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Hybrid modelling of sliding–sticking zones at the tool–chip interface under dry machining and tool wear analysis

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ABSTRACT

Tool wear in machining processes strongly depends on the tool–chip interface. The sliding–sticking zones at this interface depend on the evolution of the local conditions of stress, velocity and temperature. Several authors have shown that because of the complexity of the tool–chip contact, the tribological conditions are not fully understood and accurate predictive models have yet to be developed. To propose a realistic model of chip formation, a hybrid analytical–numerical approach is presented in this work for the orthogonal cutting process. This simplified approach can be very useful for analysing the interaction between the chip formation process and the tribological conditions at the tool–chip interface. An analytical model is used to analyse the thermomechanical material flow in the primary shear zone, the tool–chip contact length, the local friction coefficient and the sliding–sticking zones. In addition, the temperature distribution in the chip is studied by numerical means. The effects of cutting conditions and material behaviour are evaluated. In the case of machining of Ti6Al4V titanium alloy, a quantitative comparison between model and experimental results is also provided to analyse the wear process.

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1. Introduction

The tool wear in manufacturing processes depends on mechanical and physico-chemical interactions at the tool–workpiece interfaces. From a mechanical point of view, it is important to have an access to the local distribution of tribological parameters controlling the tool–chip contact. Two types of contact can be distinguished; sticking contact with complete seizure between tool rake face and chip close to the tool tip, and sliding contact with relative motion between chip and tool. These aspects of contact have been extensively studied in many experimental investigations [1–3]. At low cutting speeds the tribological phenomenon of sliding operates at tool–chip interface [4]. As cutting speed is increased, there is a transition in tribological phenomenon from sliding to sticking (seizure) at the tool–chip interface [5–8]. The concept of sticking contact depends on coupled thermomechanical phenomena. Atomic contact is established at the tool–chip interface due to the effect of high pressure and the drop of the flow stress of the chip material resulting from the increasing of temperature. The layer of the chip in contact with the tool is stationary and relative motion takes place in adjacent layers with the shear velocity gradually increasing until the bulk chip speed is obtained.

Due to the complexity of the tool–chip contact, the full understanding of the contact conditions has not been enough developed. Thus, several simplified models have been proposed in the literature such as pure sliding contact [9], pure sticking contact [10], or a fixed part of sticking followed by sliding contact [1]. Different finite element models have been used to analyse the thermomechanical effects of friction modelling at the tool–chip interface, Childs [6,15], Ozel [11], Filice et al. [12], Haglund et al. [13], Arrazola and Özel [14].

In [11], five different friction models have been implemented: (i) constant shear friction at the tool–chip interface, (ii) Coulomb friction law, (iii) constant shear friction in the sticking region and Coulomb friction in the sliding region, (iv) sticking–sliding law and (v) variable shear friction at the tool–chip interface. The normal and shear stress distributions on the cutting tool rake face have been compared with the experimental results of Childs et al. [8]. The author concluded that the most accurate model is the one that uses variable stresses on the tool–chip interface describing the dual sticking and sliding contacts.

The tribological conditions, at the tool–chip interface, have been extensively studied in many investigations [1–16], but questions that still remain are: (i) how does the proportion of the sticking zone on the tool–chip interface varies with respect to cutting conditions, and (ii) how much are the tribological parameters affected

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Nomenclature

α	rake face angle
$\bar{\lambda}$	global friction angle
ϕ	shear angle
β	Taylor–Quinney coefficient ($\beta \simeq 0.9$)
h	width of the primary shear zone
$\bar{\mu}$	global friction coefficient at the tool–chip interface
μ_{sl}	local friction coefficient at the sliding zone
V	cutting speed
V_{c}	chip velocity
L_{c}	tool–chip contact length
a	length of the sticking zone
b	length of the transition zone
t_1	undeformed chip thickness (feed)
t_2	chip thickness
w	width of cut
ρ	workpiece material density
c	heat capacity
k	thermal conductivity
T	temperature in the primary shear zone
T	temperature in the chip
T_{w}	temperature of the workpiece
T_{r}	ambient temperature
T_{melt}	melting temperature
T_{psz}	temperature at the exit of the primary shear zone
τ	shear stress in the primary shear zone
τ_0	shear stress at the entry of the primary shear zone
τ_{psz}	shear stress at the exit of the primary shear zone
τ_{int}	shear stress at the tool-chip interface
τ_{st}	shear stress at the secondary shear zone
τ_a	shear stress at the end of the sticking zone
p	pressure at the tool–chip interface
p_0	pressure at the tool tip
ξ	coefficient controlling pressure distribution along the tool rake face interface
γ	shear strain
γ_h	shear strain at the exit of the primary shear zone
$\dot{\gamma}$	shear strain rate
$\dot{\gamma}_0$	shear strain rate reference
δt_2	width of the secondary shear zone ($0 < \delta < 1$)
v_x	velocity of material particle in the chip
Q_{p}	heat source due to the plastic deformation in the sticking zone
Q_{f}	heat source due to the friction in the sliding zone

by the degree of sticking. In addition, according to several works [6,11–15]; there is no model able to predict correctly the friction law along the tool rake face.

The main goal of this work is to propose a simplified approach which can be used to model and to analyse the tribological parameters governing the tool–chip interface and sticking–sliding contact. This information is quite necessary for better wear control. In the present paper, a hybrid analytical-FE model is presented. The analytical approach is quite useful to identify the interaction between the thermomechanical phenomena in the primary shear zone and at the tool–chip interface. The model permits also to take into account the relationship between the local friction coefficient, in the sliding zone, and the global friction coefficient which is obtained from the measured cutting forces. A quantitative comparison between model and experimental results, for dry machining of Ti6Al4V titanium alloy, is also provided to analyse the wear process.

2. Literature review

The sliding–sticking zones at the tool–chip interface depend on the evolution of the local conditions of stress, velocity, temperature and the thermomechanical behaviour of the workpiece material. Due to the complexity of interactions at this interface (extreme contact loading, high temperature, high strain rates, chemical wear), only empirical approaches have been previously developed to identify tribological parameters and conditions of contact. In machining operations, Merchant [9], considered that the tool–chip interface (at the tool rake face) was governed by a mean or global friction coefficient $\bar{\mu}$ (Coulomb friction law) which represents the ratio of the mean values of the friction force and normal force.

$$\bar{\mu} = \frac{F_{\mathrm{friction}}}{F_{\mathrm{normal}}} \tag{1}$$

It can be noted that the global friction coefficient $\bar{\mu}$ involves the whole loading on the tool–chip–workpiece contacts: flank contact, edge radius and tool–chip interface. However, the Merchant model's neglects the local aspects of the tool–workpiece contact since the secondary shear zone at the tool–chip interface is not considered. In the Merchant's model the contact at the rake face is assumed to be perfect sliding. In this particular case, the global friction coefficient $\bar{\mu}$ is equal to the local friction coefficient μ_{sl} for a perfectly sharp tool. Also, the effect of the workpiece material behaviour, subject to strain hardening and thermal softening, is not taken into account by the Merchant's model. The Merchant's theory leads to overestimation of the distribution of the main parameters governing the contact at the tool–chip interface, such as, sliding chip velocity and stresses. On the other hand, Oxley's model [10], suggests that the tool–chip contact is full sticking with internal shearing of work material within the chip (secondary shear zone). In addition, in order to estimate the shear stress at the interface, the author calculates the mean temperature $\overline{T}_{\mathrm{int}}$ using empirical coefficients from FEM study of Tay et al. [17], and experimental observations of Boothroyd [18]. Unfortunately, this method suffers some important limitations, including the absence of temperature and shear stress distributions at the interface. This information is quite important for better understanding of wear phenomena.

A recent study proposed by Childs et al. [15], shows that the tool–chip interface is divided into sticking and sliding zones. In this study, the contact and friction stresses were obtained by direct measurement using a split cutting tool technique when machining different steel alloys. Close to the tool tip, high normal stresses are reached and the friction stress becomes independent of normal stress. However, in low stress region at some distance from the cutting edge, the ratio between the friction stress τ_{int} and the normal stress σ_{n} becomes constant $\mu_{\mathrm{sl}} = \tau_{\mathrm{int}}/\sigma_{\mathrm{n}}$. In addition, the authors show that the local friction coefficient μ_{sl} can be greater than global friction coefficient $\bar{\mu}$ and can exceed unity. In this experimental study, the authors underline the fact that the local friction coefficient μ_{sl} increases with the increase of the average temperature at the tool–chip interface and depends on tool–workpiece couple properties.

For the thorough understanding and modelling of the metal cutting operations, accurate representation of contact behaviour at the tool–chip interface is needed. The identification of the local friction coefficient in the sliding part of contact and the relationship between the global friction coefficient and the local one is critical for process modelling.

The friction law given by Childs et al. [15] is a modification of the Shirakashi and Usui law [16], the shear stress at the tool–chip interface being given by the following relationship:

$$\tau_{\mathrm{int}} = mk^{*}\left(1 - \exp\left(\frac{-\mu_{\mathrm{sl}}\sigma_{\mathrm{n}}}{mk^{*}}\right)\right) \tag{2}$$

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