Cutting Tool Temperature in Cylindrical Turning

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ABSTRACT

This paper is presenting a numerical model for tool temperature during cylindrical turning process. A Fourier series approximation is used as a pattern for cutting tool temperature and this model is loaded with constant and variable heat flux input as well as convective cooling conditions. The influence of the temperature dependent material properties is also taken into consideration. The influence of these conditions on the cutting tool maximum temperature position and level is analyzed as a factor for determination of the tool wear.

Keywords: cutting tool, turning, tool temperature, wear.

1. Introduction

A part of the heat generated during the cutting process is acting on the cutting tool increasing the cutting tool temperature level. Consequently, the tool wear is higher and it is affecting the tool life, the dimensional accuracy of the workpiece and the machining efficiency. These are only some aspects of the importance detained by the cutting tool temperature research, importance that determined intense studies on this subject.

The most frequently studied processes are referring to contour turning, orthogonal cutting, interrupted turning or cylindrical turning [1÷4]. As a function of the studied process, the researchers constructed numerical models and considered:

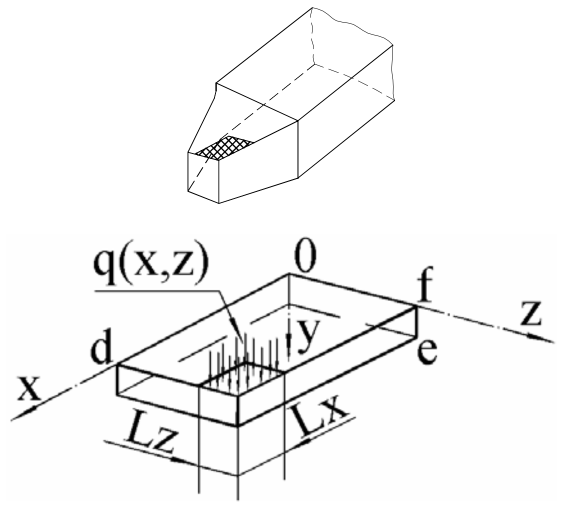
- stationary [4] or non-stationary [1÷3] thermal field for the cutting tool temperature;
- constant velocity, feed rate and depth of cut, their variation being expressed mainly as a variation of the tool/chip contact area or as the heat flux input time variation [3];
- a water-based coolant requiring the consideration of convective cooling at the "exterior" boundaries, while the oil-based lubricants or the absence of cooling require the consideration of isolated "exterior" boundary conditions [3];
- the heat flux input profile that was considered constant throughout the tool/chip contact area or variable with a semiempirical parabolic profile [1,2]. The latter case was found to provide a better agreement with the real value and position of the cutting tool wear.
- constant or variable thermal properties.

Although, a model that is using the Fourier series approach for the cutting tool temperature was used in the past ([1]÷[2]), the influence of variable thermal properties on this model was not found in the literature.

The numerical methods that were used varied from one paper to the other: some of them ([1], [3]) are using the Fourier series expression for the cutting tool transient temperature field; other works ([2]) are having in view that some materials have temperature dependent material properties and they developed a numerical model using control volume approach; some papers ([4]) used a finite element model for predicting the cutting tool temperature taking into account the insert nose radius, included angle and insert/holder materials. These works are not only reproducing the machining conditions and the temperature fields of the cutting tool but they are using these results for predicting the temperature and wear maximum level as well as for setting an adaptive control system of the cutting process.

This paper is using previous results obtained in the study of this domain (choosing a Fourier series form for the analyses of the transient cutting tool temperature) and is trying to improve the knowledge on the cutting process taking into consideration the cooling conditions, the influence of a heat flux input parabolic profile, the total energy input level and the variation of thermal properties on the distribution and level of the cutting tool temperature and, consequently, on the tool wear.

2. Mathematical formulation



(a)
(b)

Fig. 1. (a) Cutting tool with a rectangular insert; (b) cutting tool insert loaded with a flux, q, during the cutting process.

A cutting tool with a rectangular insert, Fig. 1, is considered. In a Cartesian system of reference, xyz, associated to the tool insert, the finite computational domain has the dimensions $d \times e \times f$. The heat transfer equation for the tool insert domain becomes:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q(x,y,z)}{k}, \quad (1)$$

where $T(x,y,z,t)$ is the temperature field; α is the thermal difusivity and k is the thermal conductivity.

The initial condition,

$$T(x,y,z,0) = T_0, \quad (2)$$

the Newmann,

$$\left.\frac{\partial T}{\partial x}\right|_{x=d} = \left.\frac{\partial T}{\partial y}\right|_{y=0} = \left.\frac{\partial T}{\partial z}\right|_{z=f} = 0, \quad (3)$$

and Dirichlet boundary conditions:

$$T(0,y,z,t) = T(x,y,0,t) = T_0, \quad (4)$$

are associated to it. The chip/tool contact area is $(L_X \times L_Z)$ and along this area the heat flux input is $q(x,z)$.

In the literature [1÷3], two situations are considered for the insert/support interface condition: it could have the ambient temperature,

$$T(x,e,z,t) = T_0, \quad (5)$$

or the insert could be isolated from the support,

$$\left.\frac{\partial T}{\partial y}\right|_{y=e} = 0. \quad (6)$$

Fourier series development of the insert temperature is considered [1], [5]:

$$\theta = T - T_0 =$$

$$= \sum_i \sum_j \sum_k \Theta_{ijk}(t)\sin(\alpha_i x)\cos(\beta_j y)\sin(\gamma_k z). \quad (7)$$

The coefficients α_i, β_j and γ_k are calculated from the boundary conditions (3÷6):

$\alpha_i d = \frac{2i-1}{2}\pi$; $\gamma_k f = \frac{2k-1}{2}\pi$; $\beta_j e = \frac{2j-1}{2}\pi$ or $\beta_j e = j\pi$ depending on the boundary condition at $y = e$.

The function $\Theta_{ijk}(t)$ is the solution of the following equation [1]:

$$\frac{d\Theta}{dt} + \omega\Theta = \Omega, \quad (8)$$

where

$$\Theta_{ijk}(0) = 0; \quad (9a)$$

$$\omega_{ijk} = \alpha_T\left(\alpha_i^2 + \beta_j^2 + \gamma_k^2\right); \quad (9b)$$

$$\Omega_{ijk} = \alpha\frac{Q_{ijk}}{kI_i J_j K_k}; \quad (9c)$$

$$I_i = \int_0^d \sin^2(\alpha_i x)dx = \frac{d}{2} - \frac{\sin(2\alpha_i d)}{4\alpha_i}; \quad (9d)$$

$$K_k = \int_0^f \sin^2(\gamma_k z)dz = \frac{f}{2} - \frac{\sin(2\gamma_k f)}{4\gamma_k}; \quad (9e)$$

$$J_j = \int_0^e \cos^2(\beta_j y)dy = \frac{1}{\beta_j}\left(\frac{\beta_j}{2} + \frac{\sin(2\beta_j e)}{4}\right),$$

if $T(x,e,z,t) = ct.$, or (9f)

$$J_j = \frac{e}{2} + \frac{\sin(2\beta_j e)}{4\beta_j}, \text{ if } \left.\frac{\partial T}{\partial y}\right|_{y=e} = 0. \quad (9g)$$

$$Q_{ijk}(t) = \int_0^d\int_0^e\int_0^f q(x,y,z)\sin(\alpha_i x)\cos(\beta_j y)\sin(\gamma_k z)dxdydz \quad (9h)$$

The model was completed with the consideration of the temperature dependent material properties of the insert. The temperature variation of thermal conductivity and specific heat capacity are reproducing the relations used in the literature[2] both for high speed steel,

$$k = 61.16 - 0.047T \ [W/mK];$$

$$C_p = 478 - 0.55T + 0.019T^2 \ [J/KgK], \quad (10)$$

and tungsten carbide,

$$k = 57.7 + 0.0099T \ [W/mK];$$

$$C_p = 443.7 + 0.435T \ [J/KgK]. \quad (11)$$

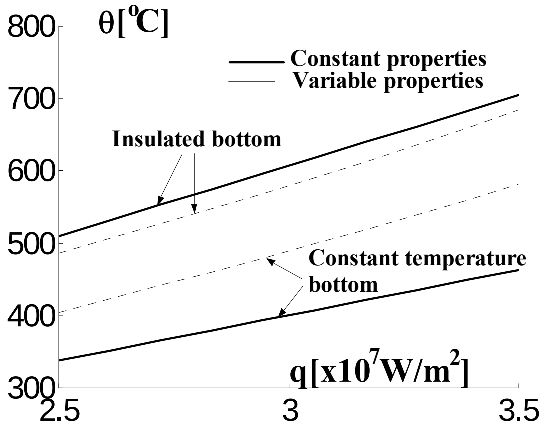
In these cases, an iterative procedure was developed for cutting tool temperature calculation.

3. Simulation results

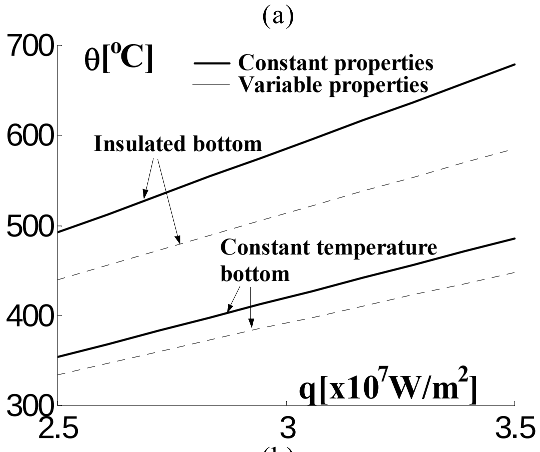
The material properties, the geometric dimensions and the working conditions used in the numerical applications are presented by Table 1. These values were considered throughout the paper unless stated otherwise.

Table 1[1]

High speed steel properties		
Thermal diffusivity	α	$8x10^{-2}cm^2/s$
Thermal conductivity	k	$61.16W/m^2K$
Density	ρ	$1000Kg/m^3$
Specific heat	cp	478.5J/Kg/°C
Tungsten Carbide Properties		
Thermal diffusivity	α	$8x10^{-2}cm^2/s$
Thermal conductivity	k	W/m^2K
Density	ρ	$1000Kg/m^3$
Specific heat	cp	443.7J/Kg/°C
Insert geometrical properties		
Dimensions	d	13.47 mm
	e	3.35 mm
	f	13.47 mm
Machining parameters		
Chip/tool contact	Lx	2.47 mm
Area	Lz	0.4 mm
Heat flux input	q	$30MW/m^2$



(a)

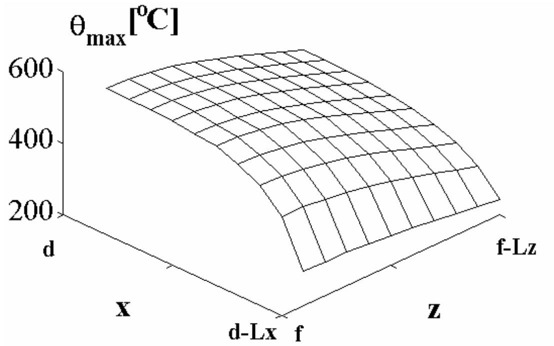


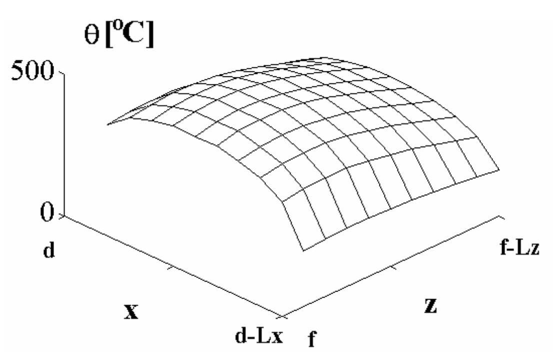
(b)

Fig. 2. θ_{max} — q variation for (a) high speed steel and (b) tungsten carbide tool insert, for two cases: isolated and constant temperature bottom; t=1s.

Figure 2 is presenting the results of the cutting tool temperature for the case of constant heat flux input and for both insulated and ambient temperature bottom, for both tool insert materials: high speed steel and tungsten carbide. Figure 2 is underlying the influence of considering variable thermal properties for tool inserts. Using an iterative procedure, the Fourier series approximation for the temperature field produces the same results as more complicated and time consuming methods [2]. For both high speed steel and tungsten carbide, the difference between the constant and variable properties cases increases as the heat flux input q increases. This is taking place because higher temperatures are imposing higher variation on the thermal properties (11÷12). For the high speed steel insert, the difference is higher for constant temperature bottom while for tungsten carbide the difference is higher for insulated bottom case.

Further, the results are considering only the high speed steel material and insulated bottom. In order to analyze the influence of the cooling conditions, the isolated boundary conditions at x=d and z=f (3) were relaxed and convective heat transfer is considered:





$$\frac{\partial\theta}{\partial x} + Bi \cdot \theta = 0 \ \text{at} \ x = d; \qquad (12)$$

$$\frac{\partial\theta}{\partial x} + \mathrm{Bi}\cdot\theta = 0 \ \text{ at } \ z = f\,. \tag{13}$$

(a)
(b)

Fig. 3. Cutting tool temperature variation; Q=35MW/m^2; t=1s; variable thermal properties; Bi=0 (a) and Bi=1 (b).

Using the equations (9) and (11), the α_i and γ_k unknowns can be found from:

$$\alpha_i \cos(\alpha_i d) + \mathrm{Bi}\cdot\sin(\alpha_i d) = 0\,, \tag{14}$$

$$\gamma_k \cos(\gamma_k f) + \mathrm{Bi}\cdot\sin(\gamma_k f) = 0\,. \tag{15}$$

As a consequence, the maximum temperature moves from the tip of the tool (Fig. 3a) towards the interior of the cutting tool (Fig. 3b). This result sustains the idea of this paper that considering the convection process is very important in the numerical modeling of the cutting tool temperature.

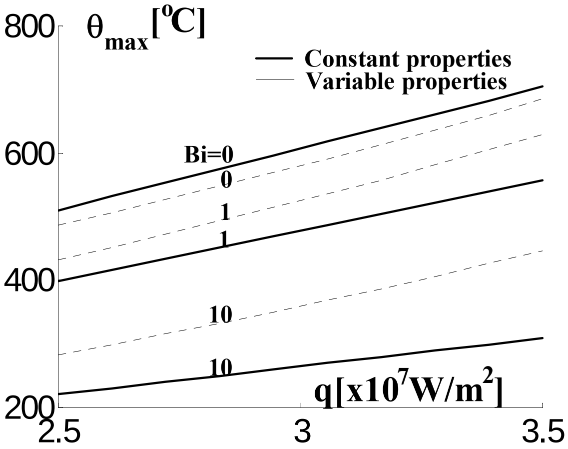


Fig. 4. θ_{max} — q variation for different cooling conditions: Bi=0; 0.1; 1.0 and 10.0; t=1s.

Not only the position, but also the level of maximum temperature depends on the cooling conditions. Fig. 4 presents the maximum temperature level variation as a function of heat flux input for three different cooling conditions, i.e., three Biot numbers. As Biot number increases (the cooling is better) the maximum temperature level decreases significantly. The influence of the temperature variable properties is higher as Biot number increases while the variation obtained for Bi=0 agrees well with the results obtained in the literature using more complex methods [2].

The research literature [2] tried to explain the position of the maximum temperature and the temperature level found experimentally using a variable input heat flux for the same total amount of energy input. For the notations and particularities of the current problem, such a heat flux input would have the following form:

$$q = q_0 \times \left[C1 + M(d-x)(L_x - d + x)(f-z)(L_z - f + z)\right], \tag{16}$$

where $$M = \frac{36(1-C_1)}{L_x^2 L_z^2}\,. \tag{17}$$

Replacing the new form of q, (9h) becomes:

$$Q_{ijk} \overset{def}{=} \int_0\int_0\int_0 q(x,y,z)\sin(\alpha_i x)\cos(\beta_j y)\sin(\gamma_k z)\,dxdydz =$$

$$= \left[-en2 + (-L_x + 2d)en1 + d(L_x - d)en\right]\times \left[-in2 + (-L_x + 2f)in1 + d(L_z - f)in\right], \tag{18}$$

where

$$en = \frac{1}{\alpha_i}\left[\cos(\alpha_i(d - L_x)) - \cos(\alpha_i d)\right]; \tag{19a}$$

$$en1 = \frac{1}{\alpha_i}\left\{(d - L_x)\cos[\alpha_i(d - L_x)] - d\cos(\alpha_i d)\right\} + \frac{1}{\alpha_i^2}\left\{\sin(\alpha_i d) - \sin[\alpha_i(d - L_x)]\right\}; \tag{19b}$$

$$en2 = \frac{\left\{(d - L_x)^2\cos[\alpha_i(d - L_x)] - d^2\cos(\alpha_i d)\right\}}{\alpha_i} + \frac{2}{\alpha_i^2}\left\{d\sin(\alpha_i d) - (d - L_x)\sin[\alpha_i(d - L_x)]\right\} + \frac{2}{\alpha_i^3}\left\{\cos(\alpha_i d) - \cos[\alpha_i(d - L_x)]\right\}; \tag{19c}$$

$$in = \frac{1}{\gamma_k}\left[\cos(\gamma_k(f - L_z)) - \cos(\gamma_k f)\right]; \tag{19d}$$

$$in1 = \frac{\left\{(f - L_z)\cos[\gamma_k(f - L_z)] - f\cos(\gamma_k f)\right\}}{\gamma_k} + \frac{1}{\gamma_k^2}\left\{\sin(\gamma_k f) - \sin[\gamma_k(f - L_z)]\right\}; \tag{19e}$$

$$in2 = \frac{\left\{(f - L_z)^2\cos[\gamma_k(f - L_z)] - f^2\cos(\gamma_k f)\right\}}{\gamma_k} + \frac{2}{\gamma_k^2}\left\{f\sin(\gamma_k f) - (f - L_z)\sin[\gamma_k(f - L_z)]\right\} + \frac{2}{\gamma_k^3}\left\{\cos(\gamma_k f) - \cos[\gamma_k(f - L_z)]\right\}; \tag{19f}$$

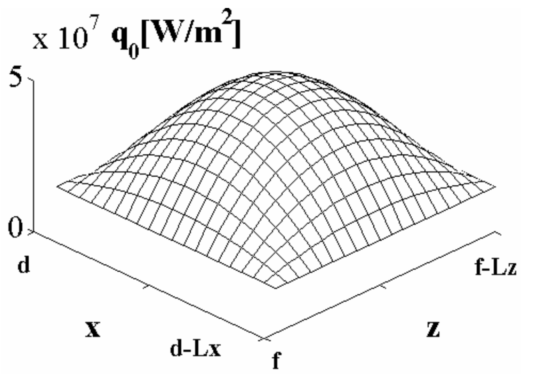


Fig. 5. Heat flux input distribution for q_0=35MW/m^2; C_1=0.5.

For q_0=35MW/m^2 and C_1=0.5, the heat flux input has the distribution presented by Fig.5. The temperature distribution for the variable heat flux cases can be analyzed from Fig.6. The way in which a parabolic distribution of the heat flux input changes the position of the maximum temperature and, consequently, the position of the maximum wear, is obvious.

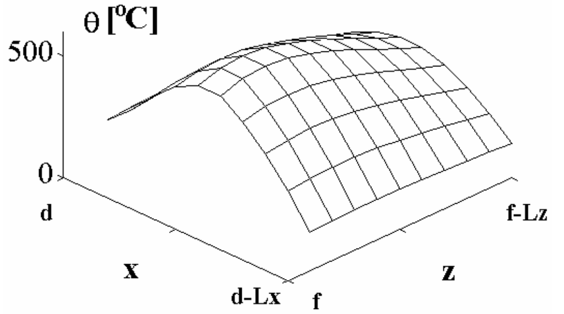


Fig. 6. Temperature distribution for C_1=0.5, q_0=35MW/m^2; Bi=10; t=1s.

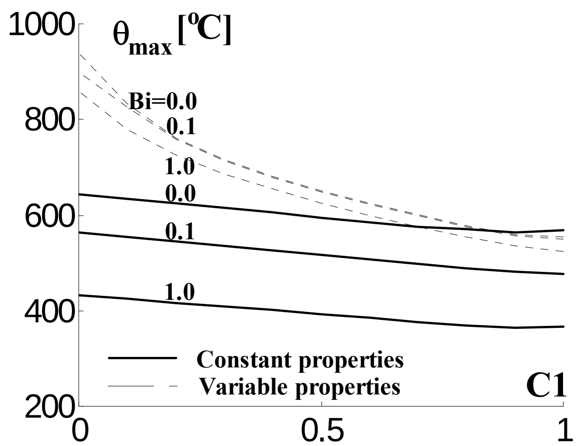
More than that, the value of the maximum temperature increase as C_1 decreases as is shown by Fig. 7. It presents maximum temperature variation, θ_{max}, as a function of heat flux input distribution (C1) for three cooling conditions: Bi=0; 0.1 and 1. As anyone would expect, the increase of Bi number, better cooling conditions, is reducing the maximum temperature level for all heat flux input distribution. The maximum temperature increases as the heat flux input distribution is more different than a constant distribution, in other words, as C_1 decreases.

4. Conclusions

This paper is presenting a numerical model for the temperature distribution of a cutting tool insert during the turning process. A Fourier series approximation is used to model the cutting tool insert temperature. The influence of the heat flux input, the cooling conditions and variable thermal properties are considered in analyzing the temperature variation and, consequently, the tool wear.

The model is verified using the results found in the literature for high speed steel and tungsten carbide inserts in two situations: an insulated and a constant temperature insert/holder condition. Considering variable thermal properties and an iterative procedure help us to reproduce the results found in the literature [2] and to validate this model.
Further, only high speed steel insert was

Fig. 7. Maximum temperature variation as a function of heat flux input (C_1) for different values of Biot number: 0; 0.1 and 1; t=1s; q_0=30MW/m^2.



considered. The convective cooling conditions move the maximum temperature towards the interior of the insert and is reducing its level. The temperature distribution agrees with the experimental results related to the tool wear position.

Considering parabolic distribution for heat flux input profile, the maximum temperature increases and its position moves further towards the interior of the insert. In this case, the cooling conditions play a fundamental role in the wear level and position.

This paper is presenting the importance of the cooling conditions on the determination of the maximum cutting tool temperature and on the position of the maximum wear. It can provide an analytical tool for setting an adaptive control for the cutting process.

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Temperatura Cuțitului de Strung la Strunjirea Cilindrică

REZUMAT

Acestă lucrare prezintă un model numeric pentru temperatura cuțitului de strung în timpul strunjirii cilindrice. O descompunere în serie Fourier este utilizată pentru modelarea temperaturii cuțitului de strung iar acestui model i se aplică o solicitare termică constantă sau variabilă precum şi condiții de răcire prin convecție. Influența proprietăților de material cu temperatura este, deasemenea, luată în considerare. Influența acestor condiții asupra amplasamentului şi mărimii temperaturii maxime a sculei aşchietoare este analizată ca un factor pentru determinarea uzurii maxime a sculei.

Ausschnitt-Werkzeug-Temperatur im zylinderförmigen Drehen

AUSZUG

Dieses Papier stellt ein numerisches Modell für Werkzeugtemperatur während des zylinderförmigen drehenprozesses dar. Ein Fourier-Reihe Näherungswert wird verwendet, während ein Muster für Ausschnittwerkzeugtemperatur und dieses Modell mit dem konstanten und variablen Hitzefluß geladen wird, der sowie Übertragungsabkühlbedingungen eingegeben wird. Der Einfluß der abhängigen materiellen Eigenschaften der Temperatur wird auch in Erwägung gezogen. Der Einfluß dieser Bedingungen auf die Position und das Niveau der maximalen Temperatur des Ausschnittwerkzeugs wird als Faktor für die Ermittlung der maximalen Abnutzung des Werkzeugs analysiert.