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ScienceDirect
Procedia CIRP 58 (2017) 539 – 542
www.elsevier.com/locate/procedia

16th CIRP Conference on Modelling of Machining Operations

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.

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

doi:10.1016/j.procir.2017.03.334

(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 y_s along the normal to this band and on the mean temperature $\overline{T}_i$. By using the one-dimensional formulation, the heat source Q_{PSZ} can be estimated as following:

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

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 $\overline{T}_i$ 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 τ, $\dot{\gamma}$, γ 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 fiction coefficient $\overline{\mu}$ are obtained respectively from the shear stress continuity at the tool-chip interface and from the chip equilibrium, see [16]:

$$\begin{cases} \mu_{sl}\dfrac{p_0}{\tau_{st}(\tilde{x}=l_{st})}\left(1-\dfrac{l_{st}}{l_c}\right)^{\xi} - 1 = 0 \\ \mu_{sl}\left(1-\dfrac{l_{st}}{l_c}\right)^{\xi}\left(\dfrac{(1+\xi)}{\tau_{st}(\tilde{x}=l_{st})\,l_c}\displaystyle\int_0^{l_{st}}\tau_{st}(\tilde{x})\,d\tilde{x} + 1 - \dfrac{l_{st}}{l_c}\right) - \overline{\mu} = 0 \end{cases} \quad (3)$$

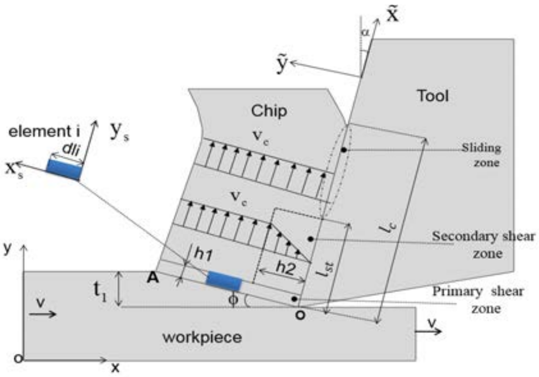

Fig.1: Modelling of the chip formation process under orthogonal cutting configuration.

In the implicit equations (3), the shear stress $\tau_{st}(\tilde{x})$ at the tool-chip interface (i.e. $\tilde{y} = 0$) for $0 \le \tilde{x} \le l_{st}$ (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:

$$\begin{cases} p_0 = \dfrac{4}{w\, l_{OA}}\dfrac{(1+\xi)}{(2+\xi)}\dfrac{\cos^2\overline{\lambda}}{\sin\left(2\left(\phi+\overline{\lambda}-\alpha\right)\right)}\displaystyle\int_0^{l_{OA}}\left(\rho V \sin\phi\, V_s + \tau_0\right) w\, dx_s \\ l_c = t_1\dfrac{(2+\xi)}{2}\dfrac{\sin\left(\phi+\overline{\lambda}-\alpha\right)}{\sin(\phi)\cos\left(\overline{\lambda}\right)} \end{cases} \quad (4)$$

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

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

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