Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 50(3) (2018) 213-216
DOI: 10.22060/mej.2017.12414.5327

Experimental Investigation and Finite Difference Modeling of Cutting Tool Temperature Distribution During Ultrasonically Assisted Turning

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ABSTRACT: This paper summarizes the experimental and numerical simulations of 2D temperature fields on the chip and cutting tool during ultrasonic assisted turning of AISI 4140 hardened steel using carbide inserts. To achieve this goal, the finite difference method is used to develop a numerical model in order to predict cutting tool's temperature during ultrasonic assisted turning. First, finite difference method is used to develop a predictive model of cutting tool's temperature in case of conventional turning and then the analysis results are used in combination with the model developed for ultrasonic assisted turning to predict cutting temperature profiles during this process. Finally, finite difference-based simulation results are validated with experimental measurements of temperatures from ultrasonic assisted turning tests using thermocouple technique. Using the analysis results, the effect of machining and vibrational parameters (cutting speed, feed rate, and vibration amplitude) can be easily studied on ultrasonic assisted turning cutting temperatures. The results show that ultrasonic assisted turning is able to lower the maximum cutting temperature in the cutting tool, about 37%, in low feed rates (≈0.11 mm/rev), with a vibration amplitude of (≈10 µm) and work velocity of (≈30 m/min).

Review History:

Received: 16 January 2017
Revised: 14 March 2017
Accepted: 16 April 2017
Available Online: 23 April 2017

Keywords:

Ultrasonic assisted turning
Finite difference Method
Temperature istribution
Thermocouple
Hardened Steel

1- Introduction

Ultrasonic Assisted Turning (UAT) combines the cutting motion of the conventional turning (CT) with a low-amplitude and high-frequency harmonic displacement, Fig. 1.

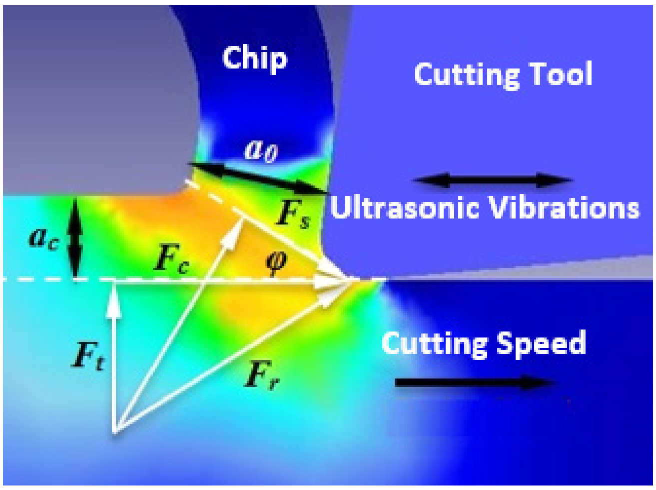

Fig. 1. Idealized one dimensional UAT

Up to now, several benefits such as increasing tool life, improving surface finish, lower cutting forces, etc. have been attributed to this technology. The reason for these benefits is mainly the conditional periodic separation of the cutting tool rake face from the uncut material, [1]. UAT has the ability to reduce the tool wear significantly, which leads to improving cooling conditions and reduces tool tip temperature [2]. Hitherto, different theories have been presented to explain this phenomenon. Some of these authors believe that ultrasonic vibrations will change the heat transfer regime on the rake face [3]. Other researchers believe that ultrasonic vibrations will change the friction regime on the rake face and this effect will lead to decreasing the amount of heat generated [4]. Another group of authors believes that the engagement between the cutting tool and work-piece is smaller in the case of UAT and as a result, cutting tool temperature will decrease [1]. Despite all the mentioned studies, thermomechanical aspects of UAT have not been fully understood and further research works would be required. Therefore, it is necessary to develop models to evaluate cutting temperature in UAT process either analytically or numerically.

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2- Methodology

Kinematics modeling of UAT starts by modeling the vibratory motion of the cutting tool. During the UAT, the cutting tool separates from the work-piece while it draws back, but the work-piece catches up with the cutting tool before it begins next vibration cycle. The duration of the first cutting cycle is t_{up}. If the duration of the full cycle is designated as T, then the cutting speed model during UAT is given as follows:

$$V_c(\tau)=\begin{cases} a\omega\cos(\omega\tau)+V_w & nT<\tau<nT+t_{up} \\ 0 & nT+t_{up}<\tau<nT+t_{up}+t_s \\ a\omega\cos(\omega\tau)+V_w & nT+t_{up}+t_s<\tau<(n+1)T \end{cases} \quad (1)$$

During the orthogonal cutting process, heat generation occurs mainly in two principal regions: primary and secondary shear zones. In addition to the heat sources mentioned above, there exists a new heat source in the case of UAT which is caused by ultrasonic vibrations. For the unit depth of cut, (i.e. ap=1 mm), heat generated in the primary shear zone is given as follows [5]:V

$$\dot{q}_s = F_s V_s = \frac{\tau_s a_c V_c \cos(\alpha_n)}{\cos(\varphi_n - \alpha_n)\sin(\varphi_n)} \quad (W) \tag{2}$$

where, F_s, V_s, V_c, and ac are cutting force components in shear plane, the cutting velocity component along the shear plane, the cutting velocity, and instantaneous uncut chip thickness, respectively. φ_n and α_n are the normal shear angle and normal rake angle, respectively. On the other hand, work-piece material is modeled using Johnson-Cook (JC) constitutive model:

$$\tau_s = \frac{1}{\sqrt{3}}\left(A + B\left(\frac{\gamma}{\sqrt{3}}\right)^n\right)\left(1 + C\ln\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)\left(1 - \left(\frac{T_w - T_r}{T_m - T_r}\right)^m\right) \tag{3}$$

$$\gamma = \frac{\cos\alpha_n}{\sin\varphi_n \cos(\varphi_n - \alpha_n)} \tag{4}$$

$$\dot{\gamma}(\tau) = \begin{cases} \dfrac{\cos\alpha_n \times (a\omega\cos(\omega\tau) + V_w)}{\cos(\varphi_n - \alpha_n) t_{s.z.}} & nT < \tau < nT + t_{up} \\ 0 & nT + t_{up} < \tau < nT + t_{up} + t_s \\ \dfrac{\cos\alpha_n \times (a\omega\cos(\omega\tau) + V_w)}{\cos(\varphi_n - \alpha_n) t_{s.z.}} & nT + t_{up} + t_s < \tau < (n+1)T \end{cases} \tag{5}$$

where τ_s, γ, $\dot{\gamma}$ and $\dot{\gamma}_0$ are equivalent Von Mises shear flow stress, equivalent plastic shear strain, shear strain rate and reference shear strain rate (i.e. $1/s$), respectively. T_w, T_r, and T_m are temperatures at the primary shear zone, room temperature, and work-piece melting point, respectively. The heat generation at secondary shear zone per unit depth of cut in ultrasonic assisted turning process varies with time and spatial variable (x) and could be declared in the following general form:

$$\dot{Q}_f(x,\tau) = q_1(x).\dot{q}_f(\tau) \tag{6}$$

$$\dot{q}_f(\tau) = \begin{cases} \dfrac{\tau_s a_c.(A\omega\cos(\omega\tau) + V_w).\sin(\beta_n)}{\cos(\varphi_n + \beta_n - \alpha_n)\sin(\varphi_n - \alpha_n)} & nT < \tau < nT + t_{up} \\ 0 & nT + t_{up} < \tau < nT + t_{up} + t_s \quad (W) \\ \dfrac{\tau_s a_c.(A\omega\cos(\omega\tau) + V_w).\sin(\beta_n)}{\cos(\varphi_n + \beta_n - \alpha_n)\sin(\varphi_n - \alpha_n)} & nT + t_{up} + t_s < \tau < (n+1)T \end{cases} \tag{7}$$

$$q_1(x) = \begin{cases} q_{max} & 0 \le x \le l_s \\ q_{max}\left(\dfrac{l_c - x}{l_c - l_s}\right) e^{\left(\frac{l_s - x}{l_c}\right)} & l_s \le x \le l_c \end{cases} \tag{8}$$

Considering the chip as a rectangular medium in the quasi-static state, chip thermal equilibrium is written as follows:

$$\begin{gathered} \frac{T_{c(x+\delta x,y)} + T_{c(x-\delta x,y)} - 2T_{c(x,y)}}{\delta x^2} + \frac{T_{c(x,y+\delta y)} + T_{c(x,y-\delta y)} - 2T_{c(x,y)}}{\delta y^2} \\ + \frac{\dot{Q}_{c(x,y)}}{k_c} = \frac{1}{\xi_c} V_c \frac{\partial T_{c(x,y)}}{\partial x} \\ \dot{Q}_{c(i)} = (1 - \Gamma_i)\frac{\dot{Q}_f \delta x}{l_c} \qquad 1 \le i \le N_x + 1 \end{gathered} \tag{9}$$

Using polar coordinates, the heat transfer equilibrium equation for the cutting tool nodal points is rewritten as follows:

$$\begin{gathered} \frac{T_{t(r+\delta r,\psi)} + T_{t(r-\delta r,\psi)} - 2T_{t(r,\psi)}}{\delta r^2} + \frac{T_{t(r+\delta r,\psi)} + T_{t(r-\delta r,\psi)} - 2T_{c(x,y)}}{2r\delta r} \\ + \frac{T_{t(r,\psi+\delta\psi)} + T_{t(r,\psi-\delta\psi)} - 2T_{t(r,\psi)}}{r^2\delta\psi^2} + \frac{\dot{Q}_{t(r,\psi)}}{k_t} = 0 \\ \dot{Q}_{t(i)} = \Gamma_i \frac{\dot{Q}_f \delta x}{l_c} \qquad 1 \le i \le N_x + 1 \end{gathered} \tag{10}$$

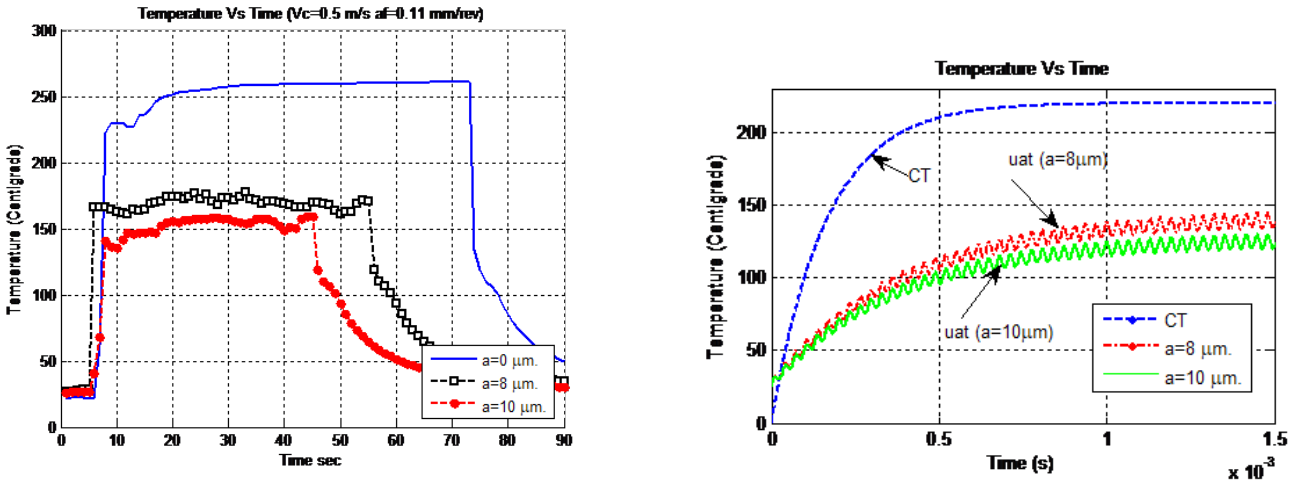
The proportion of the frictional heat flowing into the tool at the i^{th} nodal point is unknown initially and an iterative process is used to evaluate these values. In case of ultrasonically assisted turning, each vibration cycle is divided into cutting and non-cutting time intervals. The cutting period in each cutting cycle is then discretized into small time intervals. Every each of these tiny time intervals is now considered as a turning process with a different cutting speed, strain rate and boundary condition at the tool tip. Then, using the finite difference modeling, steady-state temperatures and corresponding time constants for every each of these tiny cutting processes is easily calculated. Now, using a simple analysis of the first order systems, transient response can be also determined for ultrasonically assisted turning process.

3- Results and Discussion

As shown in Fig. 2, increasing vibration amplitude from 8 to 10 µm will increase the reduction in maximum cutting temperature from 33.21% to 37.24% of the maximum cutting temperature in the case of Conventional Turning (CT). The effect of vibration amplitude is very complex due to its different effects on the process parameters: (a) Experimental measurements of tool temperature show that horn warm up due to the ultrasonic vibrations is highly dependent on vibration amplitude; (b) increasing the vibration amplitude will increase maximum tool velocity and the latter will lead to an increase in cutting temperature; (c) increasing in the tool velocity and keeping the remaining parameters constant would increase the separation time and decrease total cutting time in each cycle. Therefore, the increase in amplitude vibration would decrease cutting temperature.

4- Conclusions

The results show that numerical simulation results are in a good agreement with experimental studies and Finite Difference Method (FDM) results can be used to show the effects of cutting speed and vibration amplitude on the temperature distribution during UAT. Separation time, ts, is the main contributor to the ability of UAT in lowering cutting temperature.



(a) (b)

Fig. 2. Effect of vibration domain on cutting temperature.

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Please cite this article using:

N. Abbasi, M. Razfar, M. Khajehzadeh, Experimental Investigation and Finite Difference Modeling of Cutting Tool Temperature Distribution During Ultrasonically Assisted Turning, *Amirkabir J. Mech. Eng.*, 50(3) (2018) 657-670.

DOI: 10.22060/mej.2017.12414.5327