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Analytical and numerical solutions of transient heat conduction in monolayer-coated tools

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ABSTRACT

The heat generation during metal cutting processes affects accuracy of the machined surface and strongly influences tool wear and tool life. Knowledge of the ways in which the tool material affects the temperature distribution is therefore essential for the study of thermal effects on tool life and workpiece quality. Many studies have been done on simulation temperature distribution in coated cutting tools by means of the finite element method or the finite difference method.

In this study, a thermal analytical model is firstly developed to determine temperature distribution in monolayer-coated cutting tools during orthogonal metal cutting. In the analytical model one equivalent heat source applied on the coating layer boundary substitutes for the heat generation introduced from the primary deformation zone, the secondary deformation and the frictional zone along the tool–chip interface as well as the tertiary or the sliding frictional zone at tool–workpiece interface. A mathematical model of the transient heat conduction in monolayer-coated tools is then proposed. The temperature distribution formulations in monolayer-coated tools are obtained using Laplace transform. The influence of different parameters including thermophysical properties of tool coating and tool substrate and thickness of the coating layer on temperature distribution in monolayer-coated tools is lastly discussed and illustrated.

1. Introduction

In metal cutting operations, temperature develops both at the tool–chip interface and tool–workpiece interface, and heat transferred from these zones is a crucial factor. The heat generation and heat conduction during machining depends mainly on tool and workpiece materials, process parameters, and the material remove rate of the workpiece. Among them, thermophysical properties of tool and workpiece material used are found to be decisive factors in the distribution of temperature fields and heat dissipation (Grzesik and Nieslony, 2003, 2004). Conversely, the developed temperature field during cutting determines such key process issues as many parameters including accuracy of the machined surface, tool wear, tool life, mechanics of chip formation, surface quality, cutting forces, and cutting parameters as well as process efficiency. Consequently, temperature rise has a controlling influence on cutting process. Determination of temperature distribution in cutting domain, therefore, has been one of the major subjects in the machining researches (Dogu et al., 2006).

The methods to determine temperature in uncoated tool or coated tool include analytical method, experimental measurement, numerical analysis (Dogu et al., 2006), hybrid technique and heat source method. Analytical method is through heat transfer model building to calculate temperature mathematically. Experimental measurement is using the tool–work

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Nomenclature

A_1, B_1, A_2, B_2	constants coefficients
c	coefficient defined in Eq. (24)
k_1	thermal conductivity coefficient in coating layer (cal/(cm s °C))
k_2	thermal conductivity coefficient in substrate body of coated tool (cal/(cm s °C))
n	integer number (including zero)
q_0, q_1, q_2, q_3	heat fluxes (cal/(cm^2 s))
s	Laplace operator
t	time (s)
$T^{(1)}$	temperature for coating layer (°C)
$T^{(2)}$	temperature for substrate body (°C)
T_∞	initial temperature in coated cutting tool (°C)
x	spatial coordinates (cm)
x_1	thickness of coating layer (cm)

Greek symbols

α_1	thermal diffusivity coefficient in coating layer (cm^2/s)
α_2	thermal diffusivity coefficient in substrate body of coated tool (cm^2/s)
$\bar{\theta}^{(1)}, \bar{\theta}^{(2)}$	Laplace transforms of $\theta^{(1)}, \theta^{(2)}$

thermocouples, embedded thermocouples, thin film thermocouples, thermovisions, infrared systems, melting points of thermosensitive materials, or metallographic techniques and so on to measure temperature. Numerical analysis includes finite element analysis, finite different analysis, and boundary element analysis, etc. Hybrid technique is using two or several methods above mentioned to access temperature. Heat sources method is obtaining temperature field through adding the temperature values which all the heat sources contribute. Komanduri and Hou (2000, 2001a,b) made a general review of the analytical models of heat generation and heat conduction in workpiece, chip, and tool. They developed a more appropriate analytical method considering the heat sources from the shear plane, the primary shear zone, and the tool–chip friction interface. They pointed out that the analytical results were in good agreement with the experimental results. They also found that the analytical solutions by using relevant computer program were convenient and accurate. Wan et al. (2004) summarized the present methods used to measure the cutting temperature, and analysed their merits and demerits and application ranges. Komanduri and Hou (2001c) also gave a review of the literature on several methods of temperature measurements.

For uncoated tool, the metal cutting studies in terms of thermal aspects have focused on determining the heat distribution and the maximum temperature. Many literatures studied determining heat conduction in uncoated cutting tool. Komanduri and Hou (2001b) determined the temperature rise distribution caused by shear plane heat source and friction heat source along the tool–chip interface using analytical method. Filice et al. (2006) used 2D thermo-mechanical analysis and 3D pure thermal analysis to simulate machining processes with uncoated cutting tool. Rena et al. (2004) studied cutting temperatures in hard turning chromium with a PCBN tool using a mixed experimental and finite element simulation. Majumdar et al. (2005) used the finite element method to obtain two-dimensional steady-state heat diffusion in metal cutting processes. Ng et al. (1999) used finite element model to simulate temperature distributions when orthogonal turning a hardened hot work die steel with a polycrystalline cubic boron nitride (PCBN) tool and validated the model by experimental data from infrared chip surface temperature measurements.

There are many approaches to minimize the impact of heat generation on tool life in metal cutting. The conventional approach is to remove the heat generated through a cooling cycle in metal cutting. A novel way is using coated cutting tool obtained by means of the deposition of proper coatings on tool surfaces. The coating of cutting tools has great influence on cutting heat generation and heat conduction in the tools during machining. The effect of temperature-dependent thermal properties may become important for cases when very steep temperature gradient can be generated (Grzesik and Nieslony, 2004). So having a more clear understanding about the temperature distribution in coated cutting tool is very useful and important.

The most important discussion for cutting temperature with coated tools is about the influence of coating on heat generation, heat partition, tool–chip interface temperature, tool–workpiece interface temperature and heat transfer or heat flux within tools.

Some researches have been done to investigate heat generation and heat partition between coated tool and chip. Grzesik (2000) used experiment to investigate the influence of coating on frication heat generation with different coated tools. He found that coating layers can improve tribological properties of surfaces in sliding contact under employed cutting conditions and some coatings which have thermal barrier effect can substantially reduce contact temperatures. Grzesik and Nieslony (2003) used analytical method to predict heat partition coefficient in the stationary tool and in the moving chip with uncoated and multilayer-coated tools. Through investigating how the temperature depended on tool–chip contact length, Peclet number ($Pe = v_{ch} l_c/\alpha_t$, where v_{ch} is sliding chip velocity, l_c is tool–chip contact length and α_t denotes coating layer thermal diffusivity) and the specific friction energy, respectively, they found that multilayer-coated tool ($TiC/Al_2O_3/TiN$, $TiC/Ti(C,N)/Al_2O_3/TiN$) increase about 30% more heat into chip due to friction.

Various approaches have been used for investigating tool–chip and tool–workpiece interface temperature. Grzesik and Nieslony (2004) used equivalent parameters of coating layers to calculate tool–chip mean interface temperature and peak temperature, comparing with measured temperature of workpiece and tool thermocouple pair under the condition that cutting speeds were ranging from 100 m/min to 200 m/min. They concluded that the prediction errors for average interface temperature did not exceeded 10–15%. Kwon et al. (2001) used an infrared video camera to get chip–tool interface temperature during turning then used experimental data to determine transient temperature, a one-dimensional ellipsoidal model was constructed to estimate the average steady-state chip–tool interface temperature inversely during