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Revisiting the fundamentals of metal cutting by means of finite elements and ductile fracture mechanics

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Abstract

This paper investigates Atkins' idea that the modelling of metal cutting must include the significant work involved in the formation of new surfaces as well as the traditional components of plastic flow and friction. New finite element and algebraic calculations are presented together with specially designed orthogonal metal cutting experiments performed on lead specimens under laboratory-controlled conditions. Independent determinations of the mechanical properties of lead were made and comparisons are given between theoretical predictions and experimental results. Calculations cover a wide range of topics such as material flow, chip-compression factor, primary shear plane angle, cutting force and specific cutting pressure. It is shown that the choice of lead as workpiece material reveals important facts that would be obscured were the usual sort of workpiece metals to be cut.

The paper demonstrates quantitatively that while material flow, chip formation and the distribution of the major field variables can be modelled successfully by traditional 'plasticity and friction only' analyses, the contribution of ductile fracture mechanics is essential for obtaining good estimates of cutting forces and of the specific cutting pressure.

Keywords: Metal cutting; Experimentation; Finite element method; Ductile fracture; Toughness

1. Introduction

There are two different views of metal cutting fundamentals and how chips are formed [1]. The commonly accepted view considers (i) that new surfaces are formed simply by 'plastic flow around the tool tip'; (ii) that the energy required for cutting is overwhelmingly due to plasticity and friction; and (iii) that any energy required for the formation of new surfaces is negligible [2]. This approach (which hereafter we refer to as the 'plasticity and friction only' (PFO) line of attack) is inherent in the early theoretical analyses of metal cutting and is implicit in most of the major contributions to the understanding of the process made by Shaw [2], Zorev [3], Oxley [4] and many others.

The non-traditional, and controversial, view of metal cutting states that the energy to form new surfaces at the tip of the tool is not negligible and ought to be at kJ/m^2 levels, rather than at the few J/m^2 level of the chemical surface free energy that was employed in the calculations [2] which purported to show that surface work should be negligible. The reason why the specific work of surface formation should be at kJ/m^2 levels is because metal cutting is, in fact, a branch of ductile fracture mechanics [1,5] rather than a branch of just plastic flow. However, because cracks are not seen at the tips of tools in continuous-chip machining, there is reluctance to accept this point of view, even though Cook et al. [6] demonstrated that plasticity models of cutting cannot operate in plane strain at constant plastic volume without the formation, at the tip of the tool, of a gap having the thickness of the shear band which 'frees' material to permit chip formation. Otherwise, the plastic volume of the primary shear band *increases* during deformation which is inadmissible [5]. What happens in steady-state cutting of ductile solids is that the gaps at the tool tip (short cracks incrementally separating chip from cut surface) have the

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Nomenclature

C_L	crack length
C_0	critical distance utilized by the chip separation criterion
F_c	cutting force
L	side length of a mesh element
Q, Q^*	correction factors
R	fracture toughness
t_0	uncut chip thickness
v_c	cutting velocity
w	width of the specimens
α	rake angle
β	friction angle
$\bar{\varepsilon}$	effective strain
ϕ	angle of the shear plane
γ	shear strain
σ_c	clearance angle
$\bar{\sigma}$	effective stress

same velocity as the tool, so are 'not seen'. Whether visible cracks do appear at the tool tip is a question of crack *stability* rather than crack *formation* and, of course, in less ductile solids (or at very deep depths of cut in ductile metals [7]) cracks can be observed ahead of the tool.

By equating the external work rate to the sum of the internal work rates in cutting (i.e. plasticity, friction, and surface formation), Atkins [5] showed that the force F_c exerted in the direction of cutting is

$$F_c = \left(\frac{\tau_y \gamma w}{Q}\right) t_0 + \frac{Rw}{Q}, \tag{1}$$

where τ_y is the rigid-plastic shear yield stress (it is possible to include work hardening, [7]), γ is the shear strain along the shear plane inclined by an angle ϕ, t_0 is the uncut chip thickness, w is the width of the orthogonal cut, β is the friction angle, α is the tool rake angle, R is the fracture toughness and Q is a friction correction factor given by

$$Q = \left[1 - \left(\sin\beta \sin\phi / \cos(\beta - \alpha)\cos(\phi - \alpha)\right)\right]. \tag{2}$$

Friction depends on the force normal to the tool rake face, which in turn depends on F_c by force equilibrium; the Q factor is formed when the two force terms are collected together (see also Williams [8]). Eq. (1) without the second term on the right-hand side is the basic PFO Ernst–Merchant model. Minimization of the complete Eq. (1) predicts the orientation of the primary shear plane angle ϕ in terms of the friction angle β and the toughness/strength R/τ_y ratio of the material, made into a non-dimensional parameter $Z = (R/\tau_y t_0)$ by inclusion of the uncut chip thickness [5]. This should be contrasted with the result of minimizing the Ernst–Merchant expression, which gives the well-known expression

$$\phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha), \tag{3}$$

which is independent of workpiece material and which does accord with experimental experience. The same alloy in different thermomechanical states has different R/τ_y ratios, and this is why traditional PFO analyses based only on strength or hardness do not always agree with experience.

Calculations show that when $Z < 0.1$ (i.e. $t_0 > 10(R/\tau_y)$), γ is virtually constant for all α and β. Hence, in Eq. (1), $\tau_y \gamma$ is then also constant, and a straight line relationship between F_c and t_0 is predicted, having slope $\tau_y \gamma / Q$. It does *not* pass through the origin, however (as the Ernst–Merchant theory would predict) and the positive force intercept is a measure of toughness, that is Rw/Q. Intercepts are known experimentally, but are usually explained away in terms of rubbing on the clearance face of the tool, or tool bluntness, but they do not disappear even for experiments with the sharpest tools. When $t_0 < 10(R/\tau_y)$, it may be shown [5] that ϕ decreases, γ increases, Q increases and the F_c vs. t_0 relation curves down towards the origin but *still does not* pass through it, having an intercept equal to Rw since $Q = 1$ at zero depth of cut. At these smaller depths of cut, it is also known that the specific cutting pressure (unit power) given by F_c / wt_0 increases markedly. PFO analyses have no explanation, but dividing Eq. (1) throughout by wt_0 shows that an inverse-to relationship is expected.

Chip plasticity in the above algebraic model was, for simplicity, represented by the simplest upper bound model comprising a single shear plane from the tip of the tool to the free surface. As discussed by Astakov [9], it is well known that the single shear plane does not represent practical flow fields which have primary and secondary shear deformations that are observed experimentally, nor the flow fields predicted by work-hardening slip line field models, nor again the flow fields of finite element (FEM) computer simulations of cutting. Even so, despite this simplified treatment of the chip flow field, it is significant that Atkins' model made sense of many features of machining for which PFO analyses—however complicated the chip plastic flow field—had no explanation. It is arguable, therefore, that it is not the sophistication of the flow fields that has been lacking in models of cutting, nor questions of uniqueness in plasticity theory [10], but rather that the physically important work of surface formation has been missing from previous analyses. It follows that incorporation of significant surface work in more realistic chip flow fields (as simulated by FEM analysis for example) ought to model metal cutting even more closely, and that is one purpose of the present paper.

Analytical and numerical modelling based on the PFO approach is not always successful at estimating the cutting forces for practical metal cutting. In a recent study Tekkaya and co-authors [11] performed a comprehensive assessment of the estimates provided by three different