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An inverse method to estimate the moving heat source in machining process

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ABSTRACT

The present work propounds an inverse method to estimate the heat sources in the transient two-dimensional heat conduction problem in a rectangular domain with convective bounders. The non homogeneous partial differential equation (PDE) is solved using the Integral Transform Method. The test function for the heat generation term is obtained by the chip geometry and thermomechanical cutting. Then the heat generation term is estimated by the conjugated gradient method (CGM) with adjoint problem for parameter estimation. The experimental trials were organized to perform six different conditions to provide heat sources of different intensities. This method was compared with others in the literature and advantages are discussed.

1. Introduction

Modern manufacturing industries require the optimization of every aspect involved in the whole process of transforming simple material forms into useful pieces of equipment. When dealing with metal cutting, for example, the economical use of cutting tools is fundamentally based on their wear rate. Tool wear depends, to a big extent, on the heat produced by the interaction between the tool cutting edge and the workpiece material. Fig. 1 depicts how this interaction occurs in metal cutting operations and the main heat sources zones.

There are three heat source zones in the cutting process as shown in cross-sectional view of orthogonal cutting (see Fig. 1). As the edge of the tool penetrates into the workpiece, the material ahead of the tool is sheared over the primary heat zone to form a chip. The sheared material, the chip, partially deforms and moves along the rake face of tool, which is called the secondary heat zone. The friction area, where the flank of the tool rubs the newly machined surface, is called tertiary heat zone.

In a typical metal cutting operation almost 100% of the total energy spent is converted into heat, which has to be dissipated by the tool cutting edge, workpiece, chip and also by the cutting fluid normally used. The percentual of heat flow to the tool cutting edge, workpiece, chip is under study and little is known about this topic. Vernaza-Pena, Mason and Li [2] report that 17% of the heat generated in the primary zone of the orthogonal cutting of an aluminum alloy flows into the part. However, for low metal removal this amount is usually around 50%. Moriwaki, Sugimura and Luan [3] assumed that in orthogonal cutting of copper pieces, half the heat generated due to friction-piece tool is transmitted to the part and the other half as a tool to heat flow. There are many analytical models for determining the use of heat energy partition of Blok [4]. Table 1 shows a summary of equations used by many researchers to calculate the heat partition B flowing to workpiece or (B-1) flowing to chip in a typical machining process.

Literature on temperatures models when partitioning the heat generation among the tool, chip and workpiece assume steady state conditions. Consequently, the predicted heat fluxes into these three components are constant [10]. This implies that the amount of heat going into the workpiece for example is underestimated during the transient time. Moreover for interrupted cutting process, where heating (i.e., when the tool engages) and cooling (i.e., when the tool disengages) periods alternate, these models can severely under-predict the workpiece steady state temperature and transient times.

In machining process with cooling fluids the heat transfer coefficient is an important topic in the field of heat transfer technology. The heat transfer coefficient, regulates the heat transmission between the surface of a solid body and a neighboring fluid. In addition, the Biot number, the dimensionless form of the convective coefficient, may physically be interpreted as the ratio of the internal and external conductances of a heat problem with convective boundary.

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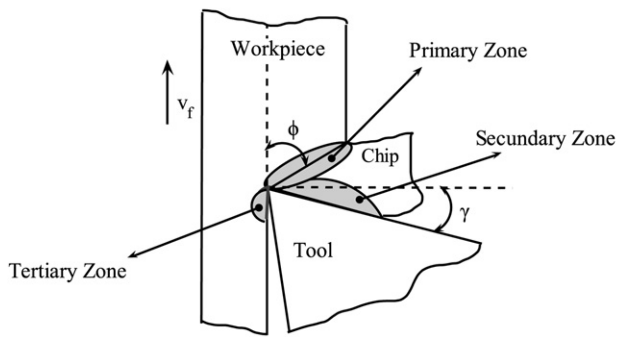

Fig. 1. Interaction between tool cutting edge, workpiece material and chip formation Source: adapted from [1].

For such purpose simple mathematical formulations to deal with heat conduction problems is of prime interest in the optimization of manufacturing processes based on metal cutting. In this context, the thermal analysis begins with the solution of a heat source of appropriate shape and intensity. The solution of heat source problem of various shapes and heat intensity using partial differential equation (PDE) method directly may not be simple and straightforward [11].

In this sense, the studies of inverse heat conduction problem (IHCP) have offered convenient alternatives, which largely scale down complex experimental work, to obtain accurate thermal physical quantities such as heat sources, material's thermal properties, and boundary temperature or heat flux distributions, in many heat conduction problems [12–15].

In this paper, a method for estimating time-dependent heat source for linear inverse heat conduction problem is proposed. The method begins with the modeling of the heat generation term. Thereafter, the method applies the finite integral transform techniques to solve the two-dimensional, transient heat-conduction problem with time-dependent heat sources and boundary conditions. Then an iterative minimization scheme called Conjugated Gradient Method (CGM) is applied for solve the inverse heat transfer problem of parameter estimation [16]. This method was tested on a plate with convective boundary conditions of third kind and heat generation.

2. Analytical model of two-dimensional temperature distribution in a finite solid

The process starts by modeling the heat distribution in a typical orthogonal cutting with the same cutting fluid surrounding in all borders of a solid surface. The model of temperature distribution on a stationary, homogeneous, isotropic solid with constant thermal properties subject a heat generation near its boundary and convection dissipation too. The problem under consideration can be governed by the following equations:

$$\nabla^2 T(x,y,t) + \frac{g(x,y,t)}{k} = \frac{1}{\alpha}\frac{\partial T(x,y,t)}{\partial t} \quad \begin{matrix} 0 < x < l_1 \\ 0 < y < l_2 \end{matrix} \tag{1}$$

$$\pm k\frac{\partial T}{\partial x} + hT = 0 \quad \begin{matrix} x = l_1 \\ x = 0 \end{matrix} \tag{2}$$

$$\pm k\frac{\partial T}{\partial y} + hT = 0 \quad \begin{matrix} y = l_2 \\ y = 0 \end{matrix} \tag{3}$$

$$T(x,y,0) = F(x,y) \tag{4}$$

The boundary conditions defined by equations (2) and (3) cover a wide variety of cases arising in engineering applications, most specifically in machining operations. In particular, conditions of prescribed surface temperature heat flux and Newtonian boundary condition or any combination of theses can be modeled by assigning appropriate values to k and h. The heat transfer coefficient h in equations (2) and (3) depends on the properties of the fluid (k_f,c,μ,ρ), speed of the fluid, the scale length and surface geometry.

The equation is a non homogeneous PDE. We can't use the method of separation variables to reduce the non homogeneous equation to a characteristic-values problem in each space variable involved. However the integral transform method is convenient for non homogeneous problems due to the presence of the term heat generation in the equation (equation (1)) or due to non-uniformity of boundary conditions, or both, see [17].

The solutions are obtained, based on the work of Nurettin Y. Ölçer [18], which remarked that the uniform convergence of the infinite series in (5) is ensured by the requirement that $F(x,y)$ and $g(x,y,t)$ possess continuous first and second order partial derivatives in the space variables, and that $g(x,y,t)$ possesses continuous first order partial derivatives with respect to t.

$$\begin{aligned} T(x,y,t) = & \frac{1}{k}\sum_{m=1}^{\infty}\frac{1}{\delta^2+\beta^2}K(\delta_m,x)K(\beta_m,y)\overline{g}(\delta_m,\beta_m,t) \\ & + \sum_{m=1}^{\infty} e^{-\alpha t\left(\delta_m^2+\beta_m^2\right)}K(\delta_m,x)K(\beta_m,y) \\ & \times \left\{\overline{F}(\delta_m,\beta_m) - \frac{1}{\left(\delta_m^2+\beta_m^2\right)}\right. \\ & \times \left.\left[\overline{g}(\delta_m,\beta_m,0) + \frac{1}{k}\int_0^t e^{\alpha\overline{t}\left(\delta_m^2+\beta_m^2\right)}\frac{\partial\overline{g}}{\partial\overline{t}}\mathrm{d}\overline{t}\right]\right\} \end{aligned} \tag{5}$$

where $\overline{g}$ and $\overline{F}$ are the Integral transformed of g and F, respectively, given by:

$$\overline{g}(\delta_m,\beta_m,t) = \int_0^{l_2}\int_0^{l_1} K(\delta_m,x)K(\beta_m,y)g(x,y,t)\mathrm{d}\overline{x}\mathrm{d}\overline{y} \tag{6}$$

$$\overline{F}(\delta_m,\beta_m) = \int_0^{l_2}\int_0^{l_1} K(\delta_m,x)K(\beta_m,y)F(x,y)\mathrm{d}\overline{x}\mathrm{d}\overline{y} \tag{7}$$

Table 1
Equations to calculate the heat partition B flowing to workpiece.

Source	Equation
Chao and Trigger [5]	$B = 0.1$
Loewen and Shaw [6]	$(B-1) = 1/\left(1+1.328\sqrt{\frac{\alpha\Gamma_z}{v_c\hbar}}\right)$
Leone [7]	$B = 1/\left(1+1.13R_c\sqrt{\frac{L_f v_f}{\alpha}}\right)$

Source: adapted from [8] and [9] where α is thermal diffusivity, Γ_z is average shear strain, $\Gamma_z = \cos(\gamma)/\sin(\phi)\cos(\phi-\gamma)$ ((γ)$e\phi$ rake angle and shear angle, respectively, see Fig. 1), v_c is the cutting speed, v_f is the feed speed, $\hbar$ is the depth of cut, or undeformed chip thickness, $R_c = \hbar'/\hbar$ is the chip thickness ratio ($\hbar'$ chip thickness), L_f width of shear band heat source.