of using TEM for cooling of cutting tools it is necessary first to make calculation of temperature fields in the cutting tools. Within this paper the finite element method (FEM) was used for calculation with added boundary condition which takes into consideration application of TEM for cooling of the tool. The applied mathematical model was suited to application od FEM [5], and the equations were solved by using the program package PAK-T developed at the Faculty of Engineering of the University of Kragujevac [8]. At the model of the cutting tools, the program generates the mesh of finite elements. Because of the method of defining boundary conditions on the face and back surfaces, the finite elements near the top are of greatly reduced dimensions [7].

The input data given are: thermophysical characteristics of material of the tool, tab. 1, values of specific heat fluxes on the surfaces of contact with the workpiece and chips, coefficients of heat transfer due to convection on the surfaces in contact with the ambient [9-12], resistance of heat conductance due to conduction on the surface of contact of the tip holder with the tool holder, specific heat flux on the surface of copper insert in contact with the cold side of TEM and ambient temperature [13, 14]. As an initial condition is given the tool temperature at the moment $t = 0$ equal to the room temperature.

Table 1. Thermophysical characteristics of tool material [13, 14]

Tool parts	Material	Characteristics of the material		
		Material density ρ, [kgm^{-3}]	Specific heat conduction λ, [Wm^{-1}K^{-1}]	Specific heat c_p, [Jkg^{-1}K^{-1}]
Insert type	P20	11600	40	523
Holder	42CrMo4	7830	46	500
Insert piece	Cu	8960	386	385

Table 2. Specific heat flux per fields and field width

Field x_i	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$\bar{q}_{1\lambda i}$, [Wm^{-2}]	3,827	4,315	5,145	5,092	3,67	1,75	0,54	0,11	0,013	0,009
b_i , [mm]	1,13	1,08	1,03	0,98	0,93	0,88	0,83	0,78	0,73	0,68

As the program does not provide for defining the boundary conditions as a function of a point position, the contact surfaces are divided into fields, and the values of the specific heat fluxes are given as the mean values of the field observed, tab. 2 [5]. The contact on the face surface is therefore divided into 10 fields 0.1 mm wide, fig. 1.

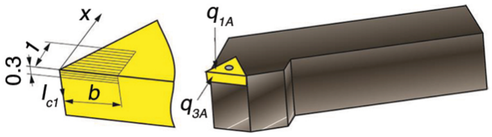

Figure 1. Boundary conditions used in the model on front and back surface of cutting tip

Table 3. Specific heat flux per fields

Field lc_i	0.1	0.2	0.3
$\bar{q}_{3Ai}$, $10^7 \cdot$W/m^2	0.0923	0.205	0.240

The contact on the back surface is also divided into fields of the same width, and the corresponding mean values of specific heat fluxes per fields are given in tab. 3 [5].

In addition to the aforementioned sources in thermal analysis of cutting tools it is also necessary to take into account thermal sinks where the tool by convection makes heat exchange with the ambient. The corresponding coefficients of heat transfer in dry machining which were calculated and given according to [5] are:

- $\alpha_{8,8'sr}$= 27.14 W/m^{2}K coefficient of heat transfer from tool back surfaces into the ambient, due to rotation of the workpiece,
- $\alpha_{6,10sr}$= 9.24 W/m^{2}K coefficient of heat transfer from vertical surfaces of the tools into the ambient, and
- α_{9sr}= 1.3·9.24 =12.1 W/m^{2}K α_{7sr} = 0.7·9.24 = 6.47 W/m^{2}K coefficient of heat transfer from horizontal surfaces of the tool into the ambient.

At the contact of the tool with the holder the heat exchange is done by conduction. Experimentally for the following conditions of the contact: contact pressure is p = 5 kN/cm^2, temperature T = 40 °C, and quality of surface machining Ra = 0.8 µm (N6) the resistance value R_t = 0.05 m^{2}K/W [5, 6] was determined. The coefficient of heat transfer represents the reciprocal value of the resistance:

$$R_t\text{: } 1/R_t = 20\ \text{W/m}^2\text{K}$$

In cooling by TEM the mean air temperature is changed in regards to the previous case whose value was T_m = 40 °C [5], and now it is T_m = 25 °C so that the coefficients of heat transfer for the applied cutting conditions [15-17] have the following values:

$$\alpha_{8,8'\text{sr}} = 27.53\ \text{W/m}^2\text{K} \ \text{ and } \ \alpha_{6,10\text{sr}} = 6.42\ \text{W/m}^2\text{K}$$

while the horizontal surfaces are calculated as mentioned already:

$$\alpha_{9\text{sr}} = 1.3 \cdot 6.42 = 8.34\ \text{W/m}^2\text{K} \ \text{ and } \ \alpha_{7'\text{sr}} = 0.7 \cdot 6.42 = 4.5\ \text{W/m}^2\text{K}$$

The boundary condition, at the point of TEM is defined by specific heat flux which is given [5]:

$$q_C = q_{Co} - K_1 \Delta T$$

where q_C – is the heat flux density from the object toward the cooling system, q_{Co} – the heat flux density extracted by the module from the cutting tool in idling at ΔT = 0, K_1 – the coefficient of direction which represents a constant for specific value of supply voltage of TEM, and $\Delta T = T_h - T_C$ – temperature difference between the hot and cold side of the module.

The software being used in the paper does not provide for defining boundary condition in this form so that mathematical improvisation was made using other possibilities of the software [8, 9]. In this respect the cooling process was presented as a result of two components acting. The first is the heat flux density, q_{Co}, which is directed from the object being cooled. The other component, $q_{(\Delta T)}$, is of the opposite sign and takes into account reduction of the effect of mentioned cooling as a consequence of rise of temperature difference, ΔT, due to cooling and decrease of temperature on the cold side of the module, T_c. The difference of these two components is the effect of work of the thermoelectric module which decreases with the value $q_{CO,}$ in idling at $\Delta T = 0$, down to zero at $\Delta T = \Delta T_{\max}$. The value $q_{(\Delta T)}$ is defined as fictive convection of TEM towards the tool. The diagram of the cited two components is given in fig. 2 and the heat flux density which represents the effect of thermoelectric cooling is illustrated by hatched area.

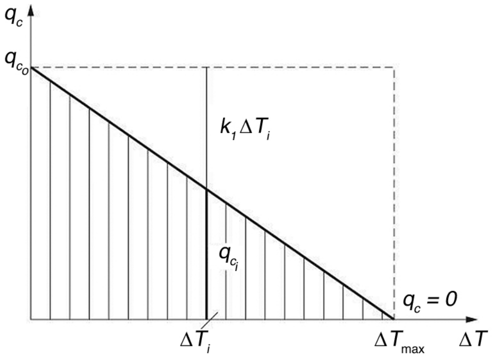

Figure 2. Defining boundary conditions at the place of TEM

Figure 3(a) shows the tool cooling system with TEM installed at the back side of tool holder and in fig. 4 shows the mesh of finite elements for tool based on TEM for this design version.

Figure 3(b) shows the tool cooling system based on TEM fitted on to the main front surface. For investigation within this paper the design version has been adopted where the cooling system is installed on the main back surface below the cutting wedge so as to be closer to heat sources. The reason for this is the fact that the effects of cooling when fitting TEM on the back side of the cutting tool are significantly lower when compared with the cooling effects if TEM is at the front side immediately below the cutting wedge. For this design version of the cooling system, the mesh of finite elements is given in fig. 5.

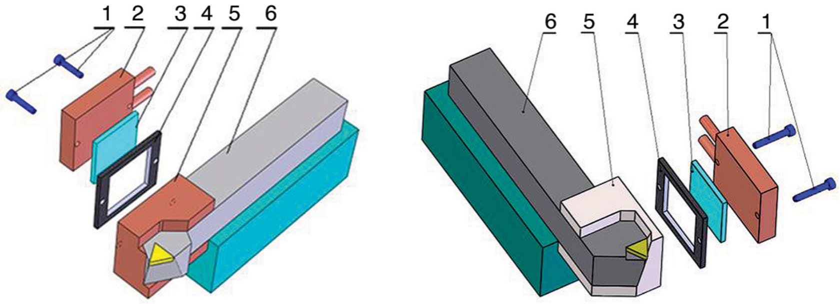

Figure 3. (a) Tool cooling system with TEM, at the back side of tool holder, (b) tool cooling system based on TEM, fitted onto the main back surface: *1−screws, 2−coole li-201, 3−TEM, 4−thermal insulation, 5−insert piece 6 tip holder*

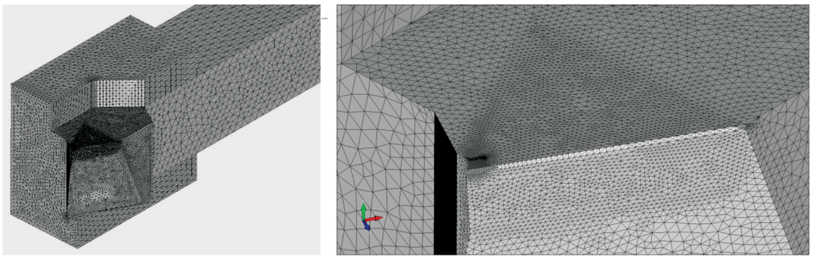

Figure 4. Tool cooling system based on TEM installed at the back side of tool holder with the mesh of finite elements

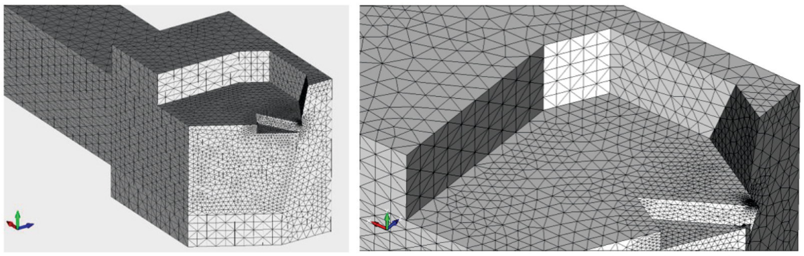

Figure 5. Tool cooling system based on TEM, fitted onto the main front surface of the cutting tool with the mesh of finite elements

Experimental investigation of temperature fields

Experimental investigation was made on a universal lathe PA-30, the product of company "POTISJE" Ada, for the following machining conditions:

- production operation: turning, fine longitudinal machining,
- method of fixing: between centres,
- machining parameters: cutting speed V_c = 100 m per minute, cutting depth a_p = 1.0 mm and feed f = 0.15 mm/o,
- cutting tool: carbide tip TPMN 160408, quality P20, "Sandvic Coromant" with holder CTEPR 3030M16 from 42 CrMo4 (SRPS EN 10083-1:2004), and
- cutting geometry: $\kappa = 60°$, $\gamma = 0°$, $\alpha = 11°$, $\lambda = 0°$ and $r_\varepsilon = 0.8$ mm.

On the back surface of the tool a facet l_{c1} = 0.3 mm was made by additional grinding. Characteristics of carbide P20 and tip holder according to producers data and characteristics of the copper insert piece are given in tab. 1.

- workpiece: a round bar Ø80 mm, made of steel C60 (SRPS EN 10083-2:2004), in annealed state, R_m = 70 da N/mm^2, hardness 240 HB and
- machining is done at dry and with cooling the cutting tool by the TEM based system (three temperature values at the hot side of the module, and for each of them varying the value of operating voltage).

For the verification of the basic model, since it has been subjected to corrections primarily when calculating the power of heat sinks, the temperature was measured at one point in the contact zone of tools and chips, and at seven points along the tool body as shown in fig. 6.

The temperature was measured by an artificial thermocouple, and the value measured was compared with the calculated. The thermocouple was placed into a hole drilled from underside of the tool which through the tip goes out to the face surface at 0.6 mm far from the cutting edge. The hole accommodates the thermocouple S-type (Pt + 10% Rh) with wire diameters 0.05 mm [18].

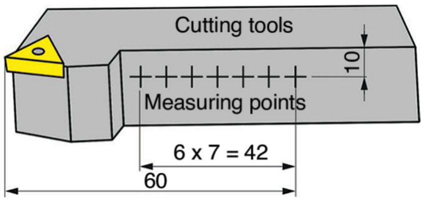

Figure 6. Arrangement of measuring points on the cutting tool

Reading of the temperature values along the tool body was made at time intervals of 2 minute. For the purpose of investigating the possibilities of TEM cooling of tools, the TEM based cooling system has been designed and made and it has been tested for cooling effects by measuring the temperature at selected points along the tool body. By comparing the measured values with the calculated ones validity of the developed mathematical model for calculation of temperatures within the tool cooled by thermoelectric module has been checked.

The TEM based cooling system was fitted onto the adapted cutting tool. The heat exchanger between the supply and discharge connector for fluid has a hole where a sensor connected with the regulator is installed. In this way the regulator obtains the signal of the temperature value on the hot side and performs regulation by comparing with the set value. When installing the cooling system, special care should be taken to achieve quality thermic contacts and insulation of the space where the module is located. All mechanical connections with the object to be cooled are at same time the thermic connections with the ambient. Functioning of the system greatly depends upon the quality of installing and therefore the installing is to be carried out exactly according to the procedure given by the producer [4].

The experimental cutting tool cooling system based on TEM is of the type HP-199-1.4-0.8, producer is TE Technology, Traverse City, Mich., USA, shown in fig. 7. Characteristics of TEM HP-199-1.4-0.8 are given in tab. 4 [19]. In fig. 8 are: *A* and *B* - with (mm), *H* - height (mm), *F* - flatness (mm), *P* - parallelism (mm), *WS* - wire size (mm^2), *WL* - wire length (mm).

The producer gives the operating characteristics of the module in the form of a diagram. These diagrams give the values of the absorbed quantity of heat as a function of temperature difference ΔT, in dependence of: temperature on the hot side and the value of operating voltage. The producers' leaflets show the module operating characteristics for three values of hot side temperature, T_h: 30, 50, and 70 °C. From the diagram are read q_{c0} and $\Delta T_{\max}$ and they serve as a base to calculate q_{c0} and k_1, whose values are shown in tab. 5.

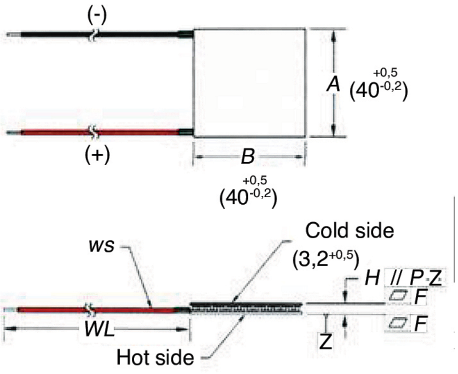

Figure 7. The TEM type HP-199-1.4-0.8 [20]

Table 4. Characteristics of TEM HP-199-1.4-0.8

Characteristics	T_h= 27 °C	T_h= 50 °C
Operating voltage, $V_{\max}$, [V]	24.6	27.3
Current intensity, $I_{\max}$, [A]	11.3	11.3
Absorbed heat, $Q_{\max}$, [W]	172.0	188.7
Temperature difference	69	78
Cooler operating temperature	− 40 do + 80°C	

Cooling of the module hot side is carried out by the heat exchanger based on fluid type LI20ICL, producer MELCOR, Trenton, N.Y. USA [20]. On the hot side the temperature is regulated by automatic regulator with digital definition of values, type MRC 150 of the same producer.

Table 5. Values q_{c0} i k_1

T_h = 30 °C			T_h = 50 °C			T_h = 70 °C		
U, V	k_1,W/mm^{2}K	q_{c0}, W/mm^2	U, V	k_1,W/mm^{2}K	q_{c0}, W/mm^2	U, V	k_1,W/mm^{2}K	q_{c0}, W/mm^2
23.9	0.00128	0.08125	26.2	0.00125	0.0875	28.4	0.00122	0.095
18.3	0.00128	0.0775	20	0.00125	0.08375	21.7	0.00122	0.09
13.8	0.00128	0.0675	15	0.00125	0.0725	16.3	0.00122	0.0775
9.2	0.00128	0.05125	10	0.00125	0.05625	10.9	0.00122	0.06

Testing of TE cooling effects and verification of the mathematical model have been made by measuring the temperature values along the tool body at seven points. In doing this the TEM operating regimes were varied (the temperature on the hot side of the module T_h and operating voltage). Comparison of the measured values with the calculated ones has led to the conclusion about adequacy of the developed mathematical model.

Cooling effects are monitored on the basis of values of maximum temperatures. Since the basic mathematical model has been verified before testing the cooling system, all analyses have been made on the basis of calculated maximum values. Namely, since these are exchangeable tips it would be necessary to drill a new hole and install the thermocouple in the tip at each blunting and changing of the cutting edge. Measuring the tool life for various operating parameters of TEM have completed the conclusions about the possibilities of application of this method of cooling the cutting tools.

With thermoelectric cooling the temperature values from the first to the seventh point, at time intervals of 5 minutes are obtained as recordings on the tape. The reading interval can be adjusted if necessary. The reading accuracy at the measurement is 0.1 °C.

Analysis of results of the investigation

The results of calculation of temperature fields can be displayed as diagrams or in the form of temperature space field. The diagram display shows the change of temperature value along the tool body. Comparison with the experimental values is made at the points where measurements have been taken, and the time interval of the readings at dry machining and for cooling based on TEM installed on the back side of the tool holder is 2 minutes. In this way validity of the model has been checked. Output results in the form of a space figure are more adequate when the measurement is made by an infrared camera. In any case, the program allows for quantification of the temperature at any point of the tool, at any moment of time.

Measured temperature values at dry machining (experimental) and temperature values obtained on the basis of basic model (calculated) were shown on a diagram of change per tool length in fig. 8, order to make it possible to make comparative analysis, fig. 9.

At the end of cutting, that is, after $t = 480$ s, at the measuring point, at the contact zone on the face surface, the temperature value measured is $T = 760$ °C, while the calculated value is $T = 700$ °C. The results of the calculation are displayed in fig. 9 in the form of temperature space field.

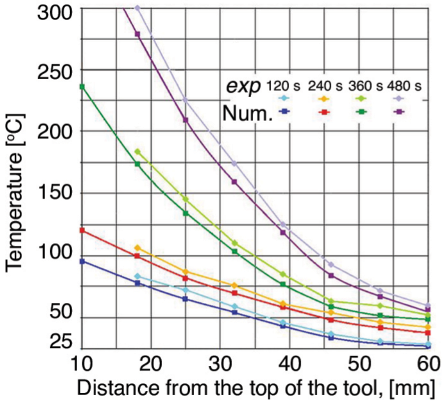

Figure 8. Temperature values at dry machining

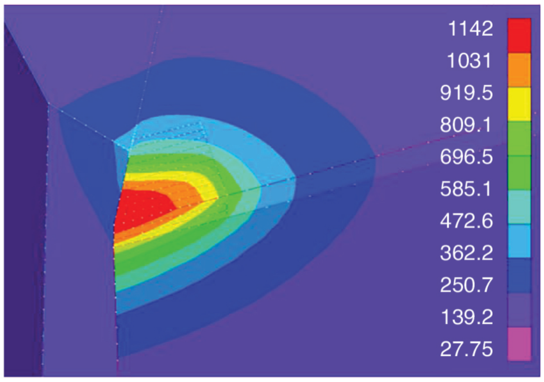

Figure 9. Calculated temperature values at dry machining

Since the deviation is within the limits allowed, the developed mathematical model gives satisfactory accuracy so it can be taken as the basic in investigation of the above mentioned cooling systems for cutting tools. In fig. 9 the calculated temperature at dry machining in tool holder.

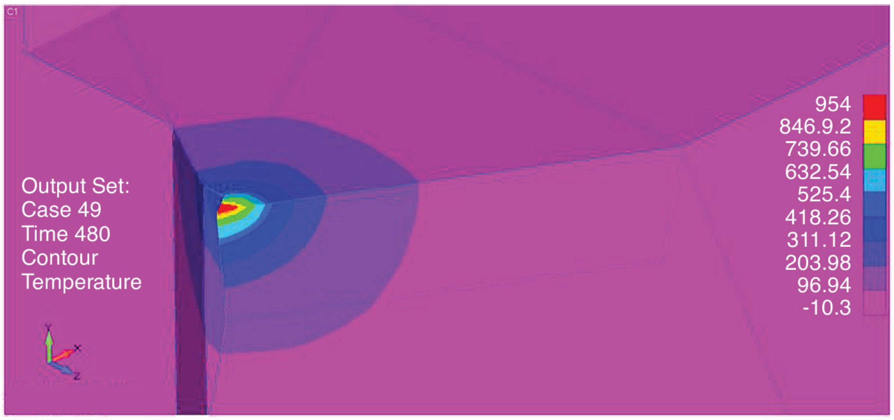

Figure 10. Temperature values in the tool with thermoelectric cooling located on the back side of the tip holder for T_h = 30 °C and U = 23.9 V, after t = 8 min

In models with cooling of cutting tools by a TEM based system located on the back side of the tip holder heating of the tool occurs in the already explained way. The power of heat sources is the same as in the previous case while the power of heat sinks is changed because the average temperatures of the surfaces from which convection is performed are changed due to cooling. By action of the cooler in the volume immediately below the module this cold front widens. In order to achieve as good cooling effects as possible, the module chosen has much greater power than the calculated power of heat sources.

The results of calculation in the form of temperature space field for machining with cooling by a thermoelectric system located on the back side of the tip holder are displayed in fig. 10. The temperature values in cooling by such a system for the particular operating parameters of the module (temperature on hot side, T_h, and operating voltage) are given in fig. 11.

Comparison of calculated and experimentally obtained values has shown that deviations are within limits up to 10%, so that the developed mathematical model can be accepted as good.

Figure 12. shows temperature change per tool length with time for the design version where TEM is located on the back

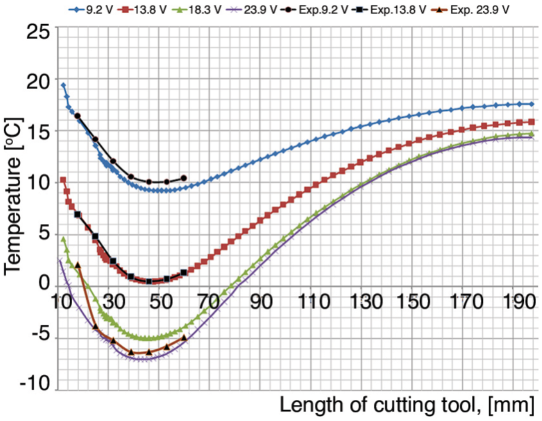

Figure 11. Temperature values within the tool with thermoelectric cooling for T_h = 30 °C

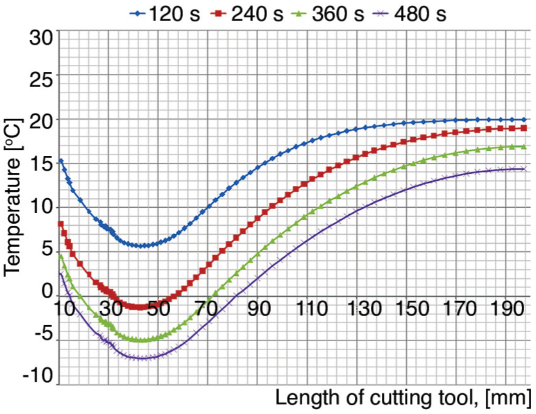

Figure 12. Change of temperature value per tool length with time with thermoelectric cooling located on the back side of the tip holder for T_h = 30 °C and U = 23.9 V

side of the tip holder for the operating regime which ensures the most effective cooling, that is, $T_h = 30$ °C and $U = 23.9$ V

Figure 13. Temperature values within the tool with thermoelectric cooling located on the main back surface for $T_h = 30$ °C and $U = 23.9$ V, after 12 minute

Figure 13. shows calculated temperature values in the cutting tool for the design version where the TEM based cooling system is located on the front side below the cutting wedge. The advantage of application of this version is significantly lower temperature on the main back surface, and thus on the cutting tool top as well.

Temperature change per tool length for this cooling conditions with time is shown in fig. 14.

Further investigations should be directed to application of new generation TEM which would be installed in the tip holder immediately below the tip. The new modules are of much greater efficiency factors and also located nearer to the heat sources so that the cooling effects would be more prominent. Besides, the time necessary to lower the temperature in the critical zone would be shorter which is also of importance.

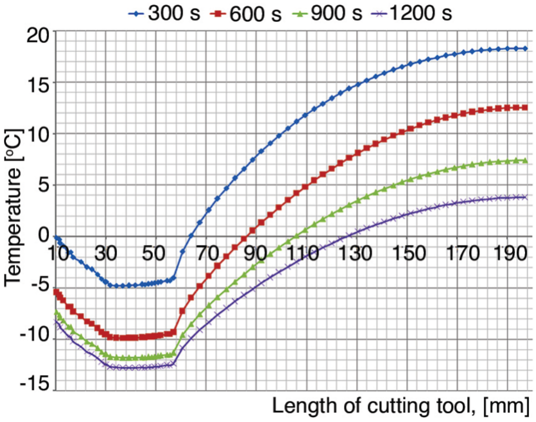

Figure 14. Temperature values within the tool with thermoelectric cooling located on the main back surface for $T_h = 30$ °C and $U = 23.9$ V, after 12 minute

Conclusions

Bearing in mind the investigations in the area of thermoelectric cooling have been intensified, this paper has focused on theoretical and experimental investigations of the possibility of application of thermoelectric cooling of cutting tools.

Within the investigation was realized the system for thermoelectric cooling of cutting tools during fine machining on lathe. In the first design version TEM based cooling system was installed on the back, lateral side of the tip holder, on the opposite side of the heat sources. To be safe with application of FEM for calculation of cutting temperature in machining with cooling by means of thermoelectric systems, the modified basic mathematical model was experimentally verified. As fine machining parameters in experimental lathe machining (cutting seed, V_c, cutting depth, a_p and feed, f) were taken the values for which the power of heat sources have been calculated in the basic model. It is applied to other conditions of machining as well. Although the cooling system have been equipped with a TEM of significantly higher power, the lowest temperature value to which the critical zone was cooled is 954 °C. In addition, cooling of this zone is not fast enough. The cooling effects of TEM are the most prominent at the operating regime $T_\mathrm{h} = 30$ °C and operating voltage $U = 23.9$ V. It should be noted that here also, as in case of the basic model, there is satisfactory agreement of calculated and experimental results, that is, the deviations are within the allowed limits so that the mathematical model can be accepted as good. However, regardless of the fact that there are expressed cooling effects at the points near TEM, the temperatures within the zone of machining were slightly lower.

In the second design version the TEM based cooling system was installed on the main back surface. In this version the calculated temperature values were retained, bearing in mind that the model has been verified by experimental testing in its first version so that of primary interest were cooling effects, that is, life of cutting tools. By cooling in this manner for the operating parameters of TEM which give the maximum cooling power ($T_\mathrm{h} = 30$°C and $U = 23.9$ V), the obtained calculated value of maximum temperature is 758.2 °C.

These theoretical and experimental investigations have shown that cooling of cutting tools using a TEM based system is possible. The developed mathematical model of cooling can be applied to any object cooled by some of such systems. Although some of the effects observed were below the expectation, the base for further investigations was made. They should be directed to new design of TE systems for cooling cutting tools and application of new generation modules which are much more compact, require less space for installing, and also have many times higher efficiency factors. This should provide for more effective cooling in terms of faster and greater lowering of the temperature in the cutting zone.

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