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Sinuous flow and folding in metals: Implications for delamination wear and surface phenomena in sliding and cutting

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ABSTRACT

We demonstrate key features of a recently uncovered mode of plastic flow – sinuous flow – with vortex-like components on the mesoscale. Based on high-resolution, *in situ* imaging of a hard wedge (asperity) sliding against a metal surface, we contrast this flow with the more well-known smooth homogeneous (laminar) flow in wear and large strain deformation processes. Sinuous flow is characterized by folding, and arises in both pure sliding and cutting of metals with large strain hardening capacity. The folds mediating the flow can transform into wear particles and surface defects by delamination via fold-splitting. Examples of this occurrence have been captured *in situ*, by high speed imaging of the sliding contact. This provides a direct mechanism for delamination wear, in just a few passes of sliding. Material heterogeneity plays an important role in the folding, as revealed by finite element simulation and experiment. This combined experiment-simulation approach reveals a number of ways in which folding can be triggered, suggesting an important role for sinuous flow in delamination wear. A close relationship between sinuous flow and mechanochemical Rehbinder effects in machining of metals is also highlighted. Technological implications of sinuous flow for sliding wear and manufacturing processes are briefly discussed.

1. Introduction

A central theme in modern tribology is the role of plastic deformation of asperities in sliding contacts [1–3]. Together with adhesive interactions, this has enabled a description of wear and friction in the adhesive and abrasive wear regimes, including formation of surface defects and wear particles [4–9]. A model system commonly used to study single-asperity contacts in tribology and machining is a rigid, hard wedge-shaped indenter or cone (asperity) sliding against a softer metal. A schematic of this contact for the case of the wedge is shown in Fig. 1. This plane-strain (2D) system has been analyzed using slip-line field (SLF) models [10,11] and finite element simulation [12], complemented by experiments [5–11]. Depending on the wedge rake angle (α), equivalently wedge incidence angle, $\theta = 90 + \alpha$, three modes of deformation are usually identified [6,11]: formation of a prow or wave ahead of the indenter (Fig. 2**a**), detachment of the prow by ductile fracture, and material removal by chip formation. Prow formation dominates at small $\theta < 20°$ (highly negative $\alpha < -70°$), typical of asperities on surfaces, while chip formation predominates at large $\theta > 70°$ ($\alpha > -20°$) as in machining processes. The sliding wedge asperity with small θ provides a good model also for the contact between a die and workpiece in metal forming processes such as extrusion, drawing and rolling; and in surface deformation processes like burnishing and shear spinning [13]. In these processes, the objective is to impose shape changes without material removal and/or large surface strains to control mechanical properties.

An intrinsic feature of the asperity/tool contact pictured in Fig. 1 is unconstrained plastic flow, which differs from the constrained flow more common in bulk metal forming processes. This flow, distinguished by large local plastic strain and strain rate, arises from high contact pressures on the order of the work material hardness [6,11] applied by the indenter onto the material surface. For interpreting wear and deformation characteristics, this

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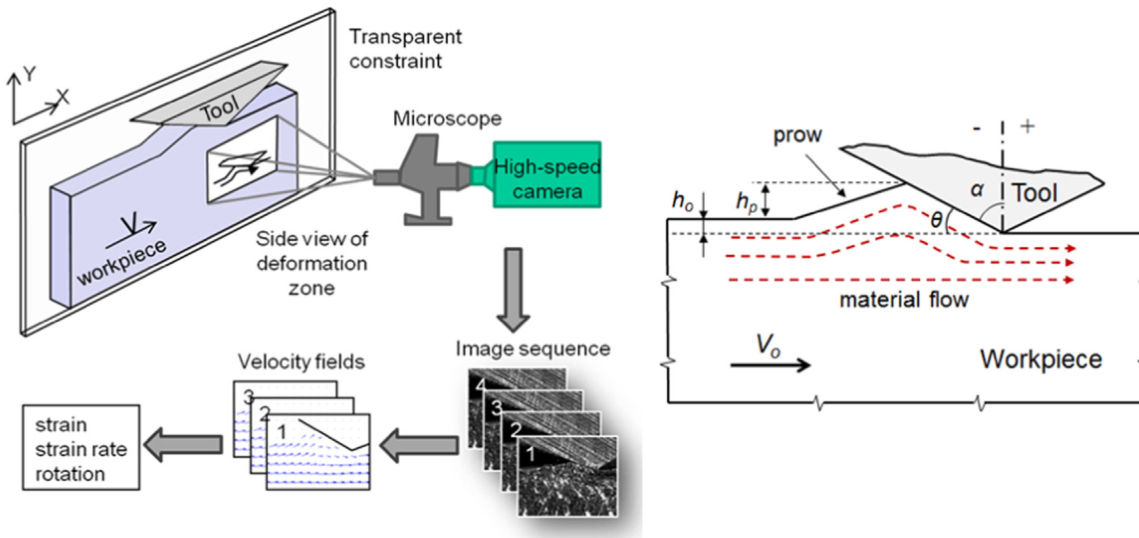

Fig. 1. Schematic of experimental setup for *in situ* observation and process parameters. The rake angle α is taken to be positive when measured clockwise from vertical.

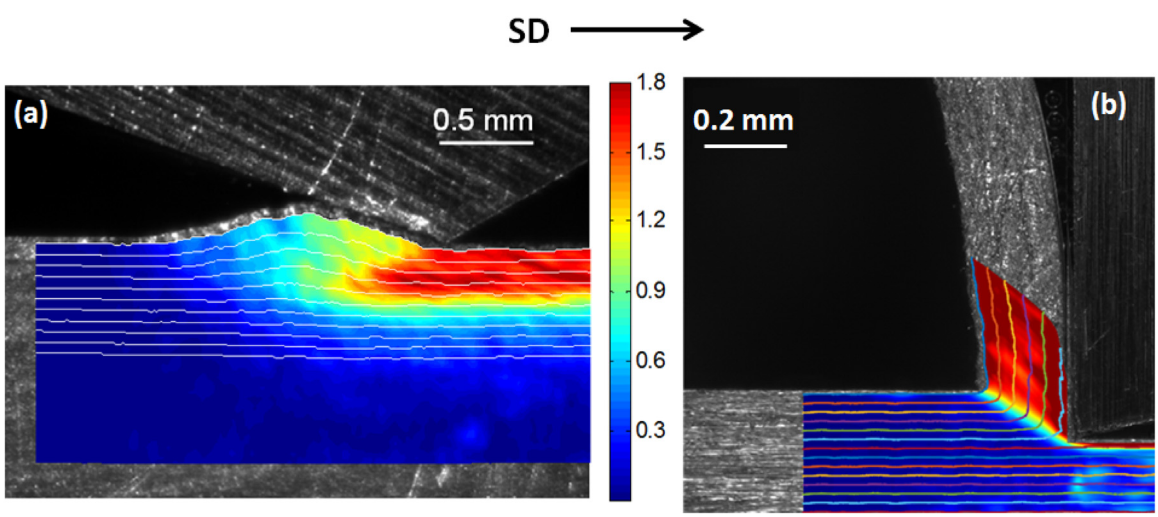

Fig. 2. Laminar flow in (hardened) Cu as revealed by smooth streaklines in low-speed (a) sliding and (b) cutting. The strain fields are shown in the background. Fluid: Mobil 1, SD – sliding direction of WP.

plastic flow is typically taken as smooth with homogeneous deformation, and with a streakline pattern as pictured in Fig. 2**a**. This streakline pattern is analogous to that of laminar flow in fluid mechanics; hence, by analogy, we term this type of flow as laminar or smooth. In this smooth flow framework, wear is described as occurring by the accumulation of damage over many cycles of interaction, with views differing over the extent to which the interaction is predominantly elastic [14], largely plastic [5,15] or elastic-plastic [6]. The chip formation at larger incidence angles is idealized to occur by ductile cutting under simple shear, with underlying smooth laminar flow (Fig. 2**b**). This view of material removal and smooth flow has been based largely on post-mortem analysis of wear debris and surface topography/morphology, and “quick-stop” observations made by interrupting the process. It should be noted that while existence of exceptions to smooth flow have been recognized, mainly the occurrence of non-homogeneous flow characterized by shear banding, the role of non-homogeneous modes in wear particle formation and other surface phenomena has received less than adequate consideration. A closely related question is: what non-homogeneous flow modes exist near surfaces and how do these modes develop?

To address these questions, we initiated an *in situ* study of deformation and flow at the mesoscale (~100 μm – 1 mm) in sliding and cutting using the model system of Fig. 1 [16,17]. By combining high speed imaging with image analysis by Particle Image Velocimetry (PIV), characteristics of the unconstrained plastic flow inherent to metal surfaces such as copper and aluminum were analyzed. A key new observation was a non-homogeneous flow mode – sinuous flow – characterized by significant vortex-like components and large amplitude-folds [16]. This flow was observed in both sliding and cutting of annealed and partially hardened metals, and shown to arise by a grain-induced plastic instability at the surface. Equally importantly, the folds were found to transform into wear particles and surface defects (e.g., cracks and tears) in the wake of the wedge. This transformation was captured *in situ* in the imaging experiments, thereby providing a direct, and hitherto unknown, mechanism for wear particle formation by surface delamination. Finite element simulations of the sliding, using a relatively simple continuum model that incorporated grain-level plasticity, captured all important phenomenological aspects of the flow revealed in the observations – the occurrence of vortex-like components, folding, transformation of folds to defects and wear particles, non-homogeneous straining of the surface and plastic instability. The studies also showed how