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Experimental Determination of Large Strain Localization in Cut Steel Chips

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Abstract**—**Metal cutting is a severe plastic deformation process involving large strains, high strain rates, and high temperatures. Conventional analysis of the chip formation process is based on bulk material deformation disregarding the inhomogeneous nature of the material microstructure. A series of orthogonal cutting tests of AISI 1045 and 1144 steel were conducted which yielded similar process characteristics and chip formations. With similar shear angles and cut chip thicknesses, shear strains for both chips were found to range from 2.0 up to 2.8. The manganese-sulfide (MnS) precipitate in the 1144 steel has a very distinct and uniform shape which allows for comparison before and after chip formation. From close observations of MnS precipitates in the cut chips it is shown that the conventional approach underestimates plastic strains in metal cutting. Experimental findings revealed local shear strains around a value of 6. These findings and their implications are presented and discussed.

Keywords**—**Machining, metal cutting, microstructure, plastic strains, local strain.

I. Introduction

The metal cutting process involves the removal of material in the form of a chip from a workpiece. The actual removal process is a shearing process where the workpiece material is sheared by a tool with a geometrically defined cutting edge. From Fig. 1, the two primary faces of the cutting tool are the rake and flank faces, which together meet to form the cutting edge. In its simplest form, the cutting process resembles concentrated shear along a distinct plane commonly referred to in metal cutting as the shear plane. The direction of shearing occurs at an angle relative to the cutting plane (referred to as the shear angle - ϕ) and the tool or workpiece moves with some predetermined cutting velocity.

Machining is a severe plastic deformation process involving large plastic strains (>1), very high strain rates ($>10^{-4}s^{-1}$), and elevated temperatures in excess of half the melt temperature of the metal being machined. While machining of metals is not a new process and widely utilized in shaping raw materials, the conditions under which metal cutting occurs are unique. As the workpiece material approaches and passes through the shear plane it undergoes a substantial amount of plastic strain.

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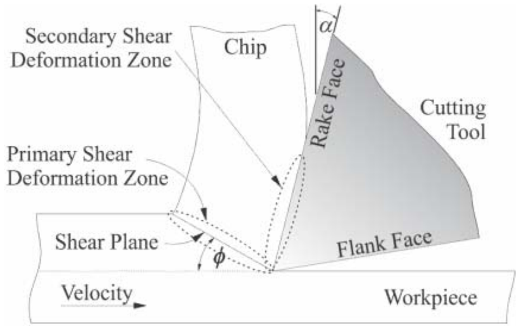

Fig. 1 General orthogonal cutting configuration highlighting two shear deformation zones, shear plane, and shear angle

The bulk of the material then flows as a chip, continuing to strain extensively along the contact length between the chip and the tool rake face in the secondary shear deformation zone. While the cutting process can take place in many different forms, one of the most widely recognized, modeled, and understood forms of metal cutting is the orthogonal metal cutting process from Fig. 1, which can easily lend itself to being modeled as a two dimensional plane strain process [1].

Depending on workpiece material and cutting parameters such as cutting speeds and feedrates, different chip formation types are possible from the classical continuous, continuous with a built up edge (BUE), and discontinuous chips [2], to cyclical, continuous chips [3]-[6], and segmental chip formations [7]-[12]. Continuous chip formation is not a desirable result from a production standpoint as these severely work hardened chips can damage the machined surface, and will require constant supervision and manual removal from the work or cutting area. However, continuous chips are ideal for analyzing the machining process and in particular, the plastic deformation process in the different deformation zones during the chip formation process.

Generation of a continuous chip during orthogonal metal cutting has been a staple for researchers analyzing the metal cutting process given the two-dimensional nature of the process and plane strain condition of continuous chip formation in orthogonal cutting. By analyzing the cut chip microstructures using optical and scanning and transmission electron microscopy (SEM and TEM, respectively), geometric features of the cutting process such as identification of the shear deformation zones and the shear plane and shear angle, can be readily observed. From this, plastic strains, strain rates, and even temperatures in the shear deformation zones can be determined analytically. Merchants theory [13], [14], Lee and

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Shaffer's triangular slip line field [15], and Oxley's parallel-sided shear zone theory have all been based on orthogonal cutting and the formation of a continuous chip [16]-[19].

The plastic strains of a cut chip are determined by comparing the workpiece material before and after the cutting process (via the chip). Treating the material structure as a homogeneous one, the resulting deformation in the primary and secondary shear deformation zones can be determined through analysis of the mechanics of the cutting process and knowledge of the constitutive law that governs the workpiece materials mechanical properties under cutting conditions. It is believed that this approach underestimates the actual plastic strains that occur during metal cutting throughout the cut chip cross-section [20]. Adding to this speculation, is has been shown that as the scale of cutting decreases to the microscale, the heterogeneous structure of a metals microstructure has a significant effect on the chip formation process. At a scale corresponding to the grain size of 1045 steel, Simoneau, Ng, and Elbestawi showed that local strains could be 2-3 times larger than the strains predicted by the bulk measurement approach and that not only did this have an impact through the cut chip but also along the machined surface [21], [22]. This same effect was shown for conventional cutting across multiple scales of cutting and for different grain structures and sizes [23]. While it is hypothesized, and numerically shown that the strains in metal cutting at a conventional macroscale are underestimates of the actual shear strains which result from the materials heterogeneous structure, it has not been shown experimentally and is thus the aim of the current work.

II. Experimental

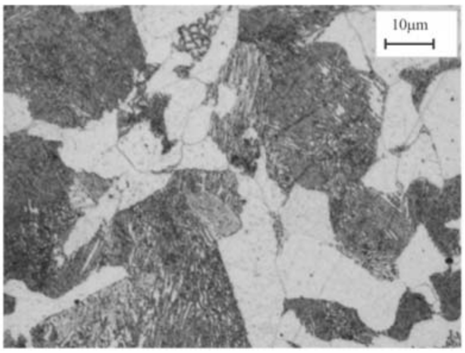
A. Cutting Test

A series of orthogonal cutting tests were performed on a Haas CNC Lathe. At cutting speeds of 100, 200, and 300m/min, feedrates of 0.05, 0.1, 0.2, and 0.3mm/rev were used to generate a series of continuous chips. These tests were performed for both AISI 1045 and AISI 1144 steel. In all cases the rake angle was 0 degrees the clearance angle was 11 degrees, and all cutting was done dry without the use of any coolant. After each cutting test the cutting insert was indexed to ensure that a new cutting edge was used for each series of cuts. While not a focus in this body of work, cutting forces were measured and recorded using a 3-compenent piezo-electric force dynamometer in conjunction with the LabView data acquisition system. After each cutting test the resulting chip was collected for analysis.

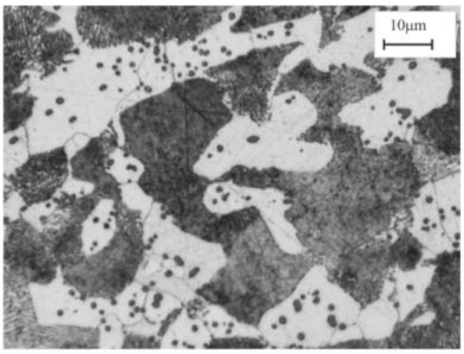
B. Workpiece Materials

AISI 1045 and 1144 steel were the two materials orthogonally machined for the study. The 1045 steel was used because of the already extensive research that has been done with this steel [20]-[24], and the 1144 steel was used to highlight how strain localizations could be determined using the material microstructure. These two steels have a similar microstructure as shown in Fig. 2. As well, the two are similar in terms of carbon content and overall mechanical properties. Both material microstructures are predominantly comprised of pearlite (dark grans in Fig. 2) and ferrite (light grains in Fig. 2). The difference between the two is that 1144 is a resulfurized steel, it has the same carbon content, but the sulfur and manganese content have both increased. The increase in sulfur and manganese is enough to cause a manganese sulfide (MnS) precipitate to form in the microstructure. These precipitates are easily identified as small circular precipitates in the ferrite grains as shown in Fig. 2 (b).

The addition of sulfur and manganese improves the machinability of the steel compared to 1045, which is a direct result of the MnS precipitates. These precipitates help to promote chip breaking and rather than continuous chip formation, a discontinuous chip is formed. Essentially, machinability and processing is improved without sacrificing material performance.



(a)



(b)

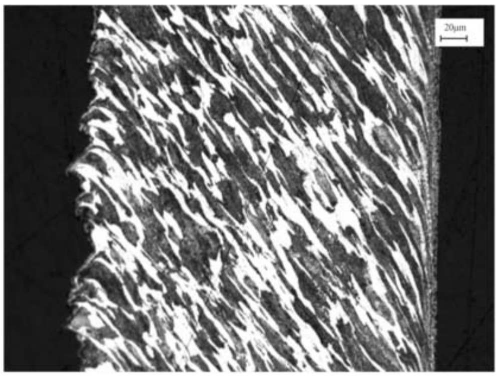
Fig. 2 Microstructure of (a) AISI 1045 steel and (b) AISI 1144 steel, Pearlite-ferrite (dark-light grains respectively) structure in both cases, but for the 1144 steel, MnS precipitates are present in the ferrite grains

C. Sample Preparation and Microscopy

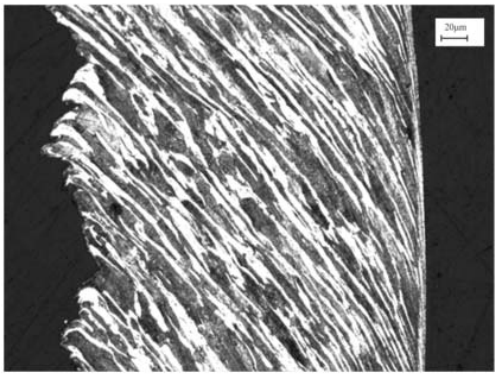
Following the cutting tests, the resulting cut chips were cold mounted in an epoxy and polished to a 3 micrometer finish. A 2% Nital etch was used in all cases to bring out the microstructure of the deformed chips for observation using both optical and scanning electron microscopy (SEM).

III. Results and Discussion

In all of the machining trials a continuous chip was generated. This was an important and necessary requirement to ensure that a proper comparison of AISI 1045 and 1144 steel cut chips could be done. Similarly it was also a necessary requirement to ensure that a proper analysis of the plastic strains through the chip cross-sections could be determined. The resulting chip cross-sections in Fig. 3 highlight that there is a clear and discernible direction of shearing that results from the workpiece material passing through the primary shear deformation zone during the cutting and chip formation process. As well, there is also a thin shear deformation zone (secondary shear deformation zone) that is observed along the back surface of the chip which relates to the tool-chip interface and the sliding contact between the cut chip and the cutting tool rake face.



(a)



(b)

Fig. 3 Cut chip cross-section of (a) AISI 1045 steel and (b) AISI 1144 steel. The distinct direction of shearing throughout the chip cross-section and a thin secondary shear zone along the back of the chip are evident. Cutting speed *V* = 200m/min, feedrate = 0.3mm for both chips

By creating a continuous chip under orthogonal cutting conditions the chips can be sectioned so that the center of the chip can be analyzed. Due to the nature of orthogonal cutting and the mechanics of continuous chip format, the center of the cut chip deforms under plane strain conditions when the width or depth of cut is sufficiently larger than the uncut chip thickness. To ensure plane strain conditions the depth of cut should be an order of magnitude larger than the uncut chip thickness. As a result the depth of cut was set to 3mm for all of the machining tests.

Based on the cut chip cross-sections the shear angle ϕ is determined based on the ratio of the uncut to cut chip thickness (chip ratio r) and the rake angle α, of the cutting tool from (1).

$$\phi = \frac{r\cos\alpha}{1 - r\sin\alpha} \qquad (1)$$

The shear angles for both 1045 and 1144 steel were very close to each other as shown in Fig. 4. Both materials generated similar chip forms, and given the similarity in material properties and microstructure, these results are not unexpected.

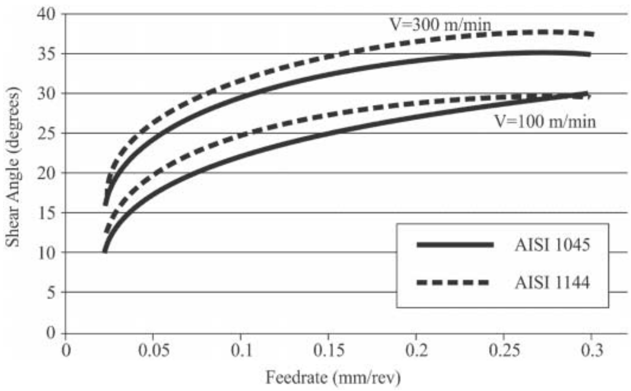


Fig. 4 Shear angle measurements for both materials based on the chip ratio as determined from the cut chips

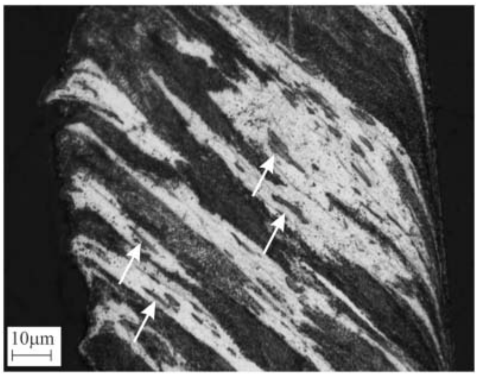
Equation (2) uses the shear and rake angles from the cutting process to determine the shear strain γ, which relies on continuous chip formation and is a function of the geometry of the chip formation process. This shear strain is the strain across the chip cross-section and is only a measure of the plastic strain as a result of material passing through the primary shear deformation zone.

$$\gamma = \frac{\cos\alpha}{\sin\phi\cos(\phi - \alpha)} \qquad (2)$$

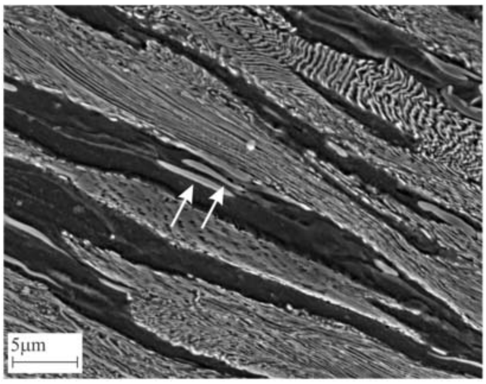
For a cutting speed of 300 m/min, the shear strain values for the cut chip were found to range from 2.1 up to 3.0 which falls into the same range observed by other researchers [20]-[24]. These strain measurements were consistent for both 1045 and 1144 steel. These shear strain values only represent the shear strains as a result of the deformation which occurs as a result of passing through the primary shear deformation zone only.

Determination of the shear strains using (2) simply treats the material as a homogeneous structure before and after the chip formation process and it ignores any affects that the heterogeneous structure of the material might have. In particular, any shear strain localizations that might be prevalent are not taken into account and the result is a potentially under-estimated shear strain value.

Close examination of the MnS inclusions in the 1144 cut chips reveals that shear strains at a local level are much larger. Using optical and scanning electron microscopy, Fig. 5 highlights the MnS precipitates that have deformed into long oblong or elliptical shapes as a result of passing through the primary shear deformation zone. Analyzing these precipitates it is apparent that the conventional approach to treating the deformed chi as a single homogeneous structure to determine the shear strains resulting from the chip formation process do indeed underestimate the actual shear strains that occur throughout the microstructure.



(a)



(b)

Fig. 5 A close-up of deformed MnS inclusions through the chip cross-section using (a) optical microscopy, and a higher magnification (b) SEM image of deformed MnS inclusion. Cutting speed was V = 300m/min

Attempts to identify local plastic strains throughout the chip cross-section are extremely difficult. This is due to the fact that in order to properly measure plastic deformation some initial geometry or frame of reference across the uncut chip thickness is required. At the same time that same point or frame of reference must be discernible after the cutting process. There are two manners in which this can be achieved. The first requires placing a grid or geometry on the material and observing that deformed geometry before and after cutting. Unfortunately this cannot be used because it means that instead of examining the middle of a chip cross-section, the edge of the chip must be used as a frame of reference. Hence plane strain conditions cannot be maintained and the analysis is no longer valid. The other approach is to of course use the material microstructure as the geometrical frame of reference. Again this poses difficulties simply because of the irregular and random nature of a materials microstructure such as 1045 steel. As well, it is not possible to view the microstructure ahead of the cutting tool and keep track of it without sectioning the workpiece material prior to cutting and rendering the plane strain condition cannot unmaintainable.

To overcome the previously stated obstacles, the MnS precipitates are treated as circles prior to the deformation process. This simplification is not that far from the actual microstructure as shown in Fig. 2 (b). Given the plane strain conditions of orthogonal cutting, and the fact that material will deform along the shear plane as it passes through the primary shear deformation zone, the deformed, oblong shape of the MnS precipitate can be related back to its original shape.

There are two potential methods for relating the deformed to undeformed MnS precipitate in the 1144 steel during the chip formation process. The first is to determine the original diameters of the MnS precipitates and use a statistical average for the overall undeformed MnS precipitates. Using this same approach for the deformed precipitates the two averages could be compared to obtain a crude estimate of the shear strain of the MnS precipitates. This approach is difficult, tedious, and would be highly inaccurate, representing a very rough estimate at best. A second method is to analyze and measure only the deformed MnS precipitates. By treating the deformed MnS precipitates as a deformed circle – an ellipse, the major and minor axis of the ellipse can be used to find the cross-sectional area of the deformed MnS precipitate which can then be translated back to an undeformed MnS precipitate as illustrated in Fig. 6. With the undeformed and deformed MnS precipitate dimensions known, the shear strains can then be determined.

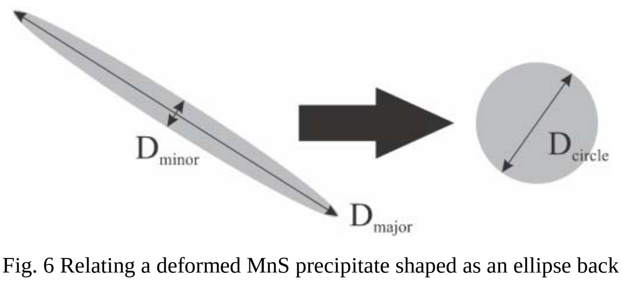


Fig. 6 Relating a deformed MnS precipitate shaped as an ellipse back to an undeformed circular MnS precipitate

Only the precipitates located along the midpoint of the cut chip thickness were examined in order to maintain some level of consistency as to location of inclusions as they passed through the primary shear deformation zone. This was done to ensure that the examined precipitates were all passing at or near the same point in the primary shear deformation zone, and it was done to ensure the precipitates near the chip free surface or close to or inside the secondary shear deformation zone were not considered because it is highly likely that the plastic strains are not consistent across the cross section of the cut chip thickness.

The transformation from a circular shape to an ellipse was assumed to involve deformation along the shear plane only. Any possibility of rotation of the precipitate or surrounding grains was ignored. While the deformation process is not physically an instantaneous process, it is treated as such since the thickness of the primary shear deformation zone is on the same order in size as the MnS precipitates. During the continuous chip formation process in orthogonal cutting deformation in the primary shear zone occurs along a plane. This deformation zone does have a finite thickness, which has been previously determined by [16]-[18] to be a ratio of the uncut chip thickness t, to the thickness of the shear zone Δs and the shear angle ϕ. With the shear angle known and the uncut chip thickness being the feedrate of the cutting process, the thickness of the primary shear zone can be found using (3).

$$\frac{t}{\Delta s \sin\phi} \approx 10 \tag{3}$$

Using the approach of relating the deformed to undeformed MnS precipitate cross-sectional areas the resulting shear strains were found to range from 5.97 up to 6.8 for a cutting speed of 300m/min. While these shear strain values are simply estimates, they demonstrate that a significant discrepancy exists between the global shear strain values obtained by treating the cut chip as a bulk deformation process, and the local shear strain values which are based on the heterogeneous structure of the material.

The treatment of the cut metal chip as a homogeneous structure underestimates the shear strains by 2 to 3 times. This is significant when considering the size of the shear strains and their potential impact on the dynamics behavior of the workpiece material as it plastically deforms. The shear strain determination impacts shear strain rates and temperature predictions during the metal cutting process.

Previous works in numerical simulation that have considered and compared the strains resulting from homogeneous versus heterogeneous microstructures have demonstrated that a large discrepancy exists between the two when analyzing the plastic strains. This however, has not been demonstrated experimentally in metal cutting.

Any numerical comparisons to date have focused on AISI 1045 steel which is the rational for its use in the current study. It produced similar shear strains as 1144 steel when treated as a bulk deformation of a homogeneous material. However in previous numerical simulations, large plastic strains have been observed throughout the chip cross-section on the order of 4 through 6. Again, this has only been done through numerical simulation. However, given the similarity of the AISI 1144 steel microstructure to that of AISI 1045, it is a reasonable conclusion that the localization effects observed during the cutting of 1144 steel would also occur in 1045 steel.

IV. Conclusions

Determining the strains in metal cutting by treating the material as a homogeneous structure during the chip formation process will lead to an underestimation of the actual plastic strains encountered during the chip formation process. This fact has been demonstrated using numerical simulation but until this point had not been shown experimentally in metal cutting. When considering the localization affects that are prevalent as a result of a workpiece materials microstructure, shear strains can in actuality be 2 to 3 times larger than previously thought. Of course the impact of this is that in simulation work, the constitutive laws used to model the dynamic behavior during large deformations may need to be reworked in order to better replicate and illicit information from processes such as metal cutting.

These localization effects will not be limited to the midsection of the cut chip thickness, and will of course be prevalent throughout the cut chip cross-section. The amount of localization and subsequent magnitude of the shear strains will likely vary across the cut chip. At or near the chip free surface the shear strains may be similar to the values obtained when treating the material as a homogeneous one. As shown in the current work, in the middle of the cut chip shear strains may increase by a factor of 2 to 3. However, as we approach the secondary shear deformation zone this increase could be substantially more.

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