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Analysis of adhered contacts and boundary conditions of the secondary shear zone

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A B S T R A C T

Prediction of the tribological parameters controlling the tool wear is one of the most complex research axes in the metal cutting literature. The nature of the friction on the tool–chip interface is the main process which influences the distribution of stresses and temperatures which in turn activates the thermomechanical process governing tool wear. Under extreme conditions of temperature, strain rates and pressure, occurring especially in high speed machining, the adhered contact phenomenon is highly localized especially near to the tool tip and extremely non-linear due to strong influence of the secondary shear zone (SSZ) and the nature of bonds between asperities of tool and chip. In addition, the analysis based on post-mortem examinations of chips and worn tools, especially in hard metal cutting alloy and high speed machining, show that the adhered friction with intimate contact and no relative motion of the material chip on the interface, are the principal cause of appearance of the plastic deformation layers (SSZ). This localized shear zone plays a role of intensive heat sources interacting with the tool side and, in turn, activates diffusive and abrasive wear. In this work, a hybrid model combining analytical and numerical approaches is performed in order to solve the non-linear thermomechanical problem on the chip and predicts the nature of friction contact, i.e. fully sliding, sticking/sliding or fully sticking contact, and these for a given distribution of asperities, characterizing the ratio between the real and apparent contact areas A_r/A_n on the interface, and a given global friction coefficient $\overline{\mu}$, characterizing the ratio of the experimental cutting forces. The shear stress generated in the primary shear band, the energy produced in the secondary shear zone, the local friction coefficient and the friction energy produced on the sliding part of contact, the proportion of the sticking/sliding interfaces, and geometrical parameters of the chip, are obtained by analytical means. The analysis of this model is based on experimental data and applied for a large cutting speed ($1\ \text{ms}^{-1} \le V \le 60\ \text{ms}^{-1}$) and able to give some correlation about the distribution of adhesions marks on the contact with respect to the distribution of the tribological parameters at the interface. This model can be used in improving tool wear prediction and the estimation of tool-life.

1. Introduction

The study of wear in machining processes is generally related to the tribological conditions in the tool–chip interface. In that way, several studies are focused to determine the link between the distribution of the thermomechanical loading along the contact surface and the dry wear modes such as adhesion, abrasion, oxidation, delamination and more. In many experiments (based on analyses of the stress distribution [1–6], temperature [7–9] and worm tools [10]), analytical and numerical approaches, three contact regimes are usually stated; a perfectly sliding contact [11,12], an alternating sticking and sliding contact [13], and a fully sticking contact [14]. From a wear point of view, the different damage mechanisms are triggered at each contact regime according to the magnitude of sliding velocity, the pressure level and the temperature rise. Moreover, the dominance of a regime with regard to another one, results in the combination of those local tribological parameters governing the contact. In high speed machining or in high strength materials machining domains, sticking regime is dominant with intensive shearing within a secondary shear zone along the tool–chip interface (TCI). Important adhesion of the workpiece material on the tool rake face has been also observed. The interface is characterized by a flow zone with a thickness of the order of 10 μm, the normal loading exceeds the GPa, the shear stress reaches the workpiece material flow stress, the temperature tends to the melting temperature, the strain 300% and the strain rate is greater than $10^3\ \text{s}^{-1}$.

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Nomenclature

Abbreviations

PSZ	primary shear zone
SSZ	secondary shear zone
TCI	tool–chip interface

Material and tool parameters

σ_{eq}	Von Mises equivalent stress (MPa)
ρ	workpiece material density (kg/m^3)

Cutting conditions

L	cutting length (mm)
V	cutting speed (m/s)
f	uncut chip thickness (mm)
t_1	uncut chip thickness (mm)
α	rake face angle (°)
α_{fl}	flank face angle (°)

Chip characteristics

t_2	chip thickness (mm)
δ	proportion of the SSZ thickness
R	proportion of the sticking zone interface
ϕ	primary shear angle (°)
τ_0	shear stress at the entry of the PSZ (MPa)
τ_{PSZ}	shear stress at the exit of the PSZ (MPa)
τ_{st}	shear stress along the sticking zone (MPa)
$\overline{\tau}_{st}$	average of the shear stress along the sticking zone
σ_0	normal stress at the tool edge (MPa)
h	primary shear zone thickness (μm)
V_c	bulk chip velocity (m/s)
V	velocity of particle on chip (m/s)

Coefficients

p	decreasing normal stress coefficient
c	coefficient controlloing the shear strain rate
ξ,ψ,ζ	cofficients of Marinov velocity field

Tool-chip interface parameters

L_c	contact length (mm)
L_s	length of the sticking zone (mm)
L_t	length of the transition zone (mm)
A_r	real contact area (mm^2)
A_n	nominal or apparent contact area (mm^2)
$\overline{\mu}$	average friction coefficient given from the ratio of the cutting forces acting at the TCI
μ_{sl}	the sliding friction coefficient

Thermal parameters

k_W,α_W	conductivity and diffusivity of workpiece, respec (W/m^{-2} K)
k_T,α_T	conductivity and diffusivity of tool
C_p	heat capacity of workpiece material
Q_{SSZ}	heat flux on the SSZ
Q_{sl}	heat flux generated by fricton on the sliding zone
T_0	room temperature (°C)
T_{PSZ}	temperature at the exit of the PSZ (°C)
T_t	absolute temperature of tool (°C)
T	absolute temperature of particle on the chip (°C)
R_{ch}	part of heat transmitted to the chip on the sliding zone
h_1	coefficient of heat convection, upper side of chip (W/m^2 K)
h_{int}	coefficient of conductance at the TCI (W/m^2 K)

Forces

F_p, F_q	cutting and feed forces, respectivly (N)
F_N, F_f	normal and tangent forces on the rake face, respectivly (N)
F_s	shear force on the PSZ (N)
M_{OA}	momentum on tool tip with respect to F_s (N m)
M_{OB}	momentum on tool tip with respect to F_N (N m)

In this work, we propose to discuss the concept of the sticking and sliding contact in light of experimental and modeling approaches in high speed machining of medium carbon steel 42CrMo4. A hybrid model of the TCI is performed based on numerical and analytical approaches. For any set of cutting conditions and the global response of the tool–chip interface, which is given by the average friction coefficient $\overline{\mu}$, the model is able to construct the local distribution of the tribological parameters governing the contact. Contrary to the previous approach, initiated by Bahi et al. [15–17] that dealing with the perfectly sliding and sticking-sliding regimes, the new approach studies the cases where high friction coefficients are involved with fully sticking regime along the TCI. The link with the scale of asperities is established introducing the assumption of heterogeneous contact at the local scale, expressed by the repartition of the real contact surface area with regards to the nominal contact surface. In order to highlight the effect the secondary shear zone on the tribological conditions at the TCI, particular attention will be attributed to the shape and the velocity field within the flow zone and to the spreading of the real contact area A_r with respect to the whole or nominal contact area A_n. The thermo-viscoplastic response of the material is described with a Johnson–Cook law and the heat balance is taking into account the effect of the thermal contact conductance at the TCI.

2. Adhered contacts and wear mechanisms

An understanding of the factors that influence the wear mode mechanism on the TCI is a valuable input for better tool life and modeling perspectives. Where severe conditions of contact are involved, three essential combined processes are taking place such as, mechanical, thermal and wear processes.

The mechanical loading is characterized by high compressive stress at the TCI, especially near to the tool tip, inducing a growth of the real surface area of contact and preventing any motion at the interface, [18,19]. This combination is sufficient to cause a plastic flow in the adjacent layer (SSZ) with the shear velocity gradually increasing until the bulk chip speed is reached, [20].

The mechanical work in deformation zone is converted to heat leading to reduce the shear flow stress on the chip and also to reduce the strength of the tool rake face. However, the analysis of worm tools surfaces becomes a fruitful method to construct the thermo-mechanical loading in the TCI. In recent research, Gerth et al. [21]