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Mechanical and thermal modeling of orthogonal turn-milling operation

Umut Karaguzel[a]*, Mustafa Bakkal[b], Erhan Budak[c]

[a]Engineering Department, Isık University, 34980, Istanbul, Turkey
[b] Mechanical Engineering Department, Istanbul Technical University, 34437 Istanbul, Turkey
[c] Faculty of Engineering and Natural Sciences, Sabanci University, 81474 Istanbul, Turkey

* Corresponding author. Tel.: +90-216-712-1460; fax: +90-216-712-1468. *E-mail address:* umut.karaguzel@isikun.edu.tr

Abstract

Turn-milling is a relatively new machining technology which is performed for cutting of symmetrical or non-symmetrical rotational parts. To improve productivity, determination of cutting parameters in turn-milling is crucial. However, experimental approach is costly, hence it is important to develop predictive models, especially analytical models, for improved process outputs such as cutting force, MRR, cutting temperature etc. In this study, cutting forces, part quality, MRR, cutting temperatures are modeled for orthogonal turn-milling operation. The developed models are verified by experiments. The results show that the eccentricity parameter in turn-milling has a significant effect on process outputs.

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Keywords: Turn-milling; cutting force; MRR; cutting temperature

1. Introduction

Emerging technologies in control engineering, machine design etc. lead to new developments in machine tool industry and every day the capabilities of machine tools are being improved gradually. Hence, this makes possible to developed new cutting strategies such as turn-milling in order to improve the productivity. However, developing new cutting strategies brings some difficulties like some new cutting parameters to handle or complicated process design to make. Selecting proper cutting parameters for improved productivity is a significant challenge and it has a huge cost and is time consuming when it is carried out by using series of experiments. That’s why it is important to develop practical process models to determine the cutting parameters for optimized process outputs such as cutting forces, temperatures, surface quality etc.

Turn-milling is a quite novel machining concept which is in fact a turning operation performed by a milling tool instead of a stationary cutting tool. Conventional turning is a continuous cutting operation whereas turn-milling is an interrupted cutting operation because of milling tool. This provides some clear advantages such as lower cutting forces, temperatures which lead to longer tool life compared to conventional turning.

Since it has been a relatively new machining strategy, there is only a small amount of studies on turn-milling in literature. Besides, most of these studies are experimental work and focus on surface quality of turn-milled parts. These studies have started by the great effort of Schulz and Spur [1]. In their study turn-milling of roller bearing components made of 100Cr6 were investigated and it was pointed that it is possible to manufacture rotationally symmetrical parts with improved accuracy and surface quality by turn-milling. In another study, Choudhury and Bajpai [2] found out that the surface quality obtained by turn-milling is better than it is obtained by conventional milling operation and there is optimum value of workpiece speed for better workpiece. Schulz and Kneisel [3] claimed in their experimental study that turn-milling could be an alternative to turning from surface quality point of view. On the other hand, Zhu et al. [4] established a model that can predict the surface roughness and the topography on the

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orthogonal turn-milled parts and verified their results by experiments. Beyond surface quality studies, there are also some work on the mechanics of turn-milling operation in the literature. Filho [5] developed a cutting force model for plunge orthogonal turn-milling in which he used the calibrated cutting coefficients to predict the forces. Karaguzel et al. [6] used mechanistic model, in which the cutting coefficients are evaluated from orthogonal database, to predict the cutting forces during orthogonal turn-milling. They also defined the MRR-surface quality relationship and offered a cutting parameter selection approach for improved productivity. Qui et al. [7] calibrated the cutting coefficients by performing slot milling and plunge milling and they obtained side edge cutting force coefficients and end edge cutting force coefficients separately to use them in force modeling of non-eccentric orthogonal turn-milling. Due to simultaneous rotations of workpiece and tool, the dynamics of turn-milling is a challenging area. Yan et al. [8] investigated the stability problem in orthogonal turn-milling and came up with a model which takes account the effect of variable cutting depth and chip thickness in the process.

Besides mechanics and surface quality, cutting temperatures play a crucial role in machining operations because they have a great effect on tool life, workpiece surface integrity, chip formation mechanism and thermal deformation of tool [9]. Hence, it is so important to control cutting temperature by means of simulation. There are several investigations that deal with cutting temperatures in continuous cutting. However, it is stated in the literature that the thermal conditions in interrupted cutting have a different nature than those in continuous cutting [10]. Interrupted cutting includes heating and cooling cycles which in turn may cause thermal fatigue cracks on the cutting tool which is different from continuous cutting [11]. Cooling cycles in interrupted cutting let the cutting tool to cool down during cutting operation hence application of higher cutting speeds become possible. Turn-milling is an interrupted cutting as well and the temperatures can be modelled as they are in milling operation. Peng [12] proposed a workpiece temperature model for non-eccentric orthogonal turn-milling operation and verified it by measuring temperatures using thermocouples.

In literature there is a gap especially for developing practical models that predict the useful process outputs such as cutting forces and temperatures in turn-milling. Hence as an original contribution to the literature turn-milling is investigated from mechanics and thermal aspects in this study. At first the mechanics of orthogonal turn-milling is discussed and the definitions for uncut chip geometry and cutting forces are evaluated. Then, the surface quality and MRR relationship is built. Last, the transient cutting temperatures on tool are calculated and presented.

Nomenclature

R_t	radius of tool
R_w	radius of workpiece
e	eccentricity
r_n	speed ratio
a_p	depth of cut
n_w	workpiece speed
n_t	tool speed
a_e	radial depth of cut (feed per workpiece revolution)
f_z	feed per tooth
vf	feed rate
Vc	cutting speed
h	chip thickness
m	number of cutting teeth
$K_{t,r,a}$	cutting coefficients
T	Temperature
k	thermal conductivity
cp	heat capacity
Q	heat input
qc	heat flux
θ_{GR}	Green function
α	thermal diffusivity

2. Uncut chip geometry and cutting forces

Evaluating cutting forces in a machining is important from dimensional accuracy, power requirements etc. point of view. Before developing a model for cutting forces, definition of uncut chip geometry is needed because cutting forces are a strong function of it. In turn-milling chip is formed by both side and the bottom of the tool, thus these two regions (side and bottom) should be included in the chip geometry definition. However, by introducing eccentricity the contact area between tool bottom and the workpiece decreases and beyond a certain value the chip is formed only the side of the tool. Fig. 1 shows the parameters used to define the turn-milling operation and the chip formation.

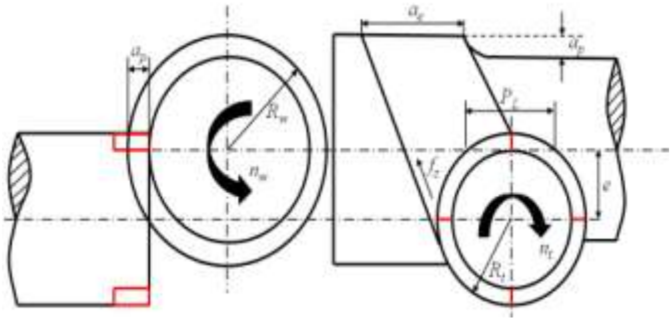

Fig. 1 Parameters used in orthogonal turn-milling operation

In Table 1 the uncut chip geometry is given for three different cases in which x1, x2 and x3 represent the boundary of uncut chip geometry shown in Fig. 2. Different cases correspond to different eccentricity values. X1 and x2 stand for the boundaries for the portion of the chip formed by the bottom of tool, thus it can be said that for case 3 the chip is formed by only the side of the tool which corresponds to an eccentricity value beyond a certain amount. Additionally, in Fig. 2 ϕ, ϕ_{st} and ϕ_{ex} are the immersion angles, θ is the angle between the first position of the tool and the last position of the tool after one revolution and a function of nt, nw and the number of teeth, m. Finally, z(x) equals to h+(Rw-ap).

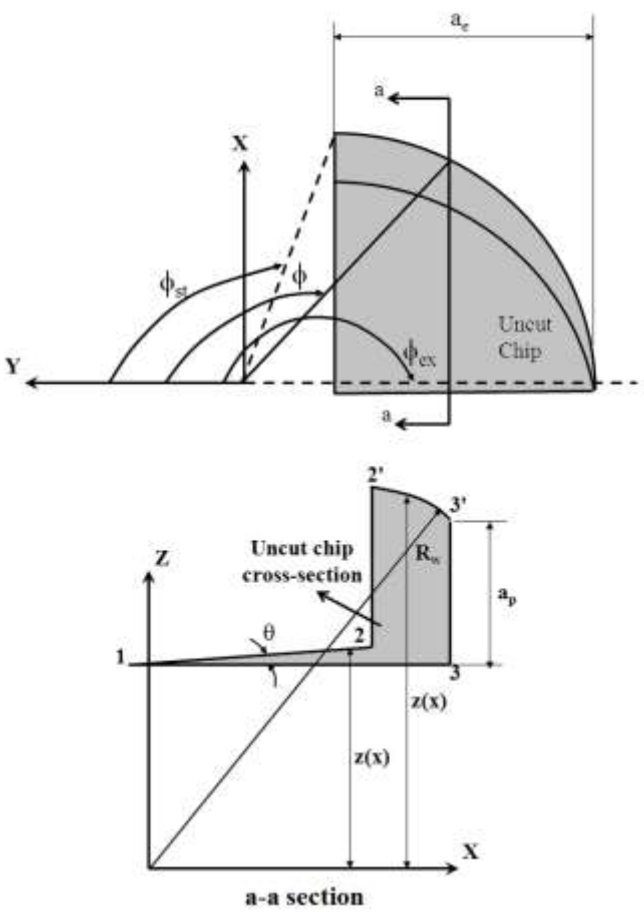

Fig. 2 Parameters used to define uncut chip geometry

Table 1 Uncut chip geometry equations

	$x_1<x<x_2$	$x_2<x<x_3$
Case1	$h=\tan(\theta)*x+((R_w-a_p)*\tan(\theta/2)-e)*\tan(\theta)$	$h=\sqrt{R_w^2-(x-e)^2}-(R_w-a_p)$
Case2	$h=\tan(\theta)*(x-(e-(R_w-a_p)*\tan(\theta/2)))$	$h=\sqrt{R_w^2-(x-e)^2}-(R_w-a_p)$
Case3	None	$h=\sqrt{R_w^2-(x-e)^2}-(R_w-a_p)$

After uncut chip geometry evaluation, the force model is developed. In force model mechanistic modeling of cutting forces for an oblique geometry is used. In mechanistic modeling cutting forces are presented by function of chip geometry and so called cutting coefficients [13]. Cutting coefficients for tangential, radial and axial components of cutting forces are given by following equations:

$$
\begin{aligned}
K_{tc} &= \frac{\tau}{\sin\phi_{sn}}\frac{\cos(\beta_n-\alpha_n)+\tan\eta_c\sin\beta_n\tan\psi}{k}\\
K_{rc} &= \frac{\tau}{\sin\phi_{sn}\cos\psi}\frac{\sin(\beta_n-\alpha_n)}{k}\\
K_{ac} &= \frac{\tau}{\sin\phi_{sn}}\frac{\cos(\beta_n-\alpha_n)\tan\psi-\tan\eta_c\sin\beta_n}{k}\\
k &= \sqrt{\cos^2(\phi_{sn}+\beta_n-\alpha_n)+\tan^2\eta_c\sin^2\beta_n}
\end{aligned}
\tag{1}
$$

In order to calculate cutting coefficients shear stress, shear angle, friction angle on the rake face and the tool geometry should be known. Tool geometry is selected and the other unknowns are evaluated by using orthogonal cutting data for WC-AISI 1050 in this study. The orthogonal cutting database is given by following:

$$
\begin{aligned}
\tau &= 524.95e^{V_c.0.0005302}-21.72.f\\
\phi_s &= 10.342e^{V_c.0.001236}+10.912e^{f^{0.35}}\\
\beta &= 33.753e^{-V_c\,0.00123}-7.33f
\end{aligned}
\tag{2}
$$

Then the elemental forces are calculated for differential axial depth of cut by:

$$
\begin{aligned}
dF_{t,j(\varphi,z)} &= [K_{tc}h_j(\varphi_j(z))+K_{te}]dz\\
dF_{r,j(\varphi,z)} &= [K_{rc}h_j(\varphi_j(z))+K_{re}]dz\\
dF_{a,j(\varphi,z)} &= [K_{ac}h_j(\varphi_j(z))+K_{ae}]dz
\end{aligned}
\tag{3}
$$

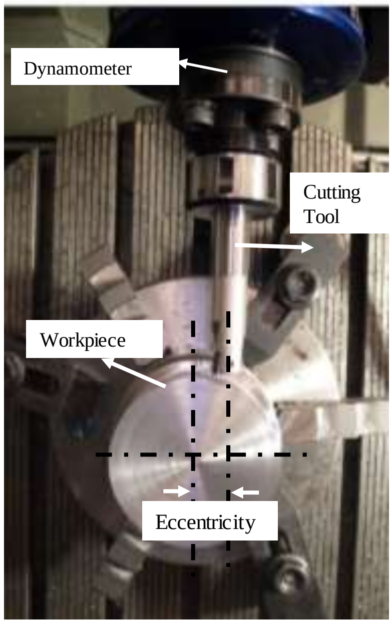

Fig. 3 Experimental setup

Finally, the cutting forces are obtained for each rotation angle of tool in immersion by integrating the elemental forces over axial depth of cut.

$$
\begin{aligned}
F_t(\phi_j(z)) &= \int_{z_{j,1}}^{z_{j,2}} dF_t(\phi_j(z))dz \\
F_r(\phi_j(z)) &= \int_{z_{j,1}}^{z_{j,2}} dF_r(\phi_j(z))dz \\
F_a(\phi_j(z)) &= \int_{z_{j,1}}^{z_{j,2}} dF_a(\phi_j(z))dz
\end{aligned} \tag{4}
$$

To validate the force model cutting experiments have been carried out and the cutting forces have been measured by a Kistler Rotating Dynamometer. The experimental setup is shown in Fig. 3. Experiments have been performed under dry cutting conditions in which the cutting tool was uncoated WC. The cutting tool used in the tests was an 8 mm diameter end mill with 4 teeth where the workpiece was 1050 steel with 80 mm diameter.

Fig. 4 shows the comparison of cutting forces between the proposed model and the experiments where the cutting conditions were nt=2500 rpm, nw=10 rpm, ap=0.5 mm and ae=0.5 mm/rev.. It can be seen from the figure that the orthogonal turn-milling operation produces periodic forces unlike conventional turning operation. Also it can be claimed that there is a good match between the model and the experimental results.

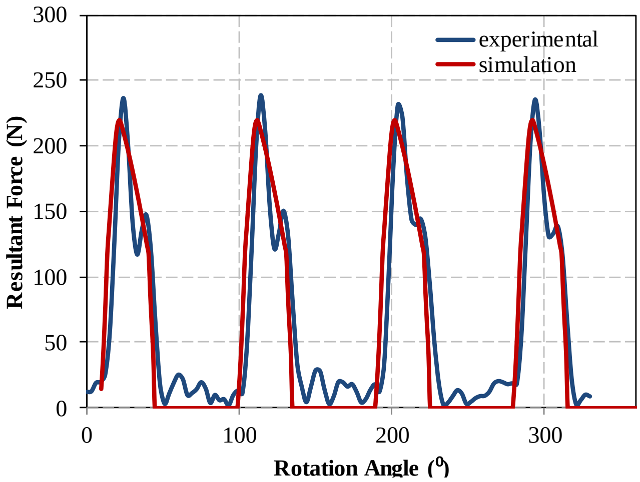

Fig. 4 Comparison of cutting forces

3. MRR and machined part quality

High material removal rate (MRR) values can be achieved by turn-milling operation. However high MRR brings some surface problems and the most important one is called cusp height formation. Cusp height can be defined as the unmachined part of the workpiece due to high feed per workpiece revolution (or radial depth of cut from analogy to milling operation). Cusp height formation can be seen in Fig. 5. In Fig. 5a the cusp height formation during experiment is represented whereas the schematic representation of the cusp height formation is given in Fig. 5b.

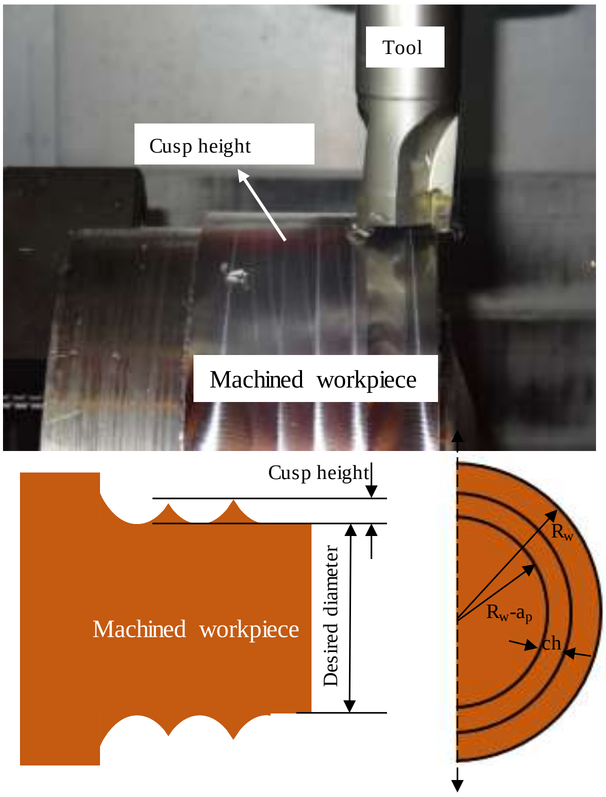

Fig. 5 Cusp height formation a) Experimental b) Schematic

As stated above cusp height formation occurs due high a_e value, but it is also a strong function of e value which eccentricity. This relationship can be built using some geometric definitions and finally a practical equation can be derived for cusp height [14]:

$$
ch = \sqrt{(R_w - a_p)^2 + \left(\left[e + \left[(R_w - a_p) * \tan\left(\frac{180^\circ}{m * r_n} \right) \right] \right] - \left[\sqrt{(R_t)^2 - \left(\frac{a_e}{2} \right)^2} \right] \right)^2} - (R_w - a_p) \tag{5}
$$

By using the expression above two critic values can be obtained for no cusp formation during turn-milling operation. The first critical value is given for eccentricity value by:

$$
e_{crit} = \sqrt{(R_t)^2 - \left(\frac{a_e}{2} \right)^2} - \left[(R_w - a_p) * \tan\left(\frac{180^\circ}{m * r_n} \right) \right] \tag{6}
$$

which tells the limit value of eccentiricty at a given value of ae for no cusp formation.

$$
a_{ecrit} = 2 * \sqrt{(R_t)^2 - \left(e + \left[(R_w - a_p) * \tan\left(\frac{180^\circ}{m * r_n} \right) \right] \right)^2} \tag{7}
$$

Similarly, Eq. (7) gives a critical value for a_e at a given value of e. Thus, one can use these equations and select the proper value of cutting parameters through high productivity.

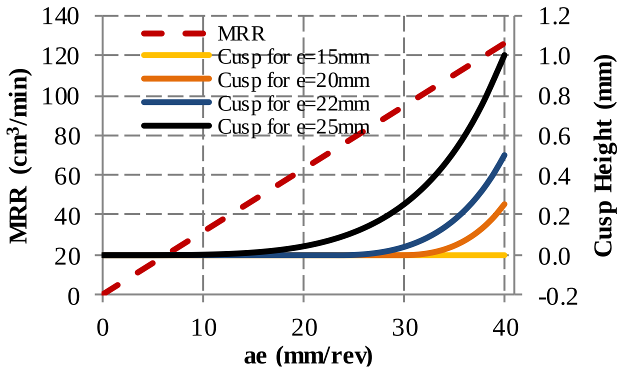

Fig. 6 Cusp height formation a) Experimental b) Schematic

$$MRR = v_f . a_p . a_e$$
$$v_f = m.n_t . f_z \qquad (8)$$
$$f_z = \frac{2.\pi.R_w.n_w}{n_t.m}$$

Fig. 6 shows the cusp height formation and MRR (Eq. (8)) values together and it can be clearly seen that there is a region without cusp formation up to a specified ae value for each eccentricity values. Moreover, for e=15mm case there is no cusp formation for all a_e values.

4. Cutting temperatures

Generated heat in cutting operation can be predicted by calculated cutting forces in Section 2. Heat generation Q can be calculated as follows by assuming that all the mechanical work done in machining operation is converted into heat energy [15]:

$$Q = F_R . V_c \qquad (9)$$

where F is the resultant cutting force and Vc is the cutting speed.

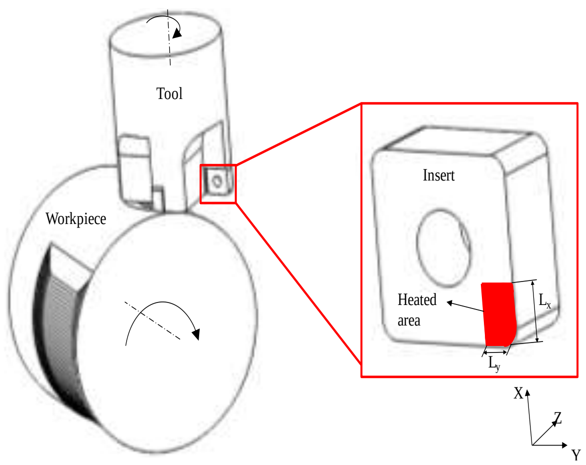

Fig. 7 Temperature analysis on cutting tool

Assuming that thermal properties of cutting tool are homogeneous and independent from time, three dimensional heat conduction equation in Cartesian coordinates is derived as:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{\rho c_p}{k}\frac{\partial T}{\partial t} \qquad (10)$$

where k is the thermal conductivity of tool material, c_p is the heat capacity and ρ is the density.

In turn-milling operation, cutting insert is exposed to cyclic heating and cooling periods, the heated area which is the tool-chip interface during cutting, is seen in Fig. 7. Hence the boundary condition for the problem in Eq. (10) is determined as:

$$-k\frac{\partial T}{\partial z} = q(x,y,t) \quad z = 0;\ 0 \le x \le L_x,\ \ 0 \le y \le L_y \qquad (11)$$

where Lx and Ly are the dimensions of the heat source area which can be seen in Fig. 7 and *q(x,y,t)* is the heat flux applied on the xy surface. The other boundary surfaces are assumed as insulated and the initial temperature for the body is considered as equal to room temperature.

Eq. (10) can be solved either analytically or numerically. According to Stephenson [10], Green's functions can be used to solve this equation analytically if the cutting tool is assumed to be as a semi-infinite rectangular volume heated from its corner. Then the Green function θ_G , which represents the temperature at the location x,y, and z, at time t, due to an instantaneous heat point source, located at x = xp, y = yp, z = 0, and releasing its energy at time $t=\tau$.

$$\theta_G = (x,y,z,x_p,y_p,0,D) = \frac{2}{(\sqrt{\pi}.D)^3}\exp\left[\frac{-z^2}{D^2}\right]$$
$$.\left[\exp\left(\frac{-(x+x_p)^2}{D^2}\right) + \exp\left(\frac{-(x-x_p)^2}{D^2}\right)\right] \qquad (12)$$
$$.\left[\exp\left(\frac{-(y+y_p)^2}{D^2}\right) + \exp\left(\frac{-(y-y_p)^2}{D^2}\right)\right]$$

where $D = 2\sqrt{[\alpha(t-\tau)]}$

The temperature field for the tool can be obtained by using heat flux function and integrating Eq. (12) over time, L_x and L_y.

$$T(x,y,z,t) = \frac{\alpha}{k}\int_0^t\int_0^{L_x}\int_0^{L_y}\theta_G(x,y,z,x_p,y_p,0,D)$$
$$.Q(x_p,y_p,\tau)dy_p dx_p d\tau \qquad (13)$$

The integration of θ_G over L_x and L_y can be denoted as θ_{GR} and can be solved as follows:

$$\theta_{GR}(x,y,z,L_x,L_y,D) = \int_0^{L_x}\int_0^{L_y}\theta_G(x,y,z,x_p,y_p,0,D)dy_p dx_p$$
$$= \frac{1}{2\sqrt{\pi}D}\exp\left[\frac{-z^2}{D^2}\right]\theta_{GU}(x,L_x,D).\theta_{GU}(y,L_y,D) \qquad (14)$$

where $\theta_{GU}(u,L,D) = erf\left(\frac{L+u}{D}\right) + erf\left(\frac{L-u}{D}\right)$

By substitution of Eq. (14) in Eq. (13), temperature field for cutting tool insert is derived in Eq. (15).

$$T(x,y,z,t) = \frac{\alpha}{k}\int_0^t \theta_{GR}(x,y,z,L_x,L_y,D).q(\tau)d\tau \qquad (15)$$

Eq. (15) includes two different expressions which are function of time, θ_{GR} and $q(\tau)$. Therefore, Eq. (15) can be solved by convolution of time.

Figs. 8 and 9 show the solution of Eq. (15) graphically. In the solution different cutting speed (Vc) and ae (feed per workpiece revolution) values are considered, results indicate that cutting temperature increases with cutting speed and ae parameter. In this example used parameters can be summarized as k=65 J/(s.m.ºC), α=2.5e-5 m^2/s , L_x=0.39 mm, L_y=2 mm and q=2.28e8 W/m^2. The temperature results are given for the point of x=0.8 mm, y=2mm and z=0 (surface).

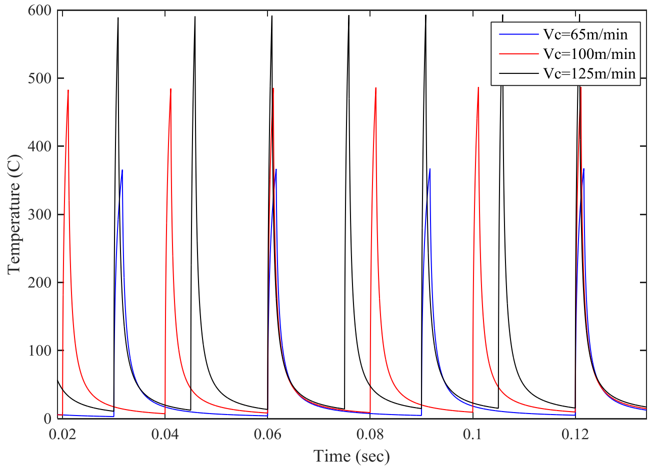

Fig. 8 Temperature analysis on cutting tool for different cutting speeds

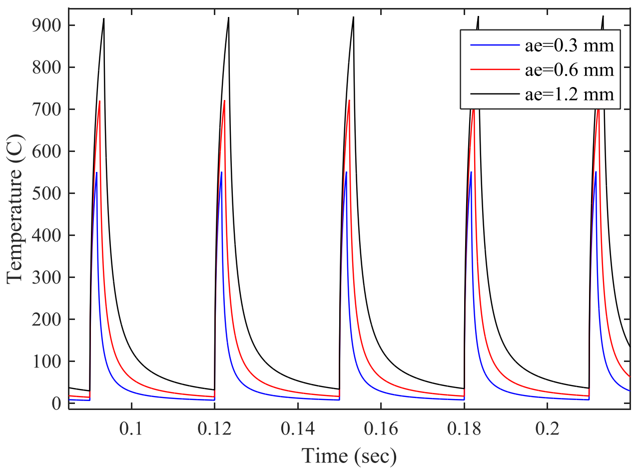

Fig. 9 Temperature analysis on cutting tool for different a_e values

5. Conclusion

In this study, a relatively new cutting technology called turn-milling was investigated. First, the chip geometry was defined and it was used to evaluate the cutting forces. It was shown in the study that the cutting forces are periodic in turn-milling. Then, the surface quality of turn-milled part was studied and the cusp height formation was discussed, in this discussion it was indicated that it is possible to increase MRR in orthogonal turn-milling, but beyond a certain value of both eccentricity and a_e value, cusp height increases drastically. On the other hand, these certain values of eccentricity and a_e were precisely calculated in this paper, so one can use them to optimize the operation outputs. Finally, the cutting temperature model was built and it was found that both increase in cutting speed and a_e values cause an increase in cutting temperatures.

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