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An advanced numerical approach on tool wear simulation for tool and process design in metal cutting

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ABSTRACT

Tool wear is an important criterion in metal cutting affecting part quality, chip formation and the economics of the cutting process. In order to account for tool wear adequately in tool and process design, simulation tools predicting tool wear in metal cutting processes are required. Within this paper, an advanced simulation approach is presented, coupling FE simulations of chip formation with a user-defined subroutine which extends the functionalities of the commercial FE code for wear simulation laying the focus on the development of this method. The continuous process of wearing is discretized in finite steps and the wear rate is modelled to be constant between. Based on the Usui wear rate equation, the local thermo-mechanical load obtained by FE simulation is transformed into local wear rates. The geometric representation of the wear progress is implemented via shifting of the finite element nodes of the engaged tool domain. A novel iterative procedure of updating the tool geometry in order to account for the wear progress is presented.

1. Introduction

1.1. Industrial context

Metal cutting is one of the most important manufacturing processes in industry [1,2]. Up to 15 % of the value of all mechanical components manufactured worldwide is derived from metal cutting operations [2]. During metal cutting, layers of material are mechanically separated from a workpiece forming chips by the means of a cutting tool which has the geometry of a wedge [3].

Metal cutting represents a tribological system consisting of two contacting surfaces with mutual interactions and relative motion [4,5]. The complex physico-chemical processes occurring in the interface, the intermediate materials and the loading of the contacting surfaces determine the resulting wear of the base object of a tribological system, which is defined as the undesired progressive loss of material from the surface of a solid body [4].

Observable wear phenomena of cutting tools are divided into flank face wear and rake face wear [3,6], cf. Fig. 1. At the flank face of the cutting tool, wear is generated in the tool-workpiece interface. A wear land develops below the engaged cutting edge resulting in a loss of relief angle. The most important characteristic parameters are the mean and the maximum flank wear land width VB_B and VB_{max}. In industrial applications threshold values for VB_B and VB_{max} are frequently used as

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Nomenclature

A, B, C, m, n	Material constants of the Johnson–Cook constitutive equation
AE	Acoustic Emission
a_v	Distance between wear node and v inner nodes
C_1, C_2	Constants of the Usui Wear Equation
$C_{1,FF}, C_{2,FF}$	Constants of the Usui Wear Equation calibrated for the flank face
$C_{1,RF}, C_{2,RF}$	Constants of the Usui Wear Equation calibrated for the rake face
KB	Crater width
KM	Crater centre distance
KT	Crater depth
n_{Sec}	Number of sections for flank wear calculation
r	Radius
ru	Chip up curl radius
r_β	Cutting edge radius
$SV\alpha$	Displacement of the cutting edge
T	Local temperature
T_0	Reference value for the temperature
Tm	Melting temperature
t_c	Cutting time
Δt_{wear}	Time step of wear discretization
v_s	Local sliding velocity
VBB	Mean flank wear
VBC	Wear at the rounded cutting edge
VB_{Max}	Maximum flank wear
VBN	Notch Wear
V_t	Status variable at the time t
V_t^*	Smoothened status variable at the time t
V_0^*	Initial value for the exponential smoothening
$\frac{dW}{dt}$	Tool wear rate (volumetric wear loss per area contact per time)
w_n	Nodal wear rate
$w_{in,v}$	Displacement of inner nodes v
w_{Sec}	Sectional wear rate
α	Smoothening coefficient for the exponential smoothening
α_o	Tool orthogonal clearance angle
γ_o	Tool orthogonal rake angle
ε	Equivalent plastic strain
$\dot{\varepsilon}$	Equivalent strain rate
$\dot{\varepsilon}_0$	Reference value for the strain rate
σ_N	Normal pressure acting on the cutting tool
σ_{yield}	Flow Stress

tool life criteria [6]. At the rake face of the cutting tool a crater develops as a result of the tribo-mechanical load impressed by the chip. The loading conditions at tool-chip interface are more severe in terms of higher temperatures and pressures [1,5].

The cutting tool wear results in a change of the tool geometry. This change in geometry in turn affects the entire chip formation process and affects the cutting process results, such as the cutting force components, temperature distributions, achievable accuracy, residual stress and chip breakage. Furthermore, the tool wear is of crucial importance for the economics of the cutting process. A trade-off between productivity and tool wear has to be made when selecting the process parameters. In addition, the tool costs depend directly on tool wear. Thus, tool wear is of major importance for metal cutting processes and therefore during process and tool design.

Due to the high significance of tool wear, predictive capabilities are of great value for tool and process design. The widely used Taylor tool life equation describes an empirical correlation between tool life and applied cutting speed but it does not provide information on the spatial resolution and the development of wear in the tribological process of metal cutting. Furthermore its validity is restricted due to it's empirical nature [6]. Online wear monitoring strategies have been developed measuring indirect data which allow to draw conclusions on the wear state on empirical basis [7]. AE has been used to detect tool breakage [8–10] and can furthermore be correlated to the wear state of cutting tools. While for crater wear, the AE of the tool is mostly relevant, for flank wear the AE of the workpiece is analyzed [11]. The spindle current and cutting forces have been successfully correlated to the wear state of a cutting tool [12,7]. The combination of different types