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Zones of material separation in simulations of cutting

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ABSTRACT

FEM simulations of orthogonal cutting are reported in which both the Johnson–Cook (JC) constitutive relation and the Johnson–Cook separation (fracture or damage) criterion are used. Results demonstrate that the damaged regions, in which separation of material occurs at the tool tip, form thin boundary layers on the top of the machined surface and on the underside of the chip. Damage was calculated in terms of the parameters of the Johnson–Cook fracture criterion appropriate for A2024-T351 aluminium alloy. The size of the damaged layers is some 35 μm and appears to be independent of the uncut chip thickness t_0 over the range investigated ($50 < t_0 < 500$ μm). In most cases, the highly-damaged boundary layers make up only a very small proportion of the uncut chip thickness, so the deformation fields by which chips are formed are essentially the same as if the damage zone were absent. The result explains the success of variables-separable algebraic models of cutting with continuous chips in which the component works of chip plasticity, friction and separation are uncoupled.

The FEM simulations predict quasi-linear relations between cutting force and uncut chip thickness, with an intercept on the force axis. This is exactly what is found experimentally and is predicted by algebraic models of continuous chip cutting under the assumption of sharp tool tip, where the slope of the plot relates to the yield stress of the workpiece and the intercept to its fracture toughness. The fracture toughness and the parameters of the JC damage relation, along with the size of the boundary layers of damage, are shown to be related.

1. Introduction

1.1. Algebraic and Slip line field analyses

Experiments show that most plastic deformation in plane strain orthogonal cutting of ductile solids is concentrated in a narrow band of shear (the so-called primary shear plane) inclined at an angle ϕ to the cut surface, the simplest representation for which is Piispannen's 'deck of cards' model, Fig. 1 [1]. In the Ernst-Merchant algebraic analysis of orthogonal cutting of ductile solids, cutting forces are determined from the plastic flow along the primary shear plane of Fig. 1 by which the chip is formed, and from secondary plastic flow and friction along the rake face of the tool, see e.g. Shaw [2]. Cook et al. [3] showed that for the kinematics of the 'deck of cards' model to operate, a gap XY having the width of the shear plane has to form at the tool tip simultaneously with slip along the shear plane. The reason is because plastic flow occurs under constant volume, and without the gap, ZWV is an inadmissible increase in plastic volume under the plane strain conditions of orthogonal cutting.

Shaw and co-workers [2] understood that the formation of new surface XY required work and that this work ought to be incorporated in analyses of cutting forces. To estimate the magnitude of the work of separation they employed the surface free energy γ of the new surface, which for all materials has an order of magnitude value of a few J/m^2. They concluded that the incremental work of formation of new surfaces in cutting (i.e. the incremental work of separation of material at the tool tip) was negligible in comparison with the component incremental works of plastic flow and friction during cutting. That became the received wisdom, so that developments of algebraic and slip line field analyses of machining in the second half of the 20th century concentrated on the effects of workhardening in flow fields more complicated than the simple deck of cards model, strain rates and temperature on primary and secondary plastic flow and friction, to link theory and experiment. Even with such refinements, many observations in machining cannot be explained by traditional

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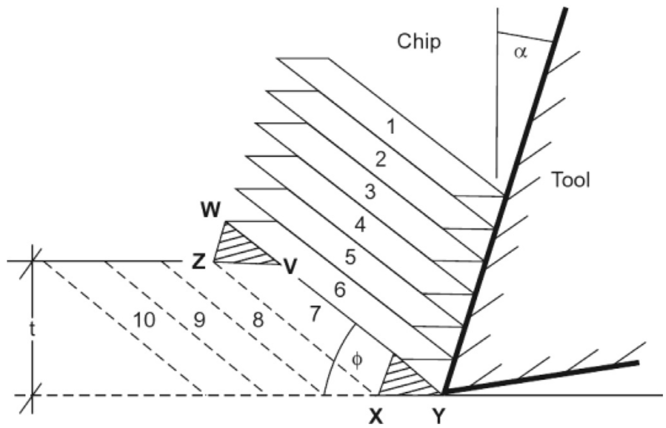

Fig. 1. Piispanen's 'deck of cards' model. If slip occurs in plane strain in a finite width band along the primary shear plane, plastic volume cannot be conserved unless a gap occurs in the region of XY. Otherwise ZWV is an increase in plastic volume [1] (adapted from Cook et al. [3]).

analyses [1].

Atkins [4] argued that the surface free energy γ was not the correct parameter by which to estimate the work of surface formation in cutting: γ is a short-range parameter concerning the unmatched chemical bonds exposed on free surfaces with the rest of the body unaffected, but surfaces in cutting are not formed that way. Instead, there are highly-deformed boundary layers contiguous with all practically-cut surfaces, and the associated work of formation per unit area within the boundary layers must be included in the total work of surface formation. The same question had arisen in the development of the subject of fracture mechanics where, because of this additional work of sub-surface deformation, Orowan and Irwin had to use 1000γ in place of γ in the Griffith formula to make sense of experimental results [5]. Even in cleavage, where sub-surface deformation is limited, γ is not used directly to predict forces from fracture mechanics formulae [6]. The '1000γ' property of materials is called the fracture toughness and is given the symbol R in this paper (G_c and J_c are also used). R represents the irreversible work done as the microstructure within the boundary layers is damaged up to failure, leading to separation at the tip of the cutting tool which, in turn, permits the tool to move forward. R may be viewed as some measure of workpiece ductility.

When R (in place of γ) is employed in modelling the mechanics of continuous chip formation [4], the controlling parameter is not just strength (equivalent to hardness) as in traditional analyses, but rather the toughness-to-strength ratio (R/k), where k is the shear yield strength. It seems reasonable that cutting mechanics should involve a measure of ductility as well as strength, since the cutting behaviour of materials having the same R but different k, and vice-versa, can be quite different. It is known [7] that the hardest material is not always the most difficult to cut. In fact, cutting is not a problem just of plasticity, but is a branch of elastoplastic fracture mechanics. The formation of continuous or discontinuous chips, with steady or fluctuating cutting forces, simply reflects 'cube-square' energy scaling inherent in the mechanics of fracture. The type of chip formed depends upon the depth of cut relative to the length scale given by (R/k). When the non-dimensional number $Z=(R/kt)$ is large, ductile cutting ensues with continuous chips; when Z is small, brittle chipping takes place [1]. At intermediate values, serrated or discontinuous chips are formed.

The new analysis explains why ϕ is different for different materials – it depends on workpiece (R/k) – and why quasi-linear plots of cutting force vs depth of cut (uncut chip thickness) do not pass through the origin, but have a positive intercept on the force ordinate. Such plots are well-known in the literature, but the intercepts are often explained away in terms of so-called ploughing (blunt tools), wear on the flank (clearance) face of the tool, rubbing on the clearance face etc. While all those factors will play a part in increasing tool forces, experiments show that when efforts are made to eliminate all these effects, an intercept remains, the magnitude of which depends on the fracture toughness of the workpiece material. The slopes of the plots are determined by the yield stress of the workpiece [1].

Favourable comparison of theory and experiment for a wide range of engineering and biological materials is summarised in Ref. [1]. Nevertheless there is an assumption in Atkins' analysis that the individual component works of plasticity, friction and separation are uncoupled. This implies that the separation work is confined to very thin boundary layers and one aim of the present paper is to investigate the size and extent of these highly-damaged zones in comparison with the rest of the plastic flow fields.

1.2. FEM modelling

As soon as plastic flow problems like forging had begun to be successfully simulated by FEM codes, the same programmes were applied to the simulation of cutting. But a difficulty arose. It was found that the cutting tool would only travel an appreciable distance when a 'separation criterion' was employed at the tool tip to release nodes, yet no separation criterion was required when the same programmes were used for plastic forming operations. It is clear that attempts to model cutting without inclusion of a separation criterion were simulating the different problem of an indentation by an inclined wedge (the tool) into the end of the workpiece, in which the material at the cutting edge is stretched around the line of the wedge but is not separated. What was being simulated was a type of hardness test. In the FEM simulations reported in subsequent sections of this paper, the 'indentation' problem, rather than the 'cutting' problem, was replicated when the criterion for separation at the cutting edge was switched off.

In finding that the cutting tool would not move appreciably, FEM modellers had rediscovered what Cook et al. [3] had said in 1954, and what Astakhov said in 1999 [8] namely that the difference between cutting and other types of plastic flow problem is that in cutting there is physical separation of the piece being removed. In ordinary plastic flow all material elements retain the same neighbours before and after deformation irrespective of the severity of the deformation. In cutting, elements just above and just below the putative cut line that were neighbours before being separated, are far removed from one another after cutting: those below the cut line remain on the machined surface, those above go away on the underside of the chip. If controlled just by plasticity they would be still attached.

Separation criteria employed in FEM simulations of cutting have taken many forms [9]: some were entirely empirical and were more by way of 'computational fixes' to overcome the singularity at the tool tip; others represented physical microstructural events that might be taking place at the tool tip to permit separation of nodes, such as the attainment of a critical effective von Mises strain or critical plastic work per volume in elements along the direction of cut. A more recent review article about separation criteria by Vaz et al. can be found from Ref. [10]. The separation criteria can be categorized based on (1) nodal distance [11–21], (2) strain energy density [22–28], (3) critical stress [20,29–33], and (4) equivalent plastic strain to fracture [17,19,32–40]. Irrespective of the actual separation criterion employed, no published FEM simulations seem to have evaluated the local work involved in separation of nodes to check whether it was negligible as averred by Shaw and co-workers. Again, the number of elements attaining the separation criterion has not been reported, nor their distribution 'above' and 'below' the cut surface to see how confined is