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Glues Make Gummy Metals Easy To Cut

Metals such as Cu, Al, Ni, Ta, and stainless steels, despite their softness and ductility, are considered difficult to machine. This is due to large cutting forces and corresponding formation of a very thick chip during cutting, and hence, these metals are referred to as "gummy." Their poor machinability of these materials arises because of an unsteady and highly redundant mode of plastic deformation referred to as sinuous flow. The prevailing plastic deformation mode during machining can be overcome by the application of certain coatings and chemical media on the undeformed free surface of the workpiece ahead of the cutting process. Using in situ imaging and concurrent force measurements, we present two different mechanochemical routes through which these media can improve machinability. The first route, which requires chemicals that adhere to the metal surface, such as glues and inks, improves cutting by inducing a change in the local plastic deformation mode—from sinuous flow to one characterized by periodic fracture or segmented flow. The second route, which requires chemicals that can react with the workpiece to form a low-friction layer, changes the sinuous flow mode to a smooth, laminar one. Both routes decrease cutting forces by more than 50% with order of magnitude improvement in surface texture as characterized by measured roughness and defect density. The results suggest a broad range of opportunities for improving the performance of machining processes for many difficult-to-cut gummy metals. [DOI: 10.1115/1.4044158]

1 Introduction

Soft metals with high strain hardening are well known for being difficult to machine. The difficulty arises because of unusually large cutting forces, formation of a thick chip, and very poor surface finish. This difficulty in cutting has earned them the title "gummy" [1]. The reason for the large forces is due to a tendency of these ductile metals to deform via an unsteady and highly redundant mode of plastic deformation termed sinuous flow [2–5]. If sinuous flow is somehow replaced with a more benign flow mode, then cutting should naturally be much improved with lower forces and improved surface finish. Examples of such favorable deformation modes include laminar flow and possibly even segmented flow [3,6,7].

A possible route to modulate plastic flow is by changing the environmental conditions during the cutting. Environmental effects on plasticity, such as hydrogen and liquid metal embrittlement, stress-corrosion cracking, have been well known for several decades [8,9]. Such mechanochemical effects are generally viewed as leading to catastrophic failure and to be avoided at all costs [8,10–14]. Furthermore, the effects are believed to be material specific—the action of a particular chemical being restricted to a specific metal. It is worth noting that these mechanochemical effects have been constructively employed in chemomechanical planarization and particle comminution which are extensively used in processing techniques in the semiconductor and ceramics industrial sectors, respectively.

In this work, we demonstrate two different types of mechanochemical effects in metals, which can be used constructively in machining. The first one is a material-agnostic effect in which application of several easily available media, such as glues and inks, on the workpiece surface prior to the cutting results in a force reduction of ∼ 50% (see Fig. 1) [15]. The media embrittles the surface and forces sinuous flow to transition to segmentation flow—one characterized by the periodic fracture initiating from the free surface of the chip.

The second is a material-specific effect where application of the chemical to the tool–workpiece region leads to improvements in the cutting forces on the order of 80%. In this case, the media reacts with the workpiece to form a low-friction "solid lubricant" between the tool and the chip and forces sinuous flow to transition to smooth laminar flow. Both effects are shown to improve surface finish as characterized by reduced roughness and defect density by an order of magnitude. Utilizing high-speed in situ imaging of the cutting process, we characterize the flow modes and corresponding effects of the surface-active (SA) media. This is supplemented by measurements of cutting forces and finish-surface attributes. The general capability of this flow-coupled mechanochemical effect in improving the machinability of high strain-hardening metals is highlighted. This effect can, potentially, be implemented in practice, since it involves SA medium action on the easily accessible workpiece free surface, rather than lubricant action along the difficult-to-access, tool–chip contact. Furthermore, the SA medium action can be tailored to be either material-agnostic or material specific as needed.

2 Experimental Details

A schematic of the experimental setup, a model plane-strain (2D) cutting system, is shown in Fig. 1. It consists of a workpiece in the shape of a plate moving orthogonally against a rigid wedge (tool) at a constant velocity, V_0. A thin layer of metal is removed with undeformed chip thickness, h_0, and a deformed chip of thickness, h_C. The angle that the tool makes with the vertical is the rake angle, α. For test conditions, h_0 was fixed equal to 50 μm, V_0 equal to 2 mm/s, and α was varied between 0 and 10 deg. The low-cutting speed helped minimize temperature and strain-rate effects on the cutting.

The process zone was imaged using a high-speed CMOS camera (PCO Dimax) in order to obtain a complete record of the deformation sequence. A glass block was clamped against the side face of the workpiece to constrain the deformation in plane-strain. Images were captured at 500 frames/s and spatial resolution of 1.4 μm per pixel. The image sequence was subsequently analyzed using digital-image-correlation (DIC) techniques to obtain velocity, strain, and strain-rate maps in the deformation zone.

Concurrently, forces on the tool, both parallel (cutting force F_c) and perpendicular (thrust force F_t) to V_0, were measured using a piezoelectric dynamometer (Kistler 9272, natural frequency ∼2 kHz). The topographical characteristics of the cut surface such as

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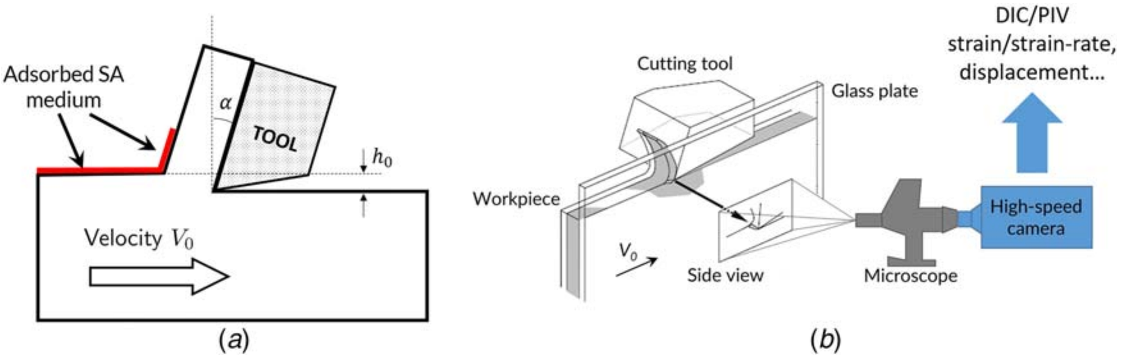

Fig. 1 Schematic of the experimental setup used for cutting experiments. The SA medium is applied to part of the workpiece surface. In situ observation of the deformation flow field via a high-speed camera gives high-resolution flow field information. The width of the workpiece into the plane (*b*) is equal to the chip width.

roughness parameters and meso/macro scale defects (e.g., pits, tears, and fractures) were evaluated using a large-area, 3D optical profilometer (Zygo NewView 8300).

Two workpiece materials, well known for their high strain-hardening capacity, were used in the cutting experiments: Cu (99.99% OFHC Cu 101) and Al (99% Al 1100). The workpiece samples were in plate form with a cutting width of 2.3 mm and a cutting length of at least 50 mm. The copper samples were annealed prior to the cutting in an inert argon atmosphere. The annealing was done at 750 °C for 4 h, followed by oven cooling. Annealing in this inert atmosphere minimizes the formation of oxide layers on the metal surfaces. The Al samples were directly procured as a sheet in the annealed state.

Two types of surface-active media were found to influence the metal cutting. Type-1 media consists of media that show strong physical adsorption to the metals. These media were glue 1 (Scotch restickable glue stick), glue 2 (Scotch super glue gel), glue 3 (Gorilla super glue), ink 1 (Sharpie permanent marker), ink 2 (Dykem), and ink 3 (paper mate liquid paper correction fluid). In order to assess their effect on the metal cutting, the type-1 media is coated on the latter half of the workpiece surface (Fig. 1(*a*)). Note that the type-1 media is present remote from the tool–workpiece interface and therefore does not influence the friction and lubrication therein.

Type-2 media consists of media that show chemical affinity (specificity) for Al only, as established by their ability to react with oxide-free Al surfaces. The following media belong to this group: isopropyl alcohol (IPA) (Fisher Chemical), ethanol (Decon Labs), and 1-butanol (Fisher Chemical). These media were applied by flooding the tool–workpiece region and influence the cutting by altering the lubrication at the tool–workpiece interface.

3 Results

The effect on the cutting forces and the chip-morphology will be presented to elucidate the effect of the two types of surface-active media on the metal cutting.

3.1 Type-1 Media. Figure 2(*a*) shows the force trace (cutting and thrust forces) when cutting annealed Cu, with the latter half of the workpiece coated with ink 1. The inset shows a schematic of the experiment. Prior to the cutting in the media coated region, the force steadily increases to ∼420 N. Once the cutting reaches the coated region, the cutting force sharply drops (∼60%). This large drop is a characteristic feature of the mechanochemical effect. This reduction in the power component of the force strongly suggests that the SA medium changes the mechanics of the deformation. A second demonstration of the SA medium effect is highlighted in the F_C trace with periodic oscillations shown in Fig. 2(*b*). In this experiment, spots of ink 1 were placed regularly along the length of the annealed Al workpiece surface. Consequently, the resulting F_C oscillates between higher (uncoated) and lower (coated) values, with the oscillation frequency matching the spatial frequency of

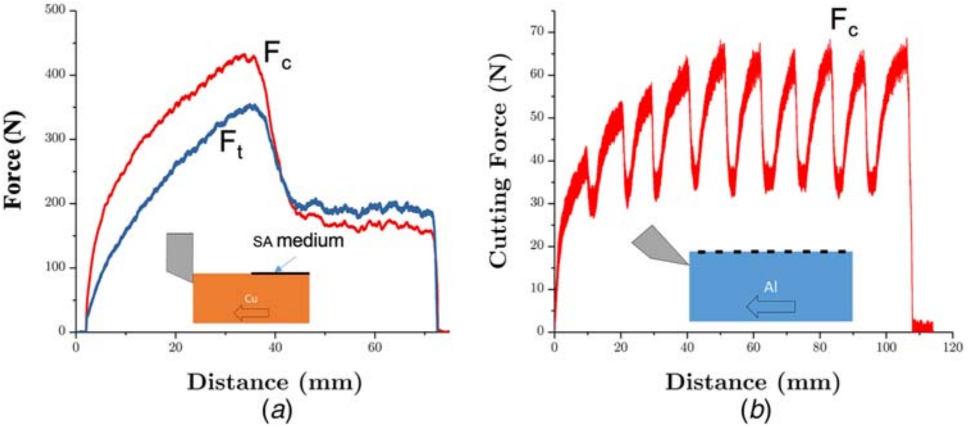

Fig. 2 Large drop in the forces is the characteristic feature of the mechanochemical effect. (*a*) Cutting and thrust components of the force when cutting annealed Cu with a $\alpha = 0$ deg tool. The latter half of the workpiece surface is coated with ink 1 (see inset). (*b*) Cutting force for annealed Al with a $\alpha = 30$ deg tool. The workpiece surface is coated at regular intervals along the length with spots of ink 1 (see inset). The force now oscillates at a frequency corresponding to the spatial frequency of the ink spots. $h_0 = 50$ μm, $V_0 = 2$ mm/s.

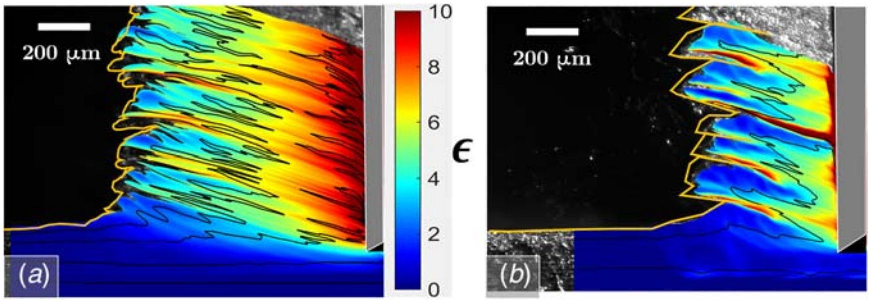

Fig. 3 Strain fields in cutting of annealed Cu ($\alpha = 0$ deg) obtained from the high-speed in situ imaging (*a*) without application of the SA medium. The flow (sinuous) is characterized by large-amplitude folding (wavy streaklines) and large nonhomogeneous strains (von Mises strain field) and (*b*) after applying glue 1 to the workpiece surface. The chip now consists of a series of cracks that nucleate from the free surface and is significantly thinner than that with sinuous flow. This flow mode represents segmented flow. $\alpha = 0$ deg, $h_0 = 50\ \mu$m, $V_0 = 2$ mm/s.

the spot pattern. Again, this reduction in force reflects a fundamental change in the cutting mechanics due to the presence of SA media.

The cause of the mechanochemical effect is best understood by examining the mesoscale plastic flow underlying chip formation, both with and without the SA medium. Figure 3(*a*) shows a typical image of the deformation zone obtained by the high-speed in situ imaging. The von Mises strain field and streaklines, which are obtained by DIC analysis, are superimposed. The strain and streaklines elucidate the nature of the flow when cutting in the absence of any medium. Three principal qualities of the flow pattern are highlighted in this figure. First, the flow—sinuous flow—is unsteady, with extremely wavy streaklines, indicating that the chip forms by folding of the material. This type of flow is the characteristic of high strain-hardening capacity metals and involves significant redundant deformation in the material [2,5]. Second, since the chip actually consists of material folds stacked on top of each other, the chip-thickness ratio (h_C/h_0) is unusually large ∼12. The repeated folding of the material results in the back-surface of the chip being decorated with mushroom-like formations. Third, the strain field is heterogeneous, oscillating between a maximum strain of ∼8 to a minimum strain of ∼3. This strain field and the streakline pattern are quite distinct from the smooth uniform (laminar) flow characteristic of shear-zone-type chip formation.

The deformation mode changes completely when the free surface is coated with an SA medium. This change is shown in Fig. 3(*b*) when annealed Cu was cut with glue 1 coated on the workpiece surface. Instead of the sinuous flow mode seen in Fig. 3(*a*), the deformation mode is now characterized by periodic cracks nucleating from the chip-free surface and propagating toward the tool-tip. In other words, the development of sinuous flow is arrested by the cracks. This not only limits the chip-thickness ratio to a much smaller value of ∼8, but it also limits the strain in the chip to ∼4. This type of flow has been called segmented flow. The key observation here is that large strain plastic deformation is suppressed by the occurrence of repeated fracture, due to the SA medium causing “local embrittlement” of the material. The reduced straining is reflected in a more slender chip with the SA medium.

3.2 Type-2 Media.

In contrast to type-1 media where the SA media is coated on the workpiece surface, type-2 media are liquids which are applied to the tool–workpiece region. Media such as IPA show a mechanochemical effect only with Al. Figures 4(*a*) and 4(*b*) show the measured force components when cutting annealed Al under two conditions, namely, with and without the application of IPA. F_c (Fig. 4(*a*)) and F_t (Fig. 4(*b*)) represent the cutting (parallel to V_0) and thrust forces (normal to V_0), respectively. In the absence of IPA, both components show a gradual increase to steady state, at which stage $F_c \simeq 600$ N. This force value is quite high even though the material being cut is soft Al (23 HV)—a consequence, once again of sinuous flow and the resulting large chip thickness and deformation occurring in the workpiece material. It is also worth noting that the friction force (component along the tool face) F_f is 1.6 times F_n. If we define a friction coefficient (μ) for the tool–chip contact as the ratio of F_f/F_n, then $\mu = 1.6$. In cutting of metals, this μ can assume values greater than unity [6].

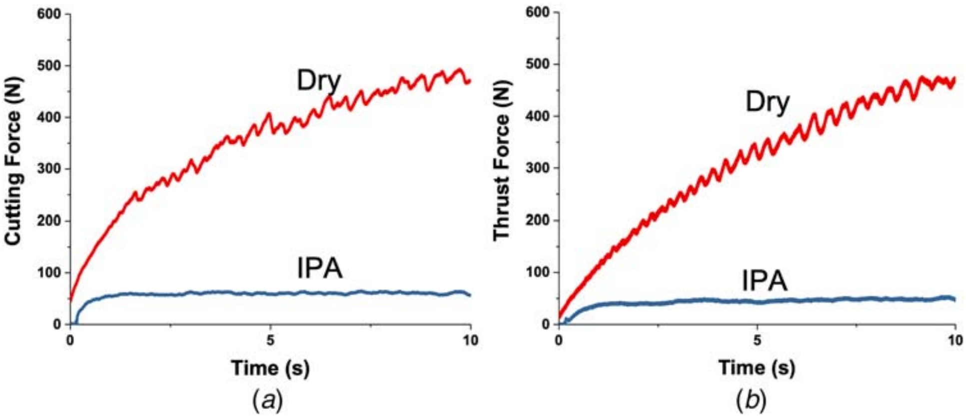

Fig. 4 Force in shear deformation under dry condition and in an IPA bath. (*a*) Cutting force (F_c) and (*b*) thrust force (F_t). F_c and F_t in IPA cutting are smaller by an order of magnitude compared to dry cutting.

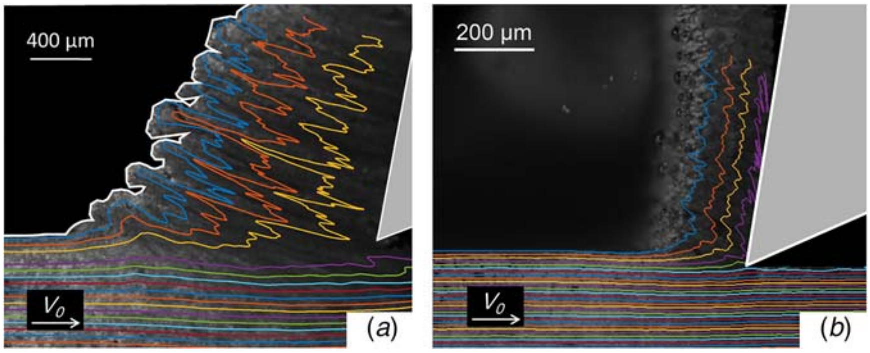

Fig. 5 Streaklines in cutting of annealed Al ($\alpha = 0$ deg) obtained from the high-speed in situ imaging (*a*) under dry conditions. The flow is sinuous, characterized by wavy streaklines and (*b*) in a bath of IPA. The flow is now smooth and laminar, and the chip is significantly thinner than that with sinuous flow. $\alpha = 10$ deg, $h_0 = 50\,\mu$m, $V_0 = 5$ mm/s.

In the presence of IPA, both F_c and F_t were around 60 N, an order of magnitude smaller than those of dry cutting (Fig. 4). Furthermore, unlike with the sinuous flow, F_c and F_t reached their steady values much more quickly for the laminar flow mode. The tangential force, F_t, along the tool face in the IPA cutting was also an order of magnitude smaller than in the dry cutting case. Since this force is a measure of the frictional drag at the tool–chip contact, it shows that the IPA action at this contact has also reduced the frictional energy dissipation (secondary deformation) considerably. The change in friction can be inferred from the value of $\mu = 0.9$, significantly lower than dry cutting ($\mu = 1.6$).

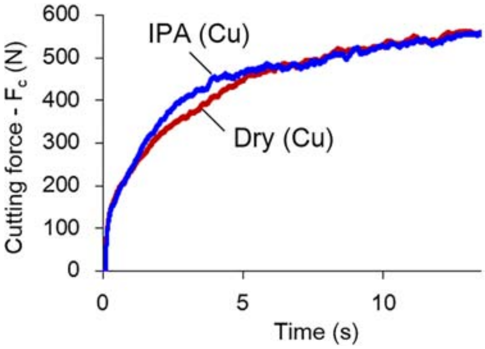

Fig. 6 Cutting force in annealed Cu for dry and IPA cutting ($\alpha =$ 0 deg, $h_0 = 50\,\mu$m, $V_0 = 5$ mm/s). In contrast to the Al cutting, IPA has no effect on cutting force in the Cu.

Figure 5 shows the mechanochemical effect on the chip and the flow mode. The flow mode is once again sinuous in the absence of any media. It has been shown previously that the cutting characteristics of annealed Cu in dry cutting are very similar to those of Al under similar conditions: a sinuous flow mode prevails with very thick chip and large cutting force [2,5]. The chip is extremely thick, with the ratio $h_C/h_0 \simeq 19$, indicative of large underlying strains. The chip strain distribution is quite nonhomogeneous, reflecting the repeated folding, and alternates between high (≈ 6) and low (<3) values.

Figure 5(*b*) shows the influence of the IPA on the chip and the deformation mode. In stark contrast to the chip in Fig. 5(*a*), the one in Fig. 5(*b*) is much thinner, with a $\lambda \simeq 5$. Most strikingly, the flow was homogeneous and laminar, as revealed by the smooth streaklines. No folding is observable on the macroscale, and the mushroom-like morphology is also absent on the chip free surface. Additionally, the strain field in IPA cutting is homogenous throughout the chip with much smaller maximum strain (~ 3). This transition is different from the one induced by type-1 media where sinuous flow transitioned to a periodic segmentation flow mode.

This transition in the flow from sinuous to laminar, with the same material and deformation geometry, is due to the lack of any buckling on the free surface in the IPA cutting. Many alcohols, including IPA, are known to be effective lubricants for aluminum under conditions when a stable alkoxide layer is established on the Al surface [16].

Figure 6 shows the cutting force with and without IPA while cutting annealed Cu. It is evident that IPA does not have any

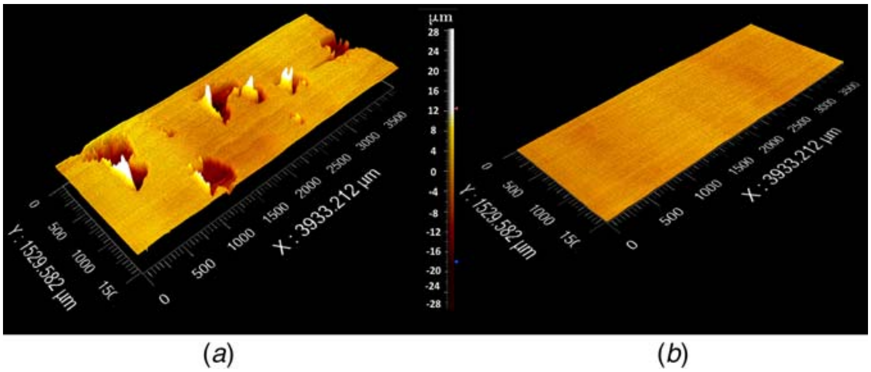

Fig. 7 3D surface profiles of machined annealed Cu surface obtained by optical profilometry. (*a*) With sinuous flow, large pit-like surface defects are observed. (*b*) With the SA medium (glue 1) applied, an order of magnitude improvement in the cut surface quality is observed, as quantified by average pit size, pit density, and surface roughness (R_a). $\alpha = 0$ deg, $h_0 = 50\,\mu$m, $V_0 = 2$ mm/s.

effect on the cutting forces. The flow mode with and without the IPA was sinuous. This indicates that the effect of the IPA in cutting Al is not merely a lubrication effect, rather it is a genuine mechanochemical effect that is material specific.

3.3 Effect of Media on Surface Finish.

Alongside transition in the flow mode and attendant force reduction, the SA medium application was found to result in a remarkable improvement in the quality of the newly created (cut) workpiece surface. As has been demonstrated clearly elsewhere, the occurrence of folding and sinuous flow is synonymous with the formation of pits, cracks, and tears on the resulting surface [17,18]. Figure 7(*a*) shows a 3D surface profile of a typical pit on the newly generated Cu surface arising from the folding process. The ratio of pit size (maximum depth from the free surface) to initial tool penetration depth was $\Delta_P/h_0 \sim 0.75$, and the average pit area and density were $3.3 \times 10^4\ \mu\text{m}^2$ and 6.2 /mm^2, respectively, reflecting significant degradation of the newly formed surface. In the presence of the SA medium, where the folding process is interrupted by segmentation with much smaller forces, the resulting surface shows no pit/crack defects (see Fig. 7(*b*)). In fact, this drastic change in surface quality could also be ascertained by directly viewing the cut surface without any optical aids. Furthermore, the surface finish improved by an order of magnitude—R_a for annealed Cu $\alpha = 0$ deg was 4.4 μm without media and 0.55 μm with glue 1.

4 Discussion and Conclusions

The in situ observations, characterizations, and subsequent analysis of the cutting process have shown how chemical media that strongly adsorb to surfaces can influence the mechanics of the material removal with high strain-hardening metals, generally in beneficial ways. The characteristic signature of this medium action is a large reduction in the cutting and thrust components of the force, by up to 80%. We have called this beneficial medium action a mechanochemical effect. At the mesoscale, the mechanochemical effect manifests as a transition in flow—from repeated folding-induced sinuous flow in the absence of the medium to either segmented flow or smooth laminar flow in the presence of an effective medium. A variety of common media such as metal marking inks, glues, and alcohols, all quite benign, produce this effect in material systems as diverse as annealed pure metals (e.g., Cu, Al, and Fe), stainless steels, and Ni alloys. This flow transition has been directly observed in the imaging experiments (Figs. 3 and 5). Furthermore, an order of magnitude improvement in the quality of the machined surfaces, e.g., reduced surface roughness, reduced defect density, and reduced plastic strains, results. These beneficial attributes of the mechanochemical effect arise from a local ductile-to-brittle transition in the material's deformation behavior at the surface, resulting in an unsteady sinuous flow mode of deformation being suppressed and replaced by segmented flow, with periodic fracturing, in the chip. Two criteria are identified as necessary for the effect to manifest: (a) the occurrence of sinuous flow, with large-amplitude folding, in the metal, when cutting in the absence of media and (b) strong adsorption, either physical or chemical, of the SA media to the metal surface. The mechanochemical effect is noncatastrophic, and its implementation for improving the machining of gummy metals in industrial settings seems quite feasible.

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