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Prediction of sticking and sliding lengths on the rake faces of tools using cutting forces

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ABSTRACT

The algebraic relationships between friction force F and normal force N on the rake face of a tool, and between average stress distributions q_F and q_N, are derived for an assumed power law stress distribution of the normal contact pressure p between chip and rake face, i.e. for $p=p_o(x/L)^n$, as used by Zorev, where x is measured towards the tip of the tool from an origin at the end of the contact region of length L, and p_o is the maximum pressure at the cutting edge. The derived expressions suggest a novel method of determining quantitatively the lengths s of stuck regions on the rake face, and unstuck lengths $(L–s)$, just from the cutting forces without the use of special devices such as split tooling. Calculations for the variations of (s/L) and $\mu_{\text{apparent}}=q_F/q_N$ with uncut chip thickness t automatically give the variation in values of p_o and n. The theory is tested using experimental cutting force data in the literature from a wide range of materials in different thermomechanical states and the predictions are compared with independent data. It is demonstrated that the usually-illustrated version of the Zorev pressure distribution where the contact pressure rises 'exponentially' to the cutting edge (i.e. where $n>1$) applies only when (s/L) is less than about 0.5. When the sticking length s is a larger proportion of L, $n<1$ giving the experimentally-known different type of pressure distribution that levels out towards the cutting edge.

Theory and experiments show that q_F plots non-linearly against q_N for all combinations of uncut chip thickness t and rake face contact length L. The plot emanates from the origin with an initial slope of μ_{Coulomb}. As soon as the sticking length s begins to increase, the slope diminishes and when $(s/L)=1$ at complete sticking, the local slope of the q_F vs q_N is zero. Increasing (s/L) corresponds to a reduction in (L/t) that may be achieved using restricted contact tools, but even in full-face cutting where $L=L_{ff}$ there is some sticking near the cutting edge at the largest (L_{ff}/t).

Plots of friction force F vs normal force N along the rake face are also predicted to be non-linear and emanate from the origin with slope μ_{Coulomb}. While some experimental results display this shape, most F vs N experimental data for full-face cutting follow linear "$F=F_o+\varpi N$" relations (having high correlation coefficients). It is shown that such linear plots with intercepts are tangents to the more general non-linear relations, and are caused by the relatively small range of q_F and q_N encountered in full-face cutting which is caused by the interplay between rates of increase of cutting forces as t increases, and rates of change of L_{ff}/t with increasing t. How (s/L), p_o and n may be determined from such plots without knowledge of μ_{Coulomb} is explained and calculations from experiments are made.

The loads expected to be measured by split tools having a Zorev contact pressure distribution are also predicted and compare favourably with experiment.

1. Introduction

Fig. 1(a) shows the geometry of orthogonal cutting with a 'full-face' tool and the associated forces; Fig. 1(b) is that for cutting with a restricted contact (controlled contact or cut-away) tool. Full-face conditions are those where the rake face of the tool is long enough to accommodate the natural contact length L_{ff} between chip and tool. By natural contact length we mean the length over which a chip flows and curls away from the rake face without any interference. With restricted contact tools ([9,27]), the contact length L is reduced below L_{ff} either by grinding back the top part of the rake face or by having a greater rake angle except for a region at the cutting edge (double rake angle tools). For a given uncut chip thickness, restricted contact tools require smaller cutting forces than full-face tools. The critical L_{ff} at the transition to full-face

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List of symbols

F	force along rake face
F_C	cutting force parallel to machined surface
F_o	intercept on F-axis for those data that plot according to $F=F_o+\mu N$
F_T	cutting force perpendicular to machined surface
k	yield strength in shear
L	contact length between chip and tool ($=L_{ff}$ in full-face cutting)
L_{ff}	contact length between chip and tool for full-face conditions
m	factor in mk giving proportion of shear yield stress
N	normal force on rake face
n	index in Zorev relation $p=p_o(x/L)^n$
p	pressure on rake face
p_o	maximum pressure on rake face (at tool cutting edge)
q_F	average friction stress on rake face ($=F/Lw$)
q_N	average normal stress on rake face ($=N/Lw$)
s	length of sticking region along the rake face measured from the cutting edge
t	uncut chip thickness in orthogonal cutting
t_{chip}	thickness of chip
w	width of cut
x	co-ordinate along rake face for pressure distribution p(x)
α	rake face angle
$\beta_{apparent}$	angle of apparent friction ($\tan\beta=\mu_{apparent}$)
τ	tangential stress on rake face
ϖ	slope for those data that plot according to $F=F_o+\varpi N$
$\mu_{Coulomb}$	coefficient of sliding friction
$\mu_{apparent}$	apparent coefficient of friction defined by $(F/N)=q_F/q_N$
ϕ	angle of inclination of primary shear plane
γ	shear strain along primary shear plane

conditions is indicated in experiments using restricted-contact tools when, at a given uncut chip thickness t, experimental cutting forces at greater and greater L level out, e.g. Usui et al. [49]; Rubenstein [42]. Critical values of (L_{ff}/t) depend upon the material, rake angle, depth of cut and lubrication; in particular (L_{ff}/t) depends on t and is smaller at greater t. L_{ff} is a difficult quantity to determine experimentally, and there is a variety of empirical expressions for L_{ff} listed by Iqbal et al. [22]. Modern tool inserts having grooves to act as chip breakers perform essentially as restricted contact tools, Jawahir [23]; Sadik and Lindström [43]. Restricted contact tools have also been employed in oblique cutting, Mittal [32], but are not considered further in this paper.

The friction force F parallel to the rake face of a cutting tool in orthogonal machining, and the normal force N, are customarily determined from resolution of dynamometer data for the cutting force F_C in the direction of cutting and the thrust force F_T perpendicular to the cut surface, for a given uncut chip thickness t. With positive F_T down into the cut surface, resolution gives

$$N=F_C\cos\alpha-F_T\sin\alpha \tag{1a}$$

$$F=F_C\sin\alpha+F_T\cos\alpha \tag{1b}$$

where α is the rake angle of the tool. N and F correspond, of course, to the normal pressure distribution p integrated over the contact length L between chip and rake face, and to the shear stress distribution τ integrated over the contact length. Since L is known *a priori* for restricted contact tools, friction data are often presented in terms of the average frictional stress on the rake face $q_F=(F/wL)$ and average normal stress $q_N=(N/wL)$ rather than F and N.

Were Amontons/Coulomb friction with constant $\mu_{Coulomb}$ to apply in cutting, F vs N and q_F vs q_N would be linear through the origin with slope $\mu_{Coulomb}$ for all combinations of t and α. While Coulomb friction is appropriate in lightly-loaded cutting of soft solids using thin blades, Atkins [3], metal cutting experiments using full-face and restricted-contact 'chunky' tooling show that a coefficient of apparent friction defined by $\mu_{apparent}=(F/N)=q_F/q_N$ systematically decreases at deeper uncut chip thickness as the cutting forces increase, and also depends on cutting speed, lubrication and tool rake angle, where larger $\mu_{apparent}$ are obtained with larger α. The reason for the variation in $\mu_{apparent}$ is well known: there are mixed sticking and sliding regions along the rake face, the relative proportions of each varying with cutting conditions. In practical full-face cutting of ductile solids, a sticking region usually exists near the tool tip, and this region lengthens as the rake face contact length is reduced below L_{ff} when restricted contact tools are employed.

Appendix A summarises experimental work to determine tool contact stresses and stuck/sliding regions under full-face conditions. Most data from instrumented tools show that the shear stress τ on the rake face attains a limiting value of the shear yield stress k over the region near the tool tip, where sticking/adhesive friction prevails with transfer of workpiece metal on to the rake face. However Bagchi and Wright [4] found that τ peaked in the centre of the contact length and Doyle et al. [18] found three regions controlling the frictional behaviour from experiments with ingenious transparent tools that enabled chip motion over the rake face to be viewed directly. Over the sliding regions, the friction stress is given by $\tau=\mu_{Coulomb}\,p(x)$ where $p(x)$ is the variation of contact pressure over the rake face. Many results show $p(x)$ rising to a maximum value at the cutting edge, and it was from one such experiment by Kattwinkel [25] in which a single full-face cut, $t=0.5$ mm deep, was taken on lead with a PMMA photoelastic tool having a rake angle of $+10°$, that Zorev [54] proposed a power law to represent approximately the pressure p on the rake face over contact length L, namely

$$p=p_o(x/L)^n \tag{2}$$

where x is measured towards the tip of the tool from an origin at the end of the contact region, and p_o is the maximum pressure at the cutting edge for a given t and α. Fig. 2a shows this familiar distribution in which $n>1$. In a 1963 experiment cutting 20 Kh steel in air with a 5° rake angle tool and with $t=0.15$ mm, Zorev found metal transfer over a length s of about 0.53 mm when the contact length was 1.26 mm, thus giving $s/L\approx 0.4$; it was also determined that 3–n–4.

In contrast, a number of results show p levelling out towards the tool tip instead of rising to large values near the cutting edge, for example with aluminium and copper [14]. In these cases, the limiting value of the shear yield stress k occupies a much greater proportion of L_{ff}, i.e. the relative length (s/L) of the stuck region is bigger. Stephenson and Agapiou [46] discuss a two-part normal stress distribution to describe pressure distributions that level out near the cutting edge. However, such pressure distributions are predicted by Eq. (2) when $n<1$, as illustrated in Fig. 2(b). The probability that $n<1$ when (s/L) is large follows from consideration of the transition from sticking to sliding defined by $\mu_{Coulomb}p=k$. With the concave-up shape of Fig. 2 (a), together with the assumption that $\mu_{Coulomb}$ is constant for all (s/L), both p_o and n would have to increase to very large values when (s/L) approaches unity if $\mu_{Coulomb}p=k$ was always obeyed at the transition. In contrast, were the normal stress distribution concave down with $n<1$, Fig. 2(b), the steep rise of p at small values of x permits