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Modeling and measurement of cutting temperatures in milling

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Abstract

Milling is the one of most common cutting operations in industry. Interrupted nature of the milling process allows use of higher speeds which in turn improves productivity. Cutting temperature is one of the key factors to be investigated in process optimization. In milling, cutting temperature analysis is harder compared to turning due to experimentation difficulties and transient characteristics. In this study, a new experimental technique is proposed to measure the face milling temperatures which are used to verify the analytical model developed. Results indicate a good agreement between the model predictions and dry cutting experiments at different cutting speeds.

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1. Introduction

Machining operations can be divided into two fundamental groups as continuous and interrupted cutting. Milling is an interrupted cutting operation which is used to generate a flat or a three-dimensional free-formed surface. In case of any machining operation high temperatures occur due to excessive amount of plastic deformation and friction between tool, chip and workpiece [1]. It is stated that most of the power (90-95%) generated in a machining operation is converted to heat [2]. Generated heat dissipates into tool, workpiece and chip which determines the tool life and the surface integrity of the finished part as well as the machined part quality. Thus, in order to improve productivity, thermal analysis of machining operation is worth to investigate scientifically.

It requires great effort to measure and predict the temperatures experienced in machining due to characteristics of the operation such as high speeds, number of parameters, size of the heat generation zone etc. Process modeling of cutting temperature contributes to determine the effects of cutting parameters and select them to achieve more effective production. On the other hand measuring cutting temperature can provide useful data to verify the proposed models, and can also be used in online monitoring.

In the machining literature the majority of the work is on continuous cutting whereas there is only limited number of studies on interrupted cutting. Chakraverti et al. [3] proposed a unidimensional model to predict tool temperature distribution during intermittent cutting in which the heat flux is assumed as a periodic rectangular wave. It was found in the study that thermal stresses increase as amplitude of temperature fluctuation increases. Palmai [4] claimed that in interrupted cutting, temperature increases with cutting speed up to a certain limit and this relationship can be defined with an empirical formula. Stephenson and Ali [5] developed an analytical model using Green’s functions to calculate the tool temperatures during interrupted cutting. In order to validate their model, they performed a series of experiments and measured cutting temperature by tool-workpiece thermocouple technique. They concluded that the temperatures in interrupted cutting are lower than those obtained in continuous cutting. Another analytical model was proposed by Radulescu et al. [6]. In their study,

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cutting temperatures on tool are calculated by using prescribed heat flux taking into account the convection to surrounding air. The proposed model could be used for both interrupted and continuous cutting. Islam et al. [7] introduced a finite difference model which can calculate transient and steady state temperatures in chip, tool and workpiece.

Measuring cutting tool temperature is a significant challenge in milling operation due to tool rotation. Wang et al. [8] used a garter spring pickup and thermocouples located in the inserts to measure the tool temperature. They investigate the effect of number of teeth on the temperature, and concluded that increasing number of inserts caused increased cutting temperature. McFeron et al. [9] measured the average tool-chip interface temperatures using a tool-workpiece thermocouple. Ueda et al. [10] developed a technique which includes a two-color pyrometer and two optical fibers one is rotating with tool insert and the other one is stationary located in tool spindle to measure the tool temperature. Kerrigan et al. [11] used a wireless telemetric system which is designed with tool holder to measure the cutting temperatures during milling of CFRP composites by a coupled thermocouple.

This paper presents a novel experimental technique to measure transient tool temperatures in dry milling operation with a K type thermocouple. Additionally, an analytical model is proposed which uses Green's functions to solve the 3D transient heat conduction problem. The proposed experimental technique was used to verify the results obtained by the model.

2. Cutting tool temperature model

Generated heat in cutting operation can be predicted by calculated cutting forces. Heat generation Q can be calculated as follows by assuming that all the mechanical work done in machining operation is converted into heat energy [1]:

$$Q = F_R . V_c \tag{1}$$

Where F_R is the resultant cutting force, V_c is the cutting speed. Assuming that thermal properties of cutting tool are homogeneous and independent of time, three dimensional heat diffusion equation in Cartesian coordinates is derived as:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{\rho c_p}{k} \frac{\partial T}{\partial t} \tag{2}$$

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

In milling operation, a 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. 1. Hence the boundary condition for the problem in Eq. (2) is determined as:

$$-k \frac{\partial T}{\partial z} = q(x,y,t) \quad z = 0;\ 0 \le x \le L_x,\ 0 \le y \le L_y \tag{3}$$

where L_x and L_y are the dimensions of the heat source area which can be seen in Fig. 1 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.

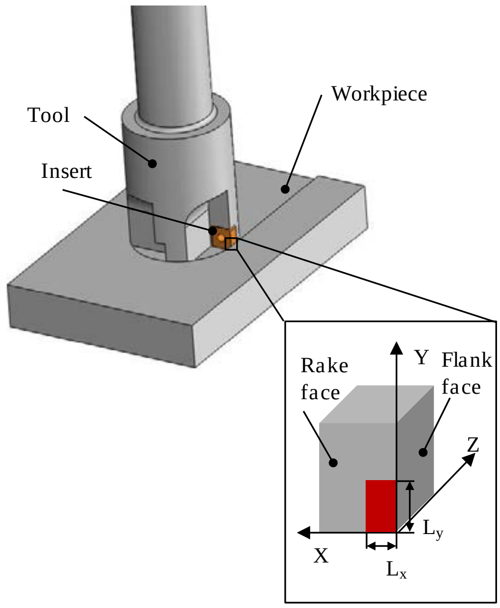

Fig. 1. Geometrical representation of tool temperature model

Eq.(2) can be solved either analytically or numerically. According to Stephenson [5], 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, z) at time t, due to an instantaneous heat point source, located at $x = x_p$, $y = y_p$, $z = 0$, and releasing its energy at time $t=\tau$.

$$\begin{aligned}\theta_G = (x,y,z,x_p,y_p,0,D) &= \frac{2}{(\sqrt{\pi}.D)^3}\exp\left[\frac{-z^2}{D^2}\right] \\ &.\left[\exp\left(\frac{-(x+x_p)^2}{D^2}\right)+\exp\left(\frac{-(x-x_p)^2}{D^2}\right)\right] \\ &.\left[\exp\left(\frac{-(y+y_p)^2}{D^2}\right)+\exp\left(\frac{-(y-y_p)^2}{D^2}\right)\right]\end{aligned} \tag{4}$$

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

The temperature field for the tool can be obtained by using heat flux function and integrating Eq. (4) over time, L_x and L_y.

$$T(x,y,z,t) = \frac{\alpha}{k}\int_0^t\int_0^{L_x}\int_0^{L_y}\theta_G(x,y,z,x_p,y_p,0,D).Q(x_p,y_p,\tau)dy_p dx_p d\tau \tag{5}$$

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

$$\begin{aligned}\theta_{GR}(x,y,z,L_x,L_y,D) &= \int_0^{L_x}\int_0^{L_y}\theta_G(x,y,z,x_p,y_p,0,D)dy_p dx_p \\ &= \frac{1}{2\sqrt{\pi}D}\exp\left[\frac{-z^2}{D^2}\right]\theta_{GU}(x,L_x,D).\theta_{GU}(y,L_y,D)\end{aligned} \tag{6}$$