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On the stability of plastic flow in cutting of metals

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ABSTRACT

We examine large-strain deformation and unsteady flow modes in cutting using high-speed imaging. For metals which exhibit large workability and strain hardening, the commonly assumed laminar flow is inherently unstable. Instead, the cutting is characterized by sinuous flow, with large-amplitude folding, that is triggered by a plastic buckling instability linked to the material microstructure. A microstructure basis is also suggested for shear band flow in high-speed cutting, with the band region showing a fluid-like characteristic with very small viscosity. Mechanochemical Rehbinder effects, long reported in cutting of metals, are found to be closely linked to the unsteady flow modes.

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1. Introduction

Chip formation in cutting of ductile metals occurs by large strain deformation, with effective strains of 1–10. In plane-strain (2-D) cutting, this deformation has long been described using a shear plane/zone model [1–3]. The underlying material flow is assumed, to borrow a fluid mechanical term, to be smooth laminar flow, characterized by its homogeneity.

An important exception to this model has also been recognized for some time, and involves metals that undergo flow localization by shear banding (*e.g.*, Ti, Ni) [4–6]. Shear band flow is highly non-uniform (non-laminar), and characterized by a saw-tooth chip (Type 4, Fig. 1) with narrow bands of intense strain, separated by large blocks of relatively unstrained material [7–9]. The oft-cited mechanism of banding is catastrophic shear, in which the localization is determined by a competition between strain/strain-rate hardening and temperature-induced softening. Another similar, but less severe, type of flow localization with fracture, leads to the segmented chip (type 3, Fig. 1).

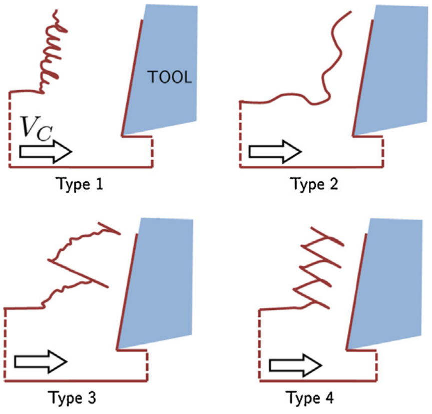

Fig. 1. Schematic of four principal chip types [10].

Since deformation in cutting is unconstrained due to proximity to a free surface, it is but natural that chip morphology is determined by the flow mode. Nakayama, in particular, recognized this and classified continuous chips into four types, as in Fig. 1 [10]. When cutting ductile (polycrystalline) metals such as Al, Cu and α-brass, the chip was sometimes very thick ($h_c \sim 15$–$20\ h_0$), with wrinkled features on its back surface (Type 1, Fig. 1). Furthermore, the cutting force was high along with a severely strained layer on the workpiece surface. In contrast, when the same metal was cut in an initially pre-worked condition, the chip was much thinner (and Type 2), the forces lower and the workpiece layer, much less strained. The thick Type 1 chip was explained within the shear zone model, by postulating a very broad deformation zone that had spread out into the workpiece. Also, the wrinkles were attributed to the “the non-uniform deformation and crack corresponding to the non-uniform nature of polycrystalline metal” [10]. The chip types of Fig. 1 are also quite important for surface integrity since evidence suggests the surface deformation state mirrors that of the chip [11,12].

We decided to re-examine the Type 1 chip in highly ductile metals in the broader context of unsteady, inhomogeneous plastic flow, since there was evidence to suggest that this chip arose from unsteady flow, triggered by material microstructure and lack of surface constraint. This re-examination is conducted using annealed pure metals, the most typical examples of ductile metals, and low-speed cutting. The results are contrasted with another inhomogeneous flow mode - shear banding with Type 4 chip - studied in high speed cutting of Ni and Ti alloys. Observational techniques, both *in* and *ex situ*, are used to map the deformation. The observations have provided new information about how

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unsteady flow modes develop, on the formation of Type 1 and Type 4 chips, and key role of microstructure in triggering unsteady flow modes *via* plastic instabilities.

2. Experimental

A linear cutting configuration (shaping), was used to analyze mechanics of chip formation and surface flow modes at speed $v_c = 1$–5 mm/s and $h_0 = 50$–100 μm. Plane-strain conditions were ensured by clamping a glass block, using a vice, against the side of the workpiece to prevent side flow. The flow was then observed *in situ* through the glass block using a high-speed camera system (pco dimax, resolution ~1.5 μm). The images were analyzed using particle image velocimetry (PIV) to obtain velocity, deformation and rotation fields at each instant; and various flow lines [13]. Shear band flow was analyzed in 2-D (rotary) high speed cutting (0.5–10 m/s) using micro-markers inscribed on the workpiece side surface [9,14], complemented by *in situ* high-speed imaging. The workpiece materials were annealed OFHC Cu (68 HV) and half-hard OFHC Cu (120 HV), representing highly workable (ductile) and partially hardened metals of moderate workability, respectively; and Ti–6Al–4V (346 HV) and Inconel 718 (458 HV) known for their propensity to flow localize. The tool was high-speed steel (Mo Max, McMaster) with rake angle $\gamma = 0^\circ$.

3. Sinuous plastic flow in cutting

Fig. 2 shows flow in the deformation zone in cutting half-hard Cu, depicted using streaklines superimposed on the von Mises (effective) strain (ε) field. The smooth streaklines indicate laminar flow, as in classical shear zone models. The chip thickness ratio $\lambda = h_c/h_0 \sim 2$ and the cutting force was ~400 N. The chip strain is quite uniform, 1.5 to 2, and close to that (~1.5) of the shear plane model. The chip shows only small-scale roughness on its back surface and is Type 2 (Fig. 1).

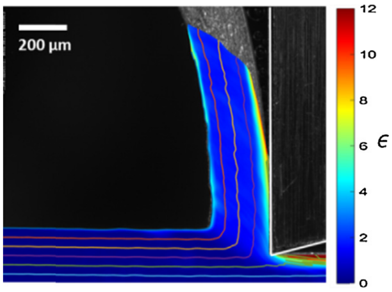

Fig. 2. Smooth streaklines and homogeneous straining in laminar flow cutting. Half-hard Cu, $\gamma = 0^\circ$, $h_0 = 100$ μm, $v_c = 1$ mm/s.

A most unusual unsteady flow mode and different type of chip (Type 1) are observed when cutting the soft annealed Cu (Fig. 3). The wavy streaklines, with significant local rotation, reflect large-amplitude folding of the material; we call this sinuous flow [13]. The chip now forms by repeated material folding, with the folds stacking up on top of each other to form a very thick chip, $\lambda \sim 12$. This λ is 6 times larger than for the laminar flow. The folding, however, is not just a transient process but occurs continuously, beginning from the formation of a bump ahead of the tool (arrows in Fig. 3**a**). The strain field (Fig. 3**b**) is also highly inhomogeneous, with strains alternating between ~10 and 4 along the chip length. This inhomogeneity arises due to the flow: repeated material folding leads to alternate regions of high and low strain, similar to the plastic buckling/bending of a beam.

The cutting force for annealed Cu was ~1600 N, 4 times higher than when cutting the same Cu in half-hard condition (Fig. 2). This high force reflects the highly redundant plastic deformation, during folding, in the chip. Similarly, the volume averaged (representative) strain in the folded chip (7.95) was nearly 5 times larger than in the chip produced by laminar flow.

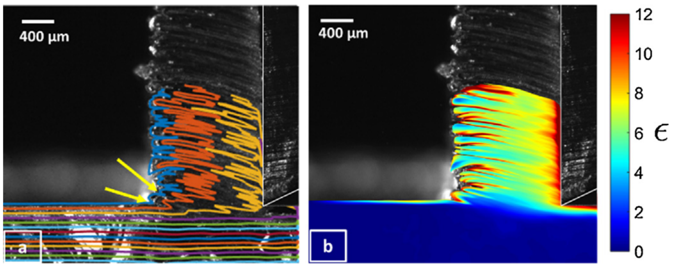

Fig. 3. Wavy streaklines and heterogeneous straining in sinuous flow cutting. Annealed Cu, $\gamma = 0^\circ$, $h_0 = 100$ μm, $v_c = 1$ mm/s.

A characteristic feature of sinuous flow is formation of mushroom-like structures on the chip back side due to material folding (Fig. 4). This morphological characteristic of the Type 1 chip can be used to identify occurrence of sinuous flow from *ex situ* observations. The mushroom morphology has been interpreted in the past [10] as arising due to cracks on the chip back surface and in the framework of the shear zone model. However, the present observations clearly show that it is caused by sinuous flow/folding, the latter also explaining the very large chip shape transformation. We observed that the workpiece surface created by sinuous flow showed poorer finish, and cracks and tears, compared to the laminar-flow surface. Importantly, a layer of material (thickness $\sim h_0$) with high strain (> 3) also resulted on the surface, in contrast to the laminar flow case (strain ~0.3).

The sinuous flow explains why annealed and highly workable metals are so difficult to cut, as evidenced by the large forces, poor finish and side flow. Sinuous flow has also been observed in experiments with commercially pure Al and α-brass.

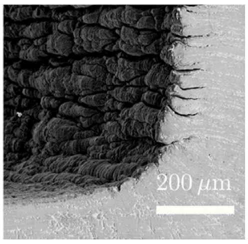

Fig. 4. Mushroom-like structures on chip backsurface due to folding as seen in an SEM image.

4. Why sinuous flow and folding?

Fold size statistics were extracted from the observed streaklines [13]. Widths and amplitudes of each fold were computed as the distance between successive valleys and between peaks and valleys, respectively. The width and amplitude naturally changed during the evolution of a fold from its initiation (initial) to collapse in the chip (final). Based on this analysis, the initial and final fold widths were 240 ± 105 μm and 84 ± 52 μm, respectively, while the final fold amplitude was 71 ± 51 μm. The fold widths appear to be correlated with the initial (mean) Cu grain size of ~ 500 μm, pointing to a microstructural origin for the initiation of sinuous flow.

The *in situ* observations provided more direct evidence for this connection. Fig. 5 shows 3 frames wherein grain flow dynamics is directly revealed by thermally etching the workpiece prior to cutting. Here, a bump is seen to correspond to a single grain (frame 1); it grows in amplitude before it rotates and shears into a fold (frame 3). Hence the statistical correlation between fold- and grain- sizes is to be expected. It is also clear from Fig. 5 how the mushroom structures on the chip surface evolve: each mushroom corresponds to a folded and deformed grain surface.

Observations such as these have indicated that development of the bump itself occurs by a process resembling plastic buckling of a beam constrained between pinning points. In the present case,

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