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Analysis of the frictional heat partition in sticking-sliding contact for dry machining: an Analytical-Numerical modelling

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Abstract

Dry high speed machining is associated with high temperatures which strongly affect the chip formation mechanisms, tribological conditions, workpiece surface integrity, tool wear and then the tool life. To predict the temperature distribution in the tool-chip system, the frictional heat partition, in sliding zone of the tool-chip contact, should be properly taken into account. The determination of the heat flux flowing into the tool is still a challenging issue that affects the models accuracy in machining. Despite the fact that an extensive published literature has been focused on the modeling of the tribological conditions in machining, the thermal aspects of the tool–chip contact require further investigations. In the present work, an analytical-finite element model is presented. The model is compared to the experimental cutting forces for a wide range of cutting speeds. The coupling between the secondary shear zone and the frictional heat partition is also presented.

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Keywords: Dry high speed machining; Analytical-FE model; Frictional heat partition

1. Introduction

Several works have been focused on temperature measurement and its prediction in machining process, [1-12]. By matching the interface temperature on each side of the tool-chip contact, different models have been proposed for the calculation of the heat partition coefficient. However, in these models, the coupling between the sticking-sliding zones and the frictional heat partition is not taken into account. In addition, only the stationary case has been considered and the influence of the temperature gradient between the tool and the chip has not been considered.

In dry high speed machining, the friction conditions at the tool-chip interface are very complex, [13-15]. The built-up layer can be formed when the temperature at the tool-chip interface and the local friction coefficient are large enough, [16-17]. The friction conditions in machining also depend on the inherent relationship among, the cutting conditions, the

workpiece material behaviour, the thermomechanical characteristics of the tool material and the frictional heat partition. To model the chip formation process, the interaction between the process formation of sticking zone along the tool rake face and the thermomechanical material flow in the primary shear zone (PSZ) have to be taken into account. Several authors have proposed different simplified approaches to model the effect of cutting conditions on the sticking-sliding zone at the tool-chip interface, [18-23].

In the present work, a hybrid Analytical-Numerical model is presented. The analytical approach is used to model the material flow in the primary shear zone, the tool–chip contact length, the link between the local friction coefficient, the sliding–sticking zones and the apparent friction coefficient. To solve the transient nonlinear thermal problem in the tool-chip-workpiece system, a FE model based on the Petrov-Galerkin formulation has been developed. This transient FE model takes into account the coupling between the primary shear zone (PSZ) (chip formation), the secondary shear zone

(sticking zone) and the frictional heat at the sliding zone. In addition, the frictional heat source was applied through the Dirac function. Thus, the model allows to analyze the influences of the cutting conditions on the evolution of the frictional heat partition at the tool-chip interface during the cutting time.

2. An analytical-finite element model

For the chip formation process, it is well known that in high speed machining, the primary shear zone can be assimilated to a thin band of constant thickness h_1 and characterized by the shear angle ϕ as shown in Fig.1. This zone is decomposed into a set of elements with thickness h_1 and length dl in the present approach. To model the material flow within each element 'i', the stationary one-dimensional approach developed in [21-23] has been modified to take into account the coupling between the material flow in the PSZ and the nonlinear thermal problem in the workpiece-chip-tool system. Thus, in this work, a quasi-stationary flow was assumed in each element 'i' where the shear velocity v_s , the shear strain γ , the shear strain rate $\dot{\gamma}$ and the shear stress τ depend only on the coordinate v along the normal to this band and on the mean temperature \bar{T}_i . By using the one-dimensional formulation, the heat source Q_{PSZ} can be estimated as following:

$$Q_{PSZ} = \sum_i \bar{q}_i \text{ with } \bar{q}_i = \frac{\beta}{h_1} \int_0^{h_1} \tau \dot{\gamma} dy_s = \frac{\beta}{2h_1} \{ \rho V \sin \phi V_s^2 + 2 \tau_0 V_s \} \quad (1)$$

where β is the Taylor-Quinney coefficient (the fraction of plastic work converted into heat). From the boundary conditions corresponding to the PSZ, we get : $v_s(y_s = h_1) = V_s = V \cos \alpha / \cos(\phi - \alpha)$. For each element 'i', the shear stress τ_0 at the entry of the primary shear is determined from an integral equation deduced from the nonlinear differential equation $dv_s/dy_s = \psi(v_s, \tau_0)$ (the function ψ is deduced from the JC law (2) by considering the mean temperature \bar{T}_i in the element ('i')). The thermoviscoplastic behaviour of the workpiece material is assumed to be isotropic and given by the Johnson-Cook law:

$$\tau = \frac{1}{\sqrt{3}} \left[A + B \left(\frac{\gamma}{\sqrt{3}} \right)^n \right] \left[1 + C \ln \left(\frac{\dot{\gamma}}{\dot{\gamma}_0} \right) \right] \left[1 - \left(\frac{T - T_0}{T_m - T_0} \right)^m \right] \quad (2)$$

The shear stress, the shear strain rate, the shear strain and the temperature are respectively denoted by $\tau, \dot{\gamma}, \gamma$ and T . The characteristics of the work material behaviour are the strain hardening exponent n , the strain rate sensitivity coefficient C , the thermal softening exponent m and the constants $A, B, \dot{\gamma}_0, T_0$ (reference temperature) and T_m (melting temperature).

At the tool-chip interface, the equations governing the sticking zone length l_{st} and the relationship between the local friction coefficient μ_{sl} in the sliding zone and the apparent friction coefficient $\bar{\mu}$ are obtained respectively from the shear stress continuity at the tool-chip interface and from the chip

equilibrium, see [16]:

$$\begin{cases} \mu_{sl} \frac{P_0}{\tau_{sl}(\tilde{x}=l_{st})} \left(1 - \frac{l_{st}}{l_c} \right)^\xi - l = 0 \\ \mu_{sl} \left(1 - \frac{l_{st}}{l_c} \right)^\xi \left(\frac{l + \xi}{\tau_{sl}(\tilde{x}=l_{st}) l_c} \int_0^{l_{st}} \tau_{sl}(\tilde{x}) d\tilde{x} + 1 - \frac{l_{st}}{l_c} \right) - \bar{\mu} = 0 \end{cases} \quad (3)$$

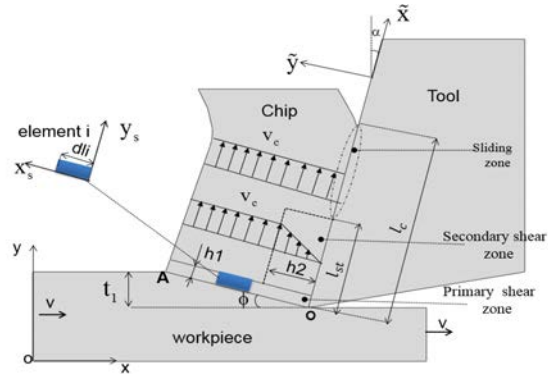


Fig.1: Modelling of the chip formation process under orthogonal cutting configuration.

In the implicit equations (3), the shear stress $\tau_{sl}(\tilde{x})$ at the tool-chip interface (i.e. $\tilde{y}=0$) for $0 \leq \tilde{x} \leq l_{st}$ (sticking zone) is calculated from (2) as indicated below.

According to [22-23], p_0 and l_c are obtained from the chip equilibrium which leads to:

$$\begin{cases} p_0 = \frac{4}{w} \frac{(l + \xi) \cos^2 \bar{\lambda}}{l_{0A} (2 + \xi) \sin(2(\phi + \bar{\lambda} - \alpha))} \int_0^{l_{0A}} (\rho V \sin \phi V_s + \tau_0) w dx_s \\ l_c = t_1 \frac{(2 + \xi) \sin(\phi + \bar{\lambda} - \alpha)}{2 \sin(\phi) \cos(\bar{\lambda})} \end{cases} \quad (4)$$

with $\bar{\lambda} = \tan^{-1}(\bar{\mu})$ and w represent respectively the apparent friction angle at the tool-chip interface and the width of cut. The length $l_{0A} = t_1 / \sin \phi$ is defined in Fig. 1.

During the chip formation process, the thermal problem is a nonlinear heat and mass transfer problem involving the combined effects of transport and diffusion. The temperature distribution $T(x, y)$, in the workpiece-chip-tool system, is governed by the following heat equation:

$$k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + Q = \rho c \frac{DT}{Dt} \quad (5)$$

with

$$\begin{cases} Q = Q_{PSZ}(x, y) + Q_{SSZ}(x, y) + Q_f(\tilde{x}) \delta(\tilde{y}) \\ \frac{DT}{Dt} = \frac{\partial T}{\partial t} + v(x, y) \frac{\partial T}{\partial x} + u(x, y) \frac{\partial T}{\partial y} \end{cases} \quad (6)$$

The coordinates (\tilde{x}, \tilde{y}) , reported in Fig. 1, are associated to the tool rake face. The variables V_c, h_2, p_0, l_c and μ_{sl} represent respectively the chip velocity, the width of the secondary shear zone, the pressure exerted on the tool tip, the tool-chip contact length and the local friction coefficient at the tool-chip interface, see Fig. 1. In addition, the heat capacity, the thermal conductivity and the x and y components of material

velocity are given by ρ , c , k , $u(x,y)$ and $v(x,y)$, respectively. The heat sources Q_{psz} and Q_{ssz} designate the heat source due to the viscoplastic deformation in the primary and secondary shear zones. Q_f is the heat source due to the frictional contact in the sliding zone:

$$Q_{ssz} = \tau_{st} V_c / h_2, \quad Q_f = \mu_{st} V_c p_0 (1 - \tilde{x}/l_c)^{\xi} \quad (7)$$

In the secondary shear zone, the effect of the strain hardening is supposed to be negligible with respect to strain rate and thermal effects. Thus, the shear stress τ_{st} in this zone is determined from the Johnson–Cook law (2) by considering: $\gamma = \gamma_h$ (which is the shear strain at the exit of the primary shear zone given by $\gamma_h = \tan(\phi - \alpha) + 1/\tan\phi$) and $\dot{\gamma} = V_c/h_2$ (V_c is the chip velocity).

Besides, the introduction of Dirac function $\delta(\tilde{y})$ in (5) allows easily to take into account the partition of the frictional heat source $Q_f(\tilde{x})$ between the tool and the chip. In this model, to determine the temperature $T(x,y)$ in the tool-chip-workpiece system, the nonlinear heat mass transfer is solved by using the FE method based on the Petrov-Galerkin approach. The implicit Euler scheme which is unconditionally stable in time has also been combined with the Newton-Raphson method to solve the thermal nonlinear problem at each time t .

3. Results and discussion

The present model is compared with the orthogonal tests of aluminum alloy AA2024–T351 under dry cutting conditions by using an uncoated carbide insert, [13]. Different cutting speeds V have been considered from 80 to 500 m/min. The rake angle α was taken equal to zero. The uncut chip thickness t_1 and the width of cut w were respectively fixed to 0.1 mm. and 4 mm. The work material and the tool parameters are deduced from the reference [17]. From Fig. 2, it appears that the cutting force is a decreasing function of V . This decay is due to the thermal softening of the work material along the tool rake face. Indeed, one of the relevant parameters for the chip formation process during its interaction with the cutting tool is the temperature at the tool-chip interface. In fact, this temperature controls the thermal softening of the work-material and affects the whole process. The temperature increase with the cutting speed is caused by (a) the self-heating of the work material due to plastic deformation in the primary and secondary shear zones and (b) the frictional heating along the sliding zone. Thus, when this thermal softening and the local friction coefficient μ_{st} are large enough, the interface shear stress τ_{st} becomes smaller and the tool-chip contact is governed by sticking conditions (i.e. $\mu_{st} p > \tau_{st}$ with p the contact pressure). Consequently, the variation of the cutting forces in terms of V is mainly controlled by the decay of the interface shear stress τ_{st} caused by the thermal softening.

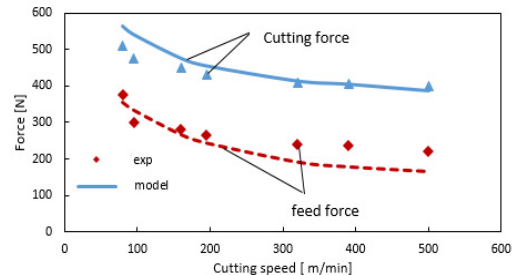


Fig.2: Effect of cutting speed on cutting force

To analyze the influence of the sticking zone length l_{st} on the heat flux Q_{chip} going to the chip for two cutting velocities $V = 8$ and 3 m/s , the following ratios $l_{st}/l_c = 0, 0.25$ and 0.5 have been considered (the sliding contact corresponds to $l_{st}/l_c = 0$). The rake angle is zero and the cutting duration is about 5 ms . From Figs. 3 and 4, it can be observed that Q_{chip} (in the sliding zone) decreases when l_{st}/l_c becomes larger. It can be reminded that the term Q_{chip} includes: (i) the part of frictional heat Q_f flowing to the chip and (ii) the heat flux caused by the temperature gradient between tool and chip at the both sides of the tool rake face. In addition, in this first approach the thermal resistance is supposed to be zero. These results indicate that if we suppose that a constant fraction of Q_f flows towards the chip, as usually used in finite element simulations, it appears that the tendencies of Figs. 3 and 4 cannot be reproduced. The model reproduces also the fact the Q_{chip} is a decreasing function of cutting speed as shown in Figs. 3 and 4. The model predictions indicate that at the end of the tool-chip contact (near to $\tilde{x}/l_c = 1$), the heat flux goes from the chip to the tool which is much colder than the chip (in the figure, this part is indicated by $Q_{chip} = 0$).

From this analysis, it appears that the frictional heat partition, between the cutting tool and the work material, depends on the thermal properties, the cutting conditions, the cutting duration and the tribological conditions.

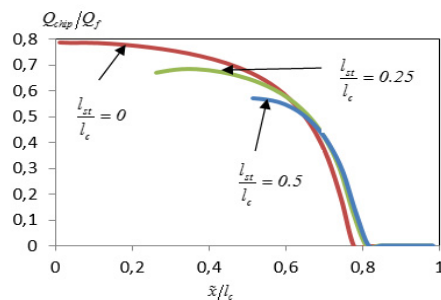


Fig.3: Effect of the sticking zone length l_{st} on the heat flux Q_{chip} flowing

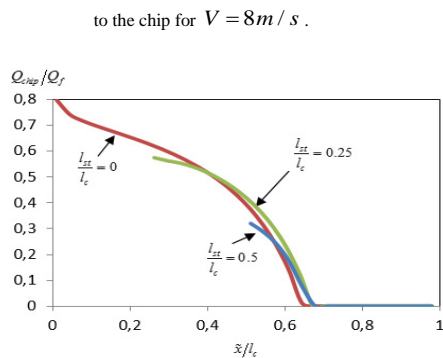


Fig.4: Effect of the sticking zone length l_{st} on the heat flux Q_{chip} flowing to the chip for $V = 3m/s$.

4. Conclusion

A hybrid Analytical-Numerical model is presented. To solve the transient nonlinear thermal problem in the tool-chip-workpiece system, a FE model based on the Petrov-Galerkin formulation has been developed. The frictional heat source was applied through the Dirac function. Consequently, the model allows to analyze the influences of the cutting conditions on the evolution of the frictional heat partition at the tool-chip interface during the cutting time. In addition, the present approach takes into account the coupling between the material flow in the primary shear zone (chip formation) and the thermomechanical load along the tool rake face (sticking-sliding contact). It represents a real alternative to the traditional finite element modelling in machining.

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