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A new abrasive wear law for the sticking and sliding contacts when machining metallic alloys

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ABSTRACT

Abrasive wear was usually identified as the main wear mode occurring at the tool–chip and the tool–workpiece interfaces during machining operations such as turning, milling, and drilling. From an experimental point of view, the mechanisms governing the abrasion process are still not fully understood. This is due on one hand to the contact confinement between tool and workpiece and on the other hand to the high thermomechanical loading applied to the cutting tool during a machining process. Abrasion is often assumed to be closely linked to the microstructure of materials and caused by hard particles trapped at the tool–workpiece interface. The objective of this research work is to develop a predictive wear modeling taking into account the sliding and sticking nature of the contact. The proposed model is based on an analytical approach including a statistical description of the distribution of particles. The latter are assumed with a conical shape and embedded in the contact area. The volume of the removed material per unit time is chosen in this study as the main parameter to describe the abrasive wear mode. The sliding and sticking zones at the tool–chip and tool–workpiece interfaces depend on the evolution of the local conditions of stress, the sliding velocity and the friction coefficient. A new abrasive wear law is then proposed to estimate the tool life which is often considered in industrial applications. Finally, a parametric study was performed to highlight the influence of cutting conditions and the contact nature on the productivity rate for a given tool-material combination.

1. Introduction

The surface quality of the machined part strongly depends on the tool wear process. In metal cutting, the nature of this wear is not clearly understood in spite of numerous investigations. It is well known from the literature that the tool wear is governed by complicated thermal, mechanical and physicochemical phenomena. Trent and Wright [1] have specifically identified three main mechanisms of wear: adhesion, abrasion, and diffusion; and reported that the dominant mechanism will depend on the tool–workpiece combination. Several examples supported by experimental works show that individual or combination of different mechanisms of wear can predominate for various conditions. As a consequence, it appears that the different modes of wear will depend on several parameters which make understanding the mechanisms governing them still incomplete. In addition, the study of these mechanisms is difficult to conduct because of the high thermomechanical loading on the tool–workpiece interface and the complex wear mechanisms involved during machining operations. Several authors have then attempted to directly correlate the tool life to machining parameters. The well-known Taylor's tool life equation and its extended form reminded in Table 1 [2,3] give the relationship between tool life and cutting parameters as the speed and the feed rate. These equations involve several constants that need to be experimentally determined for a given combination of tool and workpiece materials. Another aspect of tool wearwhich essential for optimization is the tool wear rate. Tool wear models describe the volume loss on the tool contact faces (rake and flank faces) per unit of time. Derivations of this type of wear rate models require the knowledge of wear mechanisms associated with the tool and workpiece materials and the range of cutting conditions where models could be employed. Due to the complexity and concomitant nature of the mechanisms governing wear, tool wear models are empirical and depict different mechanisms at the same time (abrasion, diffusion, and adhesion). Table 1 summarizes several models giving the tool life and tool wear rate.

Takeyama and Murata [4] developed one of the first fundamental wear rate equations by considering abrasion and diffusion wear as the main wear modes. Nevertheless, Mathew [5] who

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Nomenclature

F_i^R	family of active particles of size R_i
$F_{n/rake}$	normal force exerted by the chip on the rake face of the cutting tool
H_c	hardness of the chip material
H_t	hardness of the tool material
Kt_{lim}	maximum crater depth
$i_{min}(s)$	minimum index (used in the discretization scheme)
I	odd number (used in the discretization scheme)
$Int(i) = [R_{1i}, R_{2i}]$	interval of potentially abrasive particles (used in the discretization scheme)
L_c	total contact length
L_s	length of the sticking zone
L'_s	length of the (sticking + +half the transition) zone
L_t	length of the transition zone
N	total number of particle
N_{ij}	number of active particles, with size$R_i$and apex angleφ_j(used in the discretization scheme
$N_{act}(s)$	number of active particle at a position s
$P(s)$	contact pressure at a given position s
P_a	number of parts removed by one tool before its breakage
P_0	pressure at the tool tip identified by the position $s = 0$
$Pr^R(R_i)$	probability to find a particle with a size R_i (used in the discretization scheme)
$Pr^\varphi(\varphi_j)$	probability to find a particle with an apex angle φ_j (used in the discretization scheme)
$Pr(R_i, \varphi_j)$	probability to find a particle with a size$R_i$and an apex angleφ_j(used in the discretization scheme)
PSZ	Primary Shear Zone
R	size of the particle
$\overline{R}$	mean value of the particle size distribution
$\tilde{R}$	mode of the particle size distribution
R_{low}	location parameter related to the size
$R_{min}(s)$	smallest active particle at a position s
$[R_{inf}, R_{sup}]$	range of potentially active particles
s	position along the rake face
s^*	dimensionless position along the rake face
SSZ	Secondary Shear zone
t_1	undeformed chip thickness (feed)
t_2	chip thickness
T	tool life
$v_{loc}(s)$	local linear wear per unit time at a given position s
$v_{1p}(s, R, \varphi)$	volume removed by one particle
$v_p(s)$	volume loss per unit time at a given position s
v_{tot}	total volume loss per unit time along the tool rake
V	cutting speed
$\overline{V}_c$	mean chip velocity
$V_c(s)$	sliding velocity at a given position s
$V_c^*(s^*)$	dimensionless sliding velocity at a given position s^*
VKt_{lim}	maximum cumulated wear volume
w	width of cut
$W^R(R)$	Weibull function in its R-form
β_R	shape parameter related to the size
β_φ	shape parameter related to the shape
γ	rake angle
δV^*	small amount of V^*
η_R	scale parameter related to the size
η_φ	scale parameter related to the shape
κ	parameter controlling the rate of the velocity increase
κ^*	parameter controlling the rate of the velocity increase
μ	coefficient of friction at the sliding zone
ξ	parameter controlling the decay of the contact pressure
σ_W^R	standard deviation of the particle size distribution
φ	apex angle of the particle
φ_{low}	location parameter related to the shape
ϕ	the shear angle
$\Gamma(.)$	Gamma function
Ω_0	volume to be removed from a single blank part

analyzed the tool wear of carbide tools when machining carbon steels, shows that at cutting temperatures higher than 800 °C, the first abrasive term G(V, f) shown in Table 1 can be neglected and only diffusion mode predominate. Usui and Shirakashi [6] derived a wear rate model based on the equation of adhesive wear (and indirectly abrasive wear) which involves temperature, normal stress, and sliding velocity at the contact surface. Molinari and Nouari [7,8] developed two diffusion wear models for high speed machining when the tool–chip temperature attains large values. As a consequence of this high thermal loading, diffusion is considered in their works as the dominant damage mechanism for tools at high cutting speeds.

The current work is focused on the abrasive wear occurring on the rake and flank faces of the cutting tool during a machining process. Compared with other wear mechanisms, abrasive wear contributes to the total tool wear from 10% to 25% [9,10].

Abrasion is a mechanical phenomenon leading to the chipping of the tool surface and forms wear debris (micro-chipping). It has been shown that abrasive wear is caused by hard particles (much harder than the cutting tool material) trapped in the tool–workpiece contact. These particles can be either non-metallic inclusions [9,11] initially present in the machined workpiece or wear debris caused by other wear modes such as adhesion or diffusion [12].

Besides, the widely used models such as the model of Usui and Shirakashi [6]and the model of Takeyama and Murata [4] are employed in the literature to study the influence of abrasive wear on the total tool wear. Kramer and Turkovich [13] developed a quantitative model in which the abrasive wear model of Rabinowicz [14] has been integrated with the chemical dissolution wear model of Kramer and Suh [15]. This model was based on an algorithm that predicts wear rates of hard coatings in the case of high speed steels and cemented tungsten carbides. The authors confirmed that mechanical wear processes such as abrasion dominate at low cutting temperatures and cutting speeds.

Albeit the fact that all cited models are empirical, they involve, as for the tool life equation, a number of constants that need to be experimentally determined for a given combination of tool and workpiece materials. In addition, all these models do not take into account the mechanical and physico-chemical interactions at the tool–workpiece interfaces during the machining process. Gekonde and Subramanian [16] have shown that the tool wear process and particularly the abrasive process is strongly controlled by local parameters (shear stress, friction coefficient, pressure, sliding friction coefficient, etc.) that govern the tool–workpiece interfaces. For these reasons, the tool–chip interface requires a local characterization of the whole parameters governing the conditions of contact. This information is quite important for the development and the prediction of abrasive tool wear during the machining process.

In the cutting process, the chip is generated by the intense shearing of the workpiece material in the primary shear zone where the material flows from one direction (cutting direction) to