Proceedings of The National Conference
On Undergraduate Research (NCUR) 2019
Kennesaw State University
Kennesaw, Georgia
April 11-13, 2019

Investigating Mechanochemical Effects in Deformation of Metals and Alloys - Honey Makes Metals Easy to Cut

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Abstract

The metal cutting process can be used to investigate phenomena that occur during deformation of metals and alloys in a range of primary manufacturing processes. Examples of material removal operations include turning and drilling, or bulk deformation processes such as rolling and extrusion. The characteristics of surfaces that form during metal cutting are directly linked to the underlying deformation mechanisms and related physical phenomena that occur. Innovation and advancement of manufacturing processes that rely on material removal or bulk deformation depend on scientific understanding of the physical phenomena that occur – friction, wear, strain, strain rate, hardening, microstructure evolution, energy, and thermal effects – and how these relate to industrial scale production systems and limits of their capability and efficiency. Specifically, the forces, deformation velocity, strain and the topological features in both the metal chip removed during the cutting process, and the finished (cut) surface can be linked to the underlying deformation mechanisms and related physical phenomena. Recent work has demonstrated a mechanochemical effect where the application of a range of common benign household chemical media, such as ink and adhesives, can alter the plastic flow in metals, remarkably improves machinability and deformability even in soft and highly ductile metals that are considered difficult to machine or deform. We plan to further investigate the effects of additional common household chemicals, including inks, soaps, waxes, and adhesives, to map their influence on the deformation that occurs during metal cutting and identify potential new ways to improve efficiency of material removal and bulk deformation processes.

Keywords: Cutting, Strain, Mechanochemical

1. Introduction and Background

Metals and alloys that are highly ductile and exhibit high strain hardening can be difficult to deform – especially at high strain and strain rates that are prevalent in industrial manufacturing processes that involve deformation or metal removal (eg, stamping, rolling, cutting, drilling, grinding). Recent research has confirmed the presence of an unsteady, heterogeneous plastic flow mode called "sinuous" flow [1,2] which is the phenomena underlying the complexity of plastic deformation in these metals and alloys. In the sinuous flow the deformation field in metal cutting is highly redundant with repeated folding of the material. This is opposed to a laminar flow in which the strain is homogeneous through the deformation field with lower energy dissipation and significant improvement in machinability. For a given metal or alloy that exhibits sinuous flow, an increase in hardness and strength (by either previous plastic deformation or by thermal treatment) reduces the energy required to deform and perform material removal. The sinuous flow is responsible for an otherwise ductile and lower strength metal or alloy being difficult to cut or described as "gummy" [1]. Metal cutting involves effective plastic strains 0.5 to 10, strain rates of up to 1×10^5/sec, and shear plane temperatures from essentially ambient up to 0.8 Tm [3]. These conditions further complicate the material removal process in "gummy" metals.

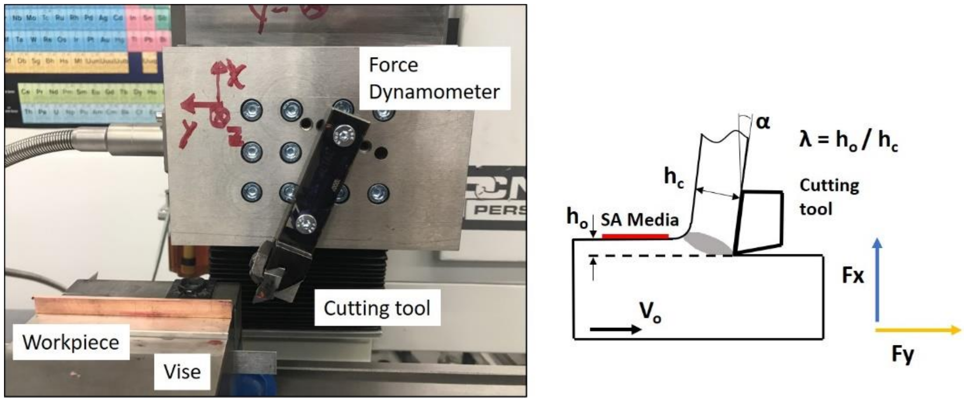


Figure 1. Experimental arrangement showing the linear cutting configuration and force dynamometer. The schematic to the right shows the variables for the cutting process and force components. A thin layer of surface-active media (SA) indicated by the red line was applied to the surface of the workpice ahead of the cutting zone.

Recent research at Purdue University, Center for Materials Processing and Tribology [1,2] has shown that the sinuous flow in the gummy metals could be suppressed by the application of a surface-active (SA) media on the undeformed free surface ahead of the cutting zone. The plastic flow mode is altered from sinuous to segmented or, in some cases, laminar flow – either of which drastically lowers the deformation strain. The benefits of suppressing the sinuous flow are quite remarkable with results showing up to 80% reduction in cutting forces, reduced deformation strain, and improvements in surface finish. The research confirmed one class of SA media are material agnostic. That is, when the media is applied to the free surface, ahead of the cutting, the mechanics of deformation are influenced regardless of the metal or alloy – as long as the metal or alloy exhibits sinuous flow and there is a strong adsorption (eg adhesion) between the SA media to the metal surface. This beneficial effect is referred to as a "mechanochemical" effect [2]. The hypotheses that the Purdue University researchers are investigating to explain the phenomena are that 1) the mechanochemical effect is mediated by an adsorbed layer of the SA media, and the MC effect is mediated by an adsorbed layer of molecules or 2) SA media changes the surface thermodynamic variables of the metal (e.g., surface energy, surface tension), thus triggering a ductile-to-brittle transition that changes the crack propagation behavior during plastic deformation. The research presented here was motivated by an interest in completely different types of media (in addition to common household chemicals) to test our hypothesis that naturally "sticky" media – specifically bee's honey or tree sap (oleoresin) would have strong adsorption (ie. adhesion) to the metal surface due from their "stickiness" and suppress sinuous flow during metal cutting (exhibited by reduced forces and deformation strain). Since all of the manufacturing sectors use a wide range of metal-working fluids, we are exploring the possibility that a completely natural SA media exhibiting the mechanochemical effect could replace the use of environmentally hazardous oils and chemicals that are prevalent in industrial machining of ductile metals and alloys.

2. Experimental Details

The experimental set-up is shown in Fig. 1 with a linear machining (cutting) framework that can be modeled as a plane-strain configuration [3]. A rectangular plate metal or alloy workpiece 1.6mm thick x 30mm high x 100mm long is clamped rigidly in a vise. The vise is mounted to a linear machine slide that drives the workpiece at a velocity, V_o (mm/min) across the sharp edge of a tungsten carbide cutting tool. The tool is pre-set to a depth-of-cut, h_o, below the workpiece surface and when the workpiece passes across the tool a layer (chip) of material is removed. The tool rake angle, α, is defined relative to the direction normal to the workpiece surface The removed (and deformed) chip has an undeformed chip thickness, h_o, pre-set by the depth-of-cut and a deformed chip thickness, h_c that is determined by the shear angle and strain behavior of the material. The tests were all conducted with h_o=0.050mm, velocity V_o=2,400 mm/min (40mm/sec), and rake angle α=+20 degrees. For the 100mm long workpiece the cut occurs in approximately 2.5 seconds total time (2.5 sec=100mm /2,400 mm/min). As shown in Fig. 1 a thin layer of SA media was applied to the workpiece covering the second half (≈50mm length) of the workpiece surface. Four different media were tested. Glue Stick (Elmer's Restick) and Sharpie (permanent marker ink) were selected to baseline previously published results on benign household chemical media [2]. Bee's honey (clover raw) and pine tree sap (Florida Long Leaf Pine) were selected due to their inherent “stickiness” and because they are 100% natural media. The bee’s honey and pine tree sap were applied in a thin layer on the workpiece surface using a small nylon brush.

The cutting forces were measured directly by a Kistler 9129AA multicomponent force dynamometer (natural frequency~3.5kHz). Since the experimental configuration is plane-strain the force component in the direction transverse to the workpiece surface is negligible, and only force measurements in the direction of the velocity and normal to the workpiece surface were collected during the experiments. The cutting forces in the direction of velocity (Fy) were measured as positive in the compressive direction of the deformation field. The cutting forces in the vertical direction Fx (normal to the workpiece surface) were measured in the positive (vertical) chip flow direction.

The cutting tool was an uncoated carbide tool Kennametal NG3189R grade K68 with a modified relief angle to allow for the α=+20 degree rake angle on the cutting tool. The workpiece material was annealed copper Cu101 (99.99% OFHC). The annealed copper was chosen because of its characteristically high strain hardening, and it represents the range of materials that have a plastic flow mode that is dominated by sinuous flow.

Each experiment was conducted by performing a series of successive cuts (typically 9 cuts) with the surface coated by a permanent marker ink (sharpie) prior to each of the preparatory cuts across the entire length of the workpiece surface (the sharpie was intentionally allowed to dry for 10 seconds just prior to cutting). This repetitive process provided a steady-state condition for the deformation (cutting) test with a specific test media. The test SA media was applied to the surface of the workpiece on the second half of the workpiece ahead of the cutting zone (approximately 50mm length) as depicted by the red line in Fig. 1. Then, the effect of the SA media was observed during the deformation field involving the second half of the workpiece surface.

It is of interest to note that bee’s honey and pine tree sap were selected for SA media because of their “stickiness” and because they are completely natural media. They are not processed by any manufacturing method (as opposed to chemical processes used to produce the sharpie and glue stick). Honey has many uses including medicinal uses and in foods – but we are unaware of any use of honey for industrial applications. Pine tree sap was the leading component of the turpentine industry in the 20th century as the sap resin was distilled for production of turpentine solvent.

The “chip” removed from the metal workpiece was collected after each preparatory cutting test and subsequently for the specific test of the SA media. The chips were inspected optically with a Nikon SMZ 1270I stereoscope with a 1X objective lens and a Pixelink 5MP CMOS digital imaging system. In addition, the relative change in the deformed chip thickness was recorded using a digital outside micrometer with spherical anvils (resolution 0.001mm).

3. Results

The four types of SA media all showed essentially the same effect on the cutting forces and the shear strain developed during the deformation.

3.1 Effects Of Surface Media Forces

Figure 2 shows the measured forces for the cutting tests performed using bee’s honey as the SA media. (in both the horizontal, cutting direction and the vertical, orthogonal direction to the workpiece surface). The force is shown as a function of time (seconds) which is directly related to the length of the cut distance along the surface of the workpiece. (cut distance is equal to the product of the cutting velocity V_o=2,400mm/min x time). The forces initially increase as the tool engages the workpiece and cutting begins. The forces reach a steady state plateau at ~400N in the cutting direction (Fy) and ~100N in the direction vertical (orthogonal) to the workpiece. Then the cutting enters the zone in which the SA media is present on the workpiece surface. The effects of the SA media are realized immediately as both primary cutting force components decrease sharply. The forces in both primary directions decrease instantaneously by nearly 40% to ~250N in the velocity direction and to ~60N in the direction normal to the workpiece surface. The effect on the force in the vertical direction (normal to the workpiece surface) is not maintained through the remaining deformation; however, importantly, the cutting force component Fy in the cutting velocity direction is sustained at the reduced level through the completion of the deformation and removal of the chip. The component of force in the velocity direction (Fx) determines the power requirements (Power = Fx V_o). Hence, the power required to deform the material is reduced by ~40% in the presence of bee’s honey. The results for all four media tested were very similar, indicating that each of these media have similar ability to mediate or suppress the sinuous flow of plastic deformation, resulting in similar reductions in cutting forces caused by the mechanochemical effect which alters the mechanics of the deformation.

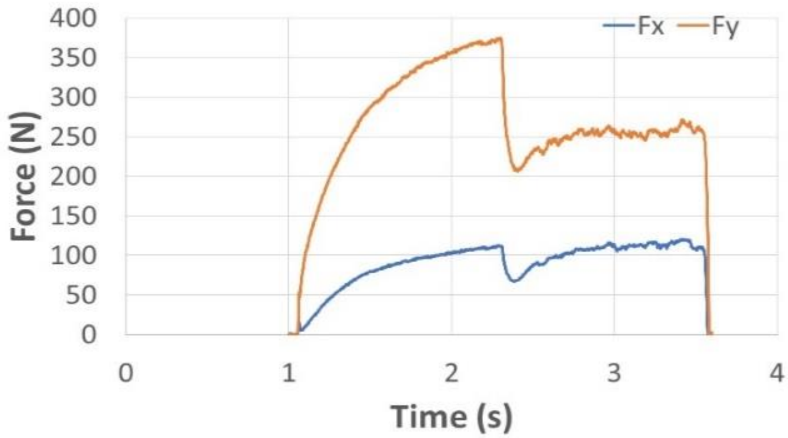


Figure 2. Cutting forces demonstrating the mechanochemical effect of bee's honey in cutting annealed Cu. The forces shown are acting in the direction of cutting velocity (Fy) and normal to the workpiece (Fx).

3.2 Effects Of Surface Media On Strain

The evolution of the shear strain is essentially unchanged regardless of the SA media in this study (sharpie marker, glue stick, bee's honey, and pine tree sap). The shear strain in the chip can be calculated from the shear-plane model where the shear angle, ϕ, can be determined by measurement of the deformed chip thickness [3]. From the relationship shown in the diagram of Fig. 3, the ratio between the deformed chip thickness, h_c, and the undeformed chip thickness, h_o, can be used to determine the chip ratio, λ (Equation 1). The actual deformed chip thickness was measured with a digital outside micrometer (resolution of 0.001mm). Knowledge of the chip ratio enables the shear angle, ϕ, to be determined by Equation 2. Then, the shear strain, γ (magnitude of shear strain in deformation), can be calculated by Equation 3.

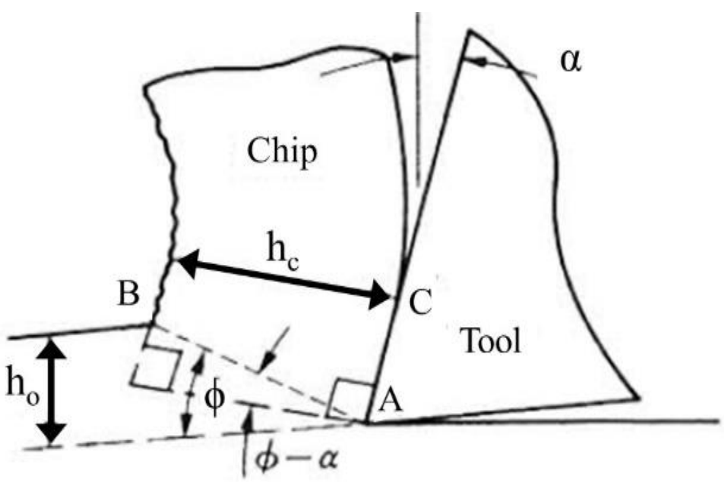


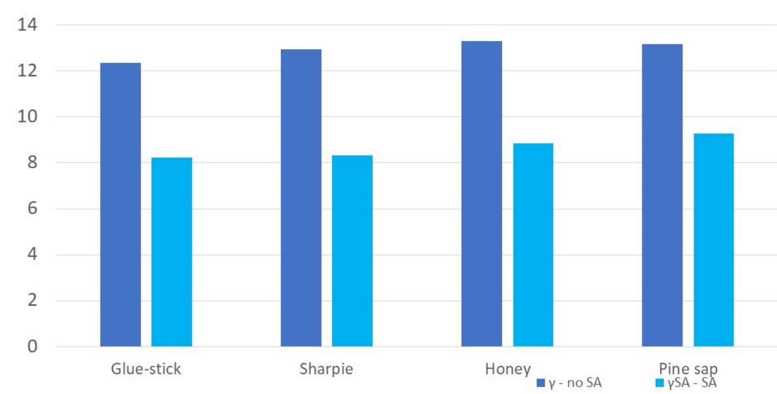
Figure 3. Shear strain in metal cutting [3]

$$\lambda = h_o/h_c = \text{AB } \sin\phi \,/\, \text{AB } \cos(\phi - \alpha) \quad (1)$$

$$\tan(\phi) = \lambda \cos(\alpha)/(1 - \lambda \sin(\alpha)) \quad (2)$$

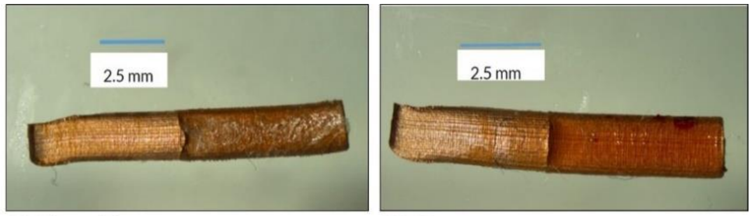
$$\gamma = \cos(\alpha) \,/\, (\sin(\phi) \cos(\phi - \alpha)) \quad (3)$$

Figure 4 summarizes the significant reductions in strain with the application of the SA media. The deformed chips from the cutting tests were measured with the digital micrometer and the values of the deformed chip thickness, h_c, were used to report the maximum strain for the portion of the chip formed in the absence of the SA media on the surface (from the first 50mm of cut length), and similarly for the portion of the chip that was deformed with SA media preset on the surface. The high strain in the chip with no SA media present (Fig. 4) is representative of the effects of sinuous flow and the evolution of a highly redundant strain field. Measurement of the deformed chip thickness with the digital micrometer was complicated by the small size of the chips and by convex curvature on the portion of the chip with no media. The quantitative values of strain shown in Fig. 4 were cross compared with calculations based on chip ration using deformed length (since volume is conserved, the chip length - undeformed and deformed - can also be used to estimate strain for the shear plane model).The average shear strain for the test conditions with no SA media present is γ=13. The presence of the surface media reduces the average deformation strain to γ=8.7. The mechanochemical effects on the deformation mechanics are quite evident. The reduction in strain was expected as a direct result of the reduced cutting forces observed with the presence of the SA media.



Media	rake agle $\alpha = +20^{\circ}$ (radians)	undeformed chip h_o (mm)	deformed chip, no SA h_c (mm)	chip ratio, no SA $\lambda = h_o/h_c$	deformed chip, SA h_c (SA)	chip ratio SA $\lambda_{SA} = h_o/h_c$	shear strain - no SA γ	shear strain - SA γ_{SA}
Glue-stick	0.349	0.050	0.610	0.082	0.415	0.120	12.3	8.2
Sharpie	0.349	0.050	0.639	0.078	0.420	0.119	13.0	8.3
Honey	0.349	0.050	0.656	0.076	0.445	0.112	13.3	8.9
Pine sap	0.349	0.050	0.650	0.077	0.465	0.108	13.2	9.3

Figure 4 Summary of deformation strains showing the effect of SA media on the shear strain



(a) Glue stick (b) Honey

Figure 5. Deformed Cu chip from cutting test with (a) Glue stick and (b) bee's honey for SA media. The SA is on the right-hand side of the chip in the images. At the center of the chip the deformation mechanics change, decreasing the deformed chip thickness, h_c, and the outside surface of the deformed chip is altered. The SA media is intact on the deformed surface in these images. Scale-bar 2.5mm

Figure 5 shows the image of the chip collected from cutting with bee's honey applied to the surface. The chips from all four media tested showed this same appearance. The portion of the chip with no media present (first 50mm of cut length) reaches significantly higher deformed thickness (Fig. 4) and exhibited much more pronounced surface features and ridges which are characteristics of the sinuous flow phenomena. The portion of the chip with media present (last 50mm of cut length) was the second half of the cut-length. The maximum thickness of the deformed chip without SA media reached an average of h_c=0.64. As can be observed in the top view of the chip (Fig. 5) there is a distinct change in the chip morphology when the deformation zone reaches the SA media. Consistent with the reduction in the cutting forces, the deformed chip thickness decreases by nearly 30%. With any of the four SA media present, the mechanochemical effect reduces the deformed chip thickness to an average of h_c=0.44. The reduced forces and strain field that develop when the sinuous flow is suppressed by the mechanochemical effects of the SA media is also manifested in a deformed chip surface (originally the surface of the workpiece) that is more continuous and smooth. The surface ridges are much smaller in amplitude and the surface contains significantly fewer visible features compared to the surface cut in the absence of SA media.

4. Conclusions

The cutting tests and analysis confirm that the experimental configuration demonstrates results consistent with recent published research on SA media influencing the mechanochemical effects in cutting of pure Cu with permanent marker ink (sharpie) and glue stick [1,2]. Importantly, the results confirm our original hypothesis that natural "sticky" media – honey and tree sap – would have strong adhesion to the workpiece surface and exhibit reduced forces and strain during deformation indicative of a plastic flow transition and an operating mechanochemical effect. The results confirm that the inherent "stickiness" of bee's honey and pine tree sap enable them to adsorb with the workpiece surface and suppress the otherwise sinuous flow that would occur during the plastic deformation in cutting.

The results indicate that natural media – bee's honey and pine tree sap –offer a totally new framework for improving cutting of "gummy" metals. Since both bee's honey and tree sap occur in nature, they have unique benefits as SA media when compared to the previous research using benign household chemicals. Moreover, in industrial applications, the bee's honey and pine tree sap media could provide a unique alternative to metal working fluid formulations that rely on processed oils or chemical compounds that can be expensive to manufacture, difficult to disposition, and introduce unknown or harmful effects to the environment. The study was conducted at cutting speeds (V_o) 20X higher than many previously reported results, providing further evidence that mechanochemical effects can operate at industrial scale machining conditions. An experimental framework with a rotating workpiece is underway to access cutting velocity approaching V_o~1-3 meters/sec. This will enable additional cutting tests with bee's honey and pine tree sap across a range of industrial conditions while measuring their relative effectiveness in reducing the force and strain (high strain and strain-rate deformation).

We are currently investigating the chemical composition of bee's honey and pine tree sap to determine if an individual component present in both media could be triggering the mechanochemical effect. For example, honey is composed of fructose, glucose, water, and a small percentage of organic and aromatic acids [4]. A series of complimentary cutting tests is planned with bee's wax as a SA media to investigate the presence of the mechanochemical effect in a media directly related to the bee's honey. In addition, we are developing the experimental platform for tracking the deformation velocity field using particle image velocimetry techniques (PIV) that will enable the deformation velocity, strain and strain rate field to be elucidated *in-situ* during the cutting process using digital imaging and image correlation techniques [5,6].

5. Acknowledgements

The authors want to recognize and thank the University of West Florida, Office of Undergraduate Research, for an undergraduate grant award that supported aspects of this work and our participation at the NCUR 2019 Conference. In addition, the authors would like to express our appreciation to Kennesaw State University for hosting the 2019 Conference which provided a forum for our team to present this research.

6. References

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