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Temperature calculation in cutting zones

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ABSTRACT

This paper presents methods for refining the calculation of cutting temperatures. The heat flow densities and temperatures in the chip forming area, the accumulation zone and the area of the plastic contact between chip and tool affect the cutting temperature considerably. The new method takes the heat distribution for moving sources into account. The temperature in the contact between the flank face and the workpiece is calculated considering how friction and the accumulation zone affect the cutting temperature in the tertiary cutting zone. The methods incorporate material softening during temperature increase. The models are verified by experimental analyses.

1. Introduction

Modelling of cutting processes can be used to determine resultant forces as well as the temperature distribution and heat flow density in the cutting zones [1]. Analytical cutting models so far mostly neglect a correlation between the temperature and the resistance characteristics of the material to be machined. This correlation is, however, significant for describing the effect of the cutting conditions on the temperature accurately. In the past, numerous analytical models for the calculation of cutting temperatures were developed and experimental analyses of the temperature distribution in tools, workpieces and in the contact between these objects were conducted [2]. In Ref. [3], the cutting process was regarded in the chip forming plane. A plane heat distribution in the heat exchange was assumed. The process of three-dimensional cutting was derived from a plane process with varying depth of cut along the cutting edge of the tool. To establish the temperature on the rake face, heat sources were considered with respect to the deformation of the material in the chip forming area as well as to the deformation and friction in the contact of the chip and the rake face. The temperature distribution along this contact was calculated from the joint effect of the heat sources. Based on the analytical solution by Hahn [4], modified by Chao and Trigger [3], Komanduri and Hou examined a temperature distribution due to deformation in the shear plane in orthogonal cutting [5]. They also modelled a temperature distribution applying the method of moving source by Carlsaw and Jaeger [6]. Recently, additional methods for the analytical modelling of the temperature distribution in the cutting zones were used [7–9].

In summary, until now, analytical models of the temperature distribution are calculated in two heat emission zones (chip forming area and rake face). In each zone, two bodies are in contact (chip and workpiece in the shear plane; chip and tool at the rake face). In these zones, the heat flow density was analysed. A distribution of the general output of the heat sources between the bodies in contact was taken into account by two principle approaches. On the one hand, a distribution of the heat flow density is established from the heat source that is independent of temperature. These temperature distributions are used as boundary conditions [3]. On the other hand, the temperature is calculated considering the correlation between temperature and heat flow density. This is done by the joint solution of the thermal conductivity equation and the constitutive equation.

This paper introduces an analytical cutting temperature calculation by taking the dependence of the heat flow density on the temperature into account as well as the peculiarities of the heat distribution at exemplary cutting speeds for AISI 1045 steel. In addition to the shear plane and the rake face, the accumulation zone and areas of plastic contact are considered.

2. Model approach

The analytical calculation model of the temperature distribution regards orthogonal cutting (Fig. 1).

The following heat sources are considered: material deformation in chip forming area A; material deformation under adiabatic conditions in accumulation zone B on the rake face; plastic contact between the chip and the rake face in the zone C; plastic contact between tool and workpiece due to the material deformation under adiabatic conditions and an intensive heat dissipation perpendicular to the cutting speed in the accumulation zone G. The temperatures are established separately for each cutting zone. The directions and the quantity of the heat flows which are diverted from the heat sources into the chips, the workpiece and the tool are characterized by certain peculiarities which simplify the temperature calculation.

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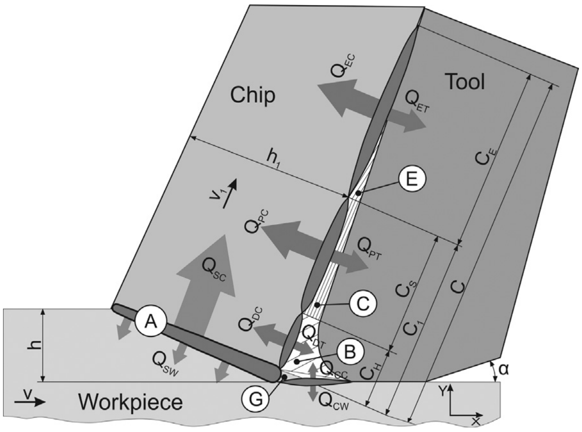

Fig. 1. Layout of heat flows in orthogonal cutting.

The Péclet similarity criterion [5],

$$P_e = \frac{v \cdot h}{\omega}, \tag{1}$$

with cutting speed v, undeformed chip thickness h and coefficient of thermal diffusivity ω, constitutes a ratio between convective and molecular heat transfer. It is increased with rising cutting speed and undeformed chip thickness. When P_e is increased, the movement of the workpiece material provides an increasing major part of convective heat transfer compared to a decreasing minor conductive heat flow from the chip forming area into the workpiece. Correspondingly, with increasing cutting speed, more heat is transferred by convection than by conductivity into the tool which is fixed relative to the heat sources. The heat flows normal to the velocities of the workpiece or the chip do not prevent a convective heat exchange. Though, heat flows in the directions of these velocities arise due to thermal conductivity. Consequently, quasi-stationary two-dimensional temperature fields in the chip and the workpiece can be expressed as one-dimensional temperature fields.

The temperature calculation applies the method of moving sources [10]. The temperatures in a half plane for the layout in Fig. 1 are established with the following equation:

$$\theta(0,x) = \frac{2}{\sqrt{\pi}} \cdot \frac{q_f}{C_V} \cdot \sqrt{\frac{x}{v_1 \cdot \omega}}, \tag{2}$$

with real coordinates x, the density of the evenly distributed heat flow q_f, the specific volumetric heat capacity of the material to be machined C_v, and the speed of the chip v_1. Considering

$$q_f = q_F \cdot v_1 \quad \text{and}\, v_1 = \frac{v}{K_a},$$

$$\Delta T' \approx \frac{2}{\sqrt{\pi}} \cdot \frac{q_F}{R_t} \cdot A_1 \cdot \sqrt{P_e}$$

with the chip compression ratio K_a and the mean specific tangential force in the area of the plastic contact between chip and tool q_F [11], it is possible to calculate the increase in homologous temperature according to the following equations:

$$\Delta T' = \frac{\Delta\theta(0,x)}{\mathrm{T}_m} = \frac{2}{\sqrt{\pi}} \cdot \frac{q_F}{R_t} \cdot \frac{R_t}{C_V \cdot \mathrm{T}_m} \cdot \sqrt{\frac{v \cdot h}{\omega} \cdot \frac{x}{a} \cdot \frac{1}{K_a}} \tag{3}$$

$$A_1 = \frac{R_t}{C_V \cdot \mathrm{T}_m} \quad \text{and}\, \Delta T' \approx \frac{2}{\sqrt{\pi}} \cdot \frac{q_F}{R_t} \cdot A_1 \cdot \sqrt{P_e}$$

with the melting temperature T_m, and the effective ultimate strength R_t. The temperature calculation is established by superposing the solutions for evenly distributed heat sources and heat flows with subsequent iterations. Small areas of the accumulation zone close to the cutting edge, in which the yield point of the machined material and thus the heat density increase up to the maximum, are taken into account.

It is required to obtain the distribution of the heat flows in the areas of the plastic contact between chip and tool as well as in the accumulation zone in the contact between tool and workpiece by jointly solving the equation of thermal conductivity and the constitutive equation. The thermomechanical model of the material resistance to cutting [12] is used here as constitutive equation, which connects the yield point to the temperature during material deformation under cutting conditions. The heat flow density in the chip forming area and in the area of the plastic contact between chip and tool is calculated on the basis of this material model. The heat flow density in the areas of the elastic contact between chip and tool (E) as well as the elastoplastic contact between tool and workpiece within the wear land are assumed to be independent of temperature. These heat flow densities are established by superposing the solutions for evenly distributed heat sources and heat flows.

3. Temperature distribution in the chip

The temperature of the chip close to its contact with the tool depends on two heat sources (Fig. 1): a heat source in the chip forming area A due to material deformation and a heat source in the contact between the chip and the rake face of the tool as a result of the material's plastic deformation. These contacts are the accumulation zone B, the zone of the plastic contact C and the zone of the elastic contact E. Passing through the chip forming area, the material to be machined is evenly warmed up to the deformation temperature. This temperature depends on the specific deformation work, the heat flow from the chip forming area into the workpiece and the specific heat capacity of the material. The material hardens in the area B with the length C_H. Its yield point attains the maximum value $\tilde{q}$ here. The material softens in the area C of the plastic contact C_1 with the length C_S. This occurs due to the influence of the temperature on the hardening effect of the strain rate [12]. In accordance with a linear law, the heat flow density decreases in the area E of the elastic contact between chip and tool with the length C_E. Friction is considered here by means of a constant tangential stress.

3.1. Calculation of the deformation temperature

In order to take account of how the heat flow density in the chip forming area and the heat flow from the chip forming area into the workpiece affect the deformation temperature, an elementary segment of the shear plane is assumed as a point heat source with the heat flow density q_w. This point heat source moves at the speed v_n normal to the shear plane (Fig. 2).

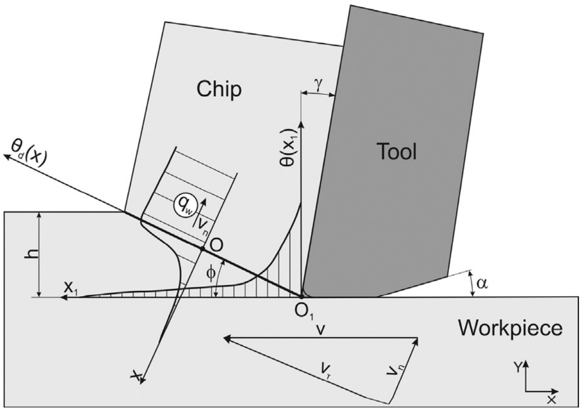

Fig. 2. Layout for calculating the deformation temperature.

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