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Effect of Finite Edge Radius on Ductile Fracture Ahead of the Cutting Tool Edge in Micro-Cutting of Al2024-T3

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Abstract:

Evidence of ductile fracture leading to material separation has been reported recently in ductile metal cutting (Subbiah and Melkote, ASME J. Manuf. Sci. Engg, Vol. 28, No. 3, 2006). This paper investigates the effect of finite edge radius on such ductile fracture. The basic question of whether such ductile fracture occurs in the presence of a finite edge radius is explored by performing a series of experiments with inserts of different edge radii at various uncut chip thickness values ranging from 15 to 105 μm . Chip roots are obtained in these experiments using a quick-stop device and examined in a scanning electron microscope. Clear evidence of material separation is seen at the interface zone between the chip and machined surface even when the edge-radius is large compared to the uncut chip thickness. Failure is seen to occur at the upper, middle, and/or the lower edges of the interface zone. Based on these observations, a hypothesis is presented for the events leading to the occurrence of this failure when cutting with an edge radius tool. Finite element simulations are performed to study the nature of stress state ahead of the tool edge with and without edge radius. Hydrostatic stress is seen to be tensile in front of the tool and hence favors the occurrence of ductile fracture leading to material separation. The stress components are, however lower than those seen with a sharp tool.

Keywords: Edge radius, ductile fracture / failure, micro-cutting.

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1. Introduction

Mechanical micro-cutting operation is a viable method to manufacture small parts, and parts with small intricate features, and to generate very fine surface finishes needed in many products such as medical and optical devices. A basic understanding of the micro-cutting process is needed to better predict the effects of this operation on the newly formed surface geometry and its integrity, both of which directly affect part performance. One of the challenges in micro-cutting is to understand the scaling effects involved, particularly the increase in specific cutting energy [1, 2] as the uncut chip thickness is decreased (referred to as the size-effect). Specific mechanisms such as material strengthening due to the lack of defects [1, 3], strain-rate hardening [2], lack of temperature softening [4, 5], strain-gradient hardening [6, 7], extension of the shear plane into the workpiece [8] have been cited as reasons for the increase in specific cutting energy. The energy associated with material separation leading to new surface creation has hitherto been considered negligible as the surface energy of solids is very small. Recently this claim has been disputed [9] and the energy associated with new surface creation attributed to ductile fracture, which cannot be neglected in cutting of ductile metals. Specifically, the work associated with the chip separation criterion in Finite Element simulations of machining is shown [9] to be orders of magnitude different from that associated with surface energy or surface tension, and comparable to fracture toughness values.

The extra plastic flow associated with a non-zero edge radius has also been considered as a reason for the size effect [10-12]. Cutting tools commonly used in machining operations are never ideally sharp but always have some bluntness. The bluntness can often be approximated as a circular radius between the flank and the rake faces of the tool as illustrated in Figure 1. Since the tool cutting edge is closest to the root of the developing chip, the edge geometry can be

expected to play a significant role in affecting the deformation processes occurring at the chip-root. This effect of the edge radius has been studied and reported by several researchers. The presence of edge radius is said to cause ploughing ahead of the tool tip. This is described in [13] and illustrated in Figure 1 as the pushing of material in a small portion in front of the rounded portion of the cutting edge, predominantly into the chip and some into the workpiece. This conclusion, derived from a basic understanding of cross-sectional micrographs, implicitly assumes that chip formation is simply one of plastic flow around the tool edge and shear and that there is no explicit material separation that occurs. It has also been interpreted and reported [14, 15], from a study of polished cross-sectional views of the chip root, that there exists a stagnation point in the material flow on the rounded edge of the tool. Above this stagnation point, material is considered to flow into the chip (see Figure 2) while below the stagnation point it is considered to flow into the workpiece to form the newly machined surface.

Based on this understanding of ploughing and the stagnation point concept, several researchers have come up with analytical models for machining [15-17]. Slip line field models incorporating the ploughing-type of metal flow have also been reported [18, 19]. The ploughing mechanism has been attributed to the observed increase in machining forces with tool edge radius and attempts have been made to isolate the ploughing force by extrapolating the forces to zero uncut chip thickness [20]. The effect of tool edge geometry on the force and energy decomposition have been reported in [10]. This experimental study showed that the nominal rake angle and the tool edge profile significantly affect the forces. In another experimental study [21], it was seen that at lower uncut chip thickness values closer to the tool edge radius, the energy consumed in the shear zone alone was unable to account for the size effect in specific cutting energy. This anomaly was attributed to sliding at the tool-work interface and ploughing.

Ploughing and the use of plastic flow around the tool edge radius have also been used in numerical simulations of chip formation in the machining process. The popular finite element software DEFORM[®] uses the concept of dynamic remeshing to simulate flow around the tool edge [22]. Other researchers have also used similar remeshing concepts to simulate chip flow around the tool edge [23, 24]. Such dynamic remeshing completely avoids the use of any chip-separation criterion. Finite element simulations using a chip separation criterion and incorporating an edge radius in the tool is reported in [25]. But the edge radius used is considerably smaller than the uncut chip thickness values reported. The presence of the edge radius becomes more important when its size is comparable to the uncut chip thickness.

It is clear that the concept of ploughing and stagnation point is one interpretation of what is commonly observed in a cross-sectional micrograph of the chip-root. The literature, however, does not say what causes the material to separate above and below this so-called stagnation point (see Figure 2). Very little proof of actual material separation by fracture (e.g. cracks) is available in ductile machining. However, many researchers [26, pp. 384-386] have acknowledged that there has to be some form of localized fracture in chip formation leading to material separation. Some researchers [26, 27] have indeed shown the presence of cracks ahead of the tool in machining low carbon steel and other ductile metals. While the presence of cracks is shown, it is not clear if chip formation occurred by material fracture. In other words, these cracks may have been produced after chip formation. Recently [28-30], it has been shown that ductile fracture leading to material separation and chip formation is observed at low and high cutting speeds in Al2024-T3 and OFHC-Cu using “up-sharp” cutting tools (see Figure 3) and the energy for material separation has been shown to be important at smaller uncut chip thickness values. Note that the phrase *ductile fracture* is used in this paper to represent ductile failure, ductile tearing or

ductile separation of material into two surfaces. The natural question then is if such a material separation also occurs with a blunt tool i.e. one with a finite edge radius. A logical extension would then be to study the chip-root created by tools with finite edge radius. Such a study can clarify the nature of material separation leading to the separation of flow above and below the so-called stagnation point.

Hence, this paper reports on an experimental investigation of material separation using tools of finite edge radii. Experiments are performed using inserts of several edge radii and chip-roots obtained using quick-stop device are used to examine for the occurrence of ductile fracture in a scanning electron microscope (SEM). Finite element simulations are used to study the nature of stresses immediately ahead of the cutting tool to determine if conditions are indeed favorable for the occurrence of ductile fracture.

2. Experimental Setup

2.1 Experimental Conditions

Orthogonal cutting experiments were performed by axially plunging a tool whose cutting edge is lined up with the centerline, into a tube shaped workpiece made of an aluminum alloy (Al2024-T3) (see Figure 4). The tube is 0.89 mm thick and its outer diameter is 38.1 mm (1.5 inches). A polycrystalline diamond (PCD) grooving insert with the following geometry is used: +5° rake angle, 3.18 mm wide (Kennametal NGP3125R). The tool holder used is Kennametal NEL-123B-NJ3. The inserts have a clearance angle of 11°. The cutting edge radius of the insert was measured using an edge qualifier system [31]. A sample edge trace of one of the inserts is shown in Figure 5. Inserts with three edge radii were used: 38 μm (case A), 50 μm (case B), and 75 μm (case C). For comparison purposes, experiments were also run with an up-sharp tool with

an edge radius of 12.5 μm (case D). The uncut chip thickness (t_o) values used for each of these inserts is summarized in Table 1.

The nominal composition of Al2024-T3 used is given in Table 2. The cutting speed was kept fixed at 150 m/min. The values of uncut chip thickness were chosen to yield t_o/r (t_o is the uncut chip thickness and r the edge radius) ratios of 0.67, 1, and 1.33. Cutting forces were measured for all tests in a separate setup without the quick stop device (described below) using a quartz 3-component Kistler 9527B dynamometer.

2.2 Quick Stop Device

In order to observe the root of the chip as it is forming at the specified cutting speed, the cutting action has to be stopped suddenly to “freeze” the chip and its root. This is commonly achieved using a quick-stop device where the tool or the workpiece is suddenly drawn away from each other to stop the cutting action. A sketch of the device operation is given in Figure 6. During the experiments, a machining cut is initiated and when steady-state cutting action is reached, a hammer blow imparted to the top of the tool holder causes the shear pin to break by fracture at the notch causing the tool holder to swivel out quickly because of the spring action and the hammer velocity. This “freezes” the cutting action and the chip remains attached to the workpiece. Similar quick-stop devices have been used and reported in the literature [29, 32]. The initial acceleration of the retracting tool holder and hence the cutting insert was measured to be $1.65 \pm 0.15 \times 10^3 \text{ m/s}^2$. This is considered sufficient for the purpose of this study.

2.3 SEM Sample Preparation and Viewing

After the chip is frozen, the chip root sample is removed from the workpiece using the wire-EDM process (Figure 7). Traditionally chip-observation is performed by mounting the chip-root in an epoxy-polymer base (for convenient handling), is then ground and polished to produce a very smooth surface. This surface is subsequently etched using chemical solutions (such as 2% Nital for steels) that are likely to bring out the structure of the workpiece material and then photographed in an optical microscope. A different method is adopted here. The chip-root is cleaned and mounted on a double-sided conducting tape that is then mounted on a SEM sample holder without any polishing or etching (Figure 7). The chip-root sample is mounted so as to facilitate the electron beam to focus directly on the interface between the chip and workpiece.

3. Chip-Root Study Results

3.1 Force measurement results

The measured cutting and thrust forces along with one-sigma error bars (based on three repetitions) are plotted as a function of uncut chip thickness in Figure 8. The cutting and thrust forces increase with uncut chip thickness. The maximum differences in forces can be seen for the up-sharp case and 75 μm edge radius (cases C and D) with the latter yielding higher forces. The difference in forces is higher in the thrust direction than in the cutting direction. Less difference in forces, both cutting and thrust, can be seen for cases A and B (37 μm and 50 μm edge radii). There is also a notable difference in the thrust force between case A (or B) and C or D, more so with case C than with Case D.

3.2 Results of SEM Observations

The chip-root interface was observed in an SEM to study the nature of the interface and to check for the presence of any ductile tearing/fracture. A sketch of the observed chip-root interface with a finite edge radius tool (cases A, B, and C) is shown in Figure 9. There is a zone of metal seen at the interface. Three areas in this zone are depicted by labels L, M and U in the figure. The area marked U refers to the upper edge of the zone that is attached to the underside of the chip. The area marked M is the middle of the zone and the area marked L is the lower edge of the interface closer to the machined surface.

In the test samples observed, ductile fracture is observed in all three areas, sometimes even within the same sample. Consider case A of the tests performed with a $38\text{ }\mu\text{m}$ edge radius tool. The SEM micrographs for sample A1 ($t_o = 68\text{ }\mu\text{m}$, $r = 38\text{ }\mu\text{m}$) where the uncut chip thickness is higher than the edge radius is shown in Figure 10. The zone of metal in the interface can be clearly seen. The evidence of ductile tearing in area M can be seen in the lower set of micrographs. In the upper set of micrographs the lifting of the material in area L can be clearly seen. Underneath this lifted material, evidence of ductile tearing is observed (see middle picture on right). There is no evidence of material separation in area U of this sample.

For the case where the uncut chip thickness is comparable to the edge radius, sample A3 ($t_o = 37\text{ }\mu\text{m}$, $r = 38\text{ }\mu\text{m}$) the SEM micrographs are shown in Figure 11. Here one can see evidence of material separation in the upper edge, U, and the lower edge L of the interface zone. The interface zone surface in the middle also seems to exhibit the characteristics of a surface that has undergone ductile fracture. For the case where the uncut chip thickness is lower than the edge radius, sample A5 ($t_o = 15\text{ }\mu\text{m}$, $r = 38\text{ }\mu\text{m}$) the SEM pictures are shown in Figure 12. Here, there is clear evidence of material separation in the lower edge of the interface zone. In this case

also the surface of the interface zone seems to be a torn surface with dimples that are characteristic of ductile fracture.

One obvious question that can be raised is if the interface zone observed is a built-up edge or not. Based on literature of cutting aluminum alloys [33], built-up edge is observed only at lower cutting speeds (< 30 m/min) and is usually not seen while cutting with a diamond tool. Also, the built-up edge usually occurs over a region on the rake face much higher than the uncut chip thickness. The interface zone seen in the micrographs shown in this paper is smaller than the uncut chip thickness. In addition, the machined surface should also exhibit strong evidence of built-up edge formation; such evidence was not found in present study.

Consider now the cases with the highest edge radius of $75\text{ }\mu\text{m}$. Evidence of ductile tearing in area M, can be seen in sample C1 ($t_o = 105\text{ }\mu\text{m}$, $r = 75\text{ }\mu\text{m}$). The chip (in the first figure on the left of Figure 13) was broken while handling during the wire-EDM process. The interface zone is again clearly visible and ductile separation by tearing can be seen in the right most micrograph. As is evident, no separation seems to occur in the upper edge, U, or the lower edge, L, of the interface. For the case where the edge radius is comparable with the uncut chip thickness, sample C3 ($t_o = 75\text{ }\mu\text{m}$, $r = 75\text{ }\mu\text{m}$), the SEM micrographs are presented in Figure 14. It is clear from these micrographs that material separation occurs in all three regions, viz., the lower, middle and upper edges of the interface zone. Finally, for the case of uncut chip thickness smaller than the edge radius, sample C5 ($t_o = 50\text{ }\mu\text{m}$, $r = 75\text{ }\mu\text{m}$), the SEM micrographs are presented in Figure 15. In this case the interface zone is clearly visible. Also, material separation was seen at the lower and upper edges, with one area in the upper edge showing clear of evidence of ridges characteristic of a ductile fractured surface. There was no evidence of material separation in the middle of the interface zone.

Case B was very similar to case A and hence, the micrographs associated with this case are not presented here. The SEM micrographs for the up-sharp tool (smallest edge radius of 12.5 μm) samples D1 ($t_o = 105 \mu\text{m}$, $r = 12.5 \mu\text{m}$), D3 ($t_o = 75 \mu\text{m}$, $r = 12.5 \mu\text{m}$) and D5 ($t_o = 50 \mu\text{m}$, $r = 12.5 \mu\text{m}$) are shown in Figure 16. For the case of the up-sharp tool a very small interface zone was seen. Here, evidence of material separation is seen at the bottom of the of the interface zone where it seems to be attached to the machined surface. This form of ductile separation in an area close to the machined surface is similar to that shown by authors in prior work [28, 29]. These observations are summarized in Table 3.

3.3 Discussion

It is clear from the micrographs described above that there is ductile fracture and material separation involved in the chip formation process even with a cutting tool of finite edge radius. However, ductile fracture is not seen just in one area as in the “sharp” tool case but in several areas in the interface zone. Based on the SEM evidence of the different ductile fracture areas in the interface zone, a hypothesis is presented here as to how the interface zone may form and why fracture is seen in more than one area. The hypothesis is sketched in Figure 17.

Consider a small unit volume of material approaching the tool edge radius. As it reaches the tool edge, it gets wrapped around the edge. As a result of cutting motion, the material is stretched in two directions – one in the direction of the chip motion, and the other in the direction of the workpiece motion (indicated in Figure 17). The stretched material forms the interface zone seen in the SEM micrographs (for e.g. Figure 13). As the cutting motion continues, the pulling action continues in both the directions. There are now three possibilities. One, the pulling action is equal in both directions and as a result the interface zone separates in the middle area, M, as

seen in sample C1 (Figure 13). Two, the interface zone material is weaker near the upper edge, U, and three, the interface zone is weaker at the lower edge and separates there. As seen in the SEM micrographs, all three possibilities can occur simultaneously (as in sample C3, Figure 14) or in combinations thereof. If the material separation happens only in the middle, then this situation is similar to the formation of a stagnation point as hypothesized in the literature [14, 15]. However, as can be seen from the micrographs this may not always be the case.

4. Analysis of the Stress State Ahead of the Tool

The stress state in the vicinity of the tool edge is fairly complex. In order to effectively model the ductile fracture ahead of the tool, the stress state needs to be determined and this can be done using the finite element (FE) method. However, given the observations of the SEM micrographs and the hypothesis of interface zone formation and multiple locations of fracture, it is difficult to simulate this in a finite element based numerical model. The reason for the difficulty arises in dealing with elements that will fail in different parts of the chip in front of the tool. This is illustrated in Figure 18. In the mesh shown on the left elements are allowed to fail anywhere based upon a given criterion. This exactly simulates real world conditions. However, this results in a problem of handling the deleted element and creation of new surfaces and importantly how to make them establish contact with the tool surfaces. On the contrary, in the mesh on the right side of Figure 18 element failure is restricted to a layer of elements (called the sacrificial layer, since the elements get deleted or sacrificed as they approach the tool edge) and the element failure is orderly and takes place one after another. Hence, it is precisely known which set of surfaces will subsequently contact the tool rake surface and contact conditions can therefore be established appropriately.

Here, a simplified model similar to the mesh on the right will be used to study the stress state in front of the tool in the presence of a cutting tool with a finite edge radius. The important question of whether the stresses ahead of the tool even permit such ductile fracture to occur in the presence of a finite edge radius can be studied using this model. A numerical model that simulates material separation in the form of a sacrificial layer whose elements fail based on a damage criterion is used in this paper.

4.1 Model Setup

Plane strain elements (CPE4RT) were used to model the workpiece and the tool. These are 4-noded quadrilateral elements with reduced integration and hourglass control. The active degrees of freedom in these elements are displacements in the X and Y directions, and temperature. The mesh was generated in ANSYS® and then imported into ABAQUS® (version 6.5). Varying mesh densities were used to minimize the total number of elements and nodes for computational efficiency. The mesh and boundary conditions are shown in Figure 19.

Below the chip layer the workpiece is 0.3 mm deep and 1.0 mm long. The number of elements is around 6500 and the number of nodes is about 6700. The workpiece is constrained on the left, bottom, and right sides, to move horizontally towards the fixed tool at the specified cutting speed. The cutting tool top, right, and bottom (close to the tool tip) are constrained in all directions. The bottom of the tool is constrained to simulate rigid tool conditions without running into noise related to numerical contact.

4.2 Material Property

Among the available forms of material models, the Johnson Cook (J-C) form is widely used and is chosen in this work. There is both a strength component and a damage component in the J-C model. The constitutive equation for the strength of the material is given as [34]:

$$\sigma = (A + B\varepsilon^n)(1 + C\dot{\varepsilon}^*)(1 - T^{*m})$$

where σ is the stress, ε is the plastic strain, $\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0$, the ratio of rate of strain to a reference strain-rate, and T^* is the homologous temperature. The tool is modeled as elastic diamond. The various properties of the Al2024-T3 workpiece and diamond tool are listed in Table 4 and Table 5. The inelastic heat fraction for the workpiece material was fixed at 0.9 i.e., 90% of the energy dissipated by plastic deformation is converted into heat.

4.3 Material Separation and Damage Model

Chip formation is assumed to occur along a narrow zone ahead of the cutting tool edge. The path of ductile fracture is assumed to be straight ahead of the cutting edge. As discussed before, these assumptions are close to what is observed in the SEM micrographs, particularly for tools with a small edge radius. A narrow line of sacrificial elements is modeled and separates the chip region from the work region (Figure 19). When the strain in an element in the sacrificial layer immediately ahead of the tool reaches a critical effective plastic strain value, the element is deemed to have "failed". It is then removed from the mesh, and the process is repeated for the duration of the cut.

The sacrificial layer needs some explanation. The height of the sacrificial layer elements is kept higher than the edge radius of the cutting tool. The reason for this is as follows. If the sacrificial element is less than the edge radius, then, upon element failure when the damage criterion is met, the nodes on the top surface of the element start to climb down and slip

underneath the tool instead of climbing on the rake face and enabling chip formation. This is illustrated in Figure 20. Hence, the sacrificial layer height is a little higher than the edge radius of the tool. A similar approach is reported by [25] although this particular problem was not stated explicitly.

The failure of the element is assumed to occur based on a ductile fracture criterion. The use of this criterion is valid given the experimental evidence of fracture shown before. Several models for ductile fracture in metals are available in the literature [35, 36]. Several fracture models implemented in commercial codes were compared in a recent study [36]. This study did not consider the effects of strain-rate or temperature in evaluating the models. One model studied was the J-C fracture model and the other was the Xue-Wierzbicki (X-W) model. According to the study, the X-W model predicted fracture more accurately than the other models. However, for the case of plane strain, the J-C and X-W models are identical. In the present study the conditions of plane strain (orthogonal cutting) are being simulated. The J-C ductile fracture model is also readily available in ABAQUS[®]/Explicit. Hence, the J-C fracture model is adopted in this work to simulate the ductile fracture immediately ahead of the cutting edge. In addition, the J-C fracture model readily incorporates strain-rate and temperature effects, important in metal cutting. The strain-to-fracture is given by the J-C model as [37]:

$$\varepsilon_f = \left[D_1 + D_2 e^{D_3 \eta} \right] \left[1 + D_4 \ln(\dot{\varepsilon}^*) \right] \left[1 + D_5 T^* \right]$$

The values of the constants for Al2024-T3 are given in Table 4. The expression in the first set of brackets says that the strain-to-fracture decreases as the hydrostatic pressure, σ_m , increases (or becomes tensile). The expression in the second set of brackets represents the effect of strain-rate and the third set of brackets represents the effect of temperature. This model is also attractive

from a computational point of view since it needs information that is already available at each time-step and requires little additional computational time.

This complete J-C fracture model is implemented in ABAQUS[®]/Explicit as a shear failure mechanism. The shear failure mechanism depends on a damage parameter evaluated at the element integration points. When this parameter exceeds a certain value, the element integration point is considered to have failed, and is removed from the model. The damage parameter is defined as,

$$\omega = \sum \frac{\Delta \varepsilon}{\varepsilon_f}$$

where, $\Delta \varepsilon$ is the incremental strain. The use of a damage model has been substantiated before by experimental evidence of ductile fracture ahead of the cutting tool [29].

4.4 Chip-Tool Interaction

The friction characteristic at the tool chip interface is difficult to determine since it is influenced by many factors such as cutting speed, contact pressure, and temperature. The friction model in [38], which reveals that two distinct regions of sliding and sticking on the interface exist, is widely accepted. In the sliding region, the shear stress, s , is a fraction of the normal contact pressure, p . As the shear stress reaches a limiting shear stress value, τ^* sticking occurs and the shear stress equals the limiting shear stress value regardless of the normal contact pressure. The extended Coulomb friction model, expressed in terms of the frictional shear stress, appears to fit the machining problem adequately and has been used successfully by several researchers [25, 39] and is chosen in this work to model the tool-chip interaction.

$$\begin{aligned} s &= \mu p & \text{when } \mu p < \tau^* \\ s &= \tau^* & \text{when } \mu p \geq \tau^* \end{aligned}$$

4.5 Heat Transfer

In the finite element model, heat generation due to plastic deformation and friction at the tool-chip interface is modeled as a volume heat flux. Heat conduction is assumed to be the primary mode of heat transfer, which occurs within the workpiece material and at the tool-chip interface. The heat flux term includes both plastic dissipation and frictional heating. The fraction of dissipated energy converted into heat due to plastic deformation and friction is assumed to be 0.9. Heat generated due to friction is distributed via a weighting factor of 0.5 between the two contact surfaces.

The rest of the paper utilizes model simulation results to analyze the stress state in front of the tool in the presence of a finite edge radius

4.7 Simulations and Results

The model has been validated for cutting with a sharp tool and presented in [29]. It will be assumed that this validation is sufficient for the purposes of studying the stresses and energy distribution. Simulations were performed for a fixed uncut chip thickness of 105 μm and under two tool edge conditions: (i) sharp tool, and (ii) tool with an edge radius of 38 μm . (Higher edge radius conditions are not simulated since the sacrificial layer elements become too tall and ill-defined and also the coarse mesh in this area will make the simulation inaccurate. Simulations with a 12.5 μm edge radius did not give results very different from the sharp tool case). The values of the damage parameter and frictional conditions between the chip and rake face of the tool were kept the same for these two tool edge conditions. The damage parameter value was 3.1, the coefficient of friction μ was 0.2 and τ^* was 20 MPa. These frictional values are consistent

with the validated model under sharp tool conditions. The damage parameter had to be altered to maintain consistent element failure in front of the tool i.e. neither too many elements fail ahead nor is the failure delayed too late before element distortion is severe. The sharp tool and edge radius tool simulations had the same sacrificial layer height.

The contour plots of the von Mises stress for the sharp tool and edge radius tool are shown in Figure 21 and Figure 22, respectively. The stress was analyzed in front of the tool in the sacrificial layer to study the differences between the two cases. A plot of the hydrostatic (mean) stress of the elements in the sacrificial layer directly ahead of the tool is shown in Figure 23. The first notable observation is that even in front of the edge radius tool, the mean stress is positive (i.e. tension) indicating that conditions are favorable for fracture to occur. It can also be seen that the mean stress in front of the edge radius tool is consistently lower than in front of the sharp tool. This is to be expected since the blunt tool imparts more of a compressive stress to the material ahead of it than the sharp tool. The compressive stress causes less favorable conditions for fracture to occur. Similar plots of the three stress components, σ_{11} , σ_{22} , σ_{33} , are shown in Figure 24, Figure 25, and Figure 26, respectively. It can be seen that all three components of the normal stress are consistently lower than those seen in front of the sharp tool. Stress component σ_{11} reaches a negative value (compressive) about 60 μm ahead of the tool edge, while σ_{33} , reaches a negative value a little at around 120 μm for both sharp and edge radius tools. Stress component σ_{22} does not become negative until much ahead in front of the tool (not shown in the plot).

Both simulations were performed from roughly the same starting point and for a fixed length of cut of 0.46 mm. It is thus possible to compare the percentage of energy being expended in different aspects of the chip and workpiece. The aspects of interest are: plastic dissipation in

the chip itself, plastic dissipation in the sacrificial layer, plastic dissipation in the immediate sub-surface of the workpiece and frictional dissipation. A bar graph of these energies as a percentage of the total energy expended is shown in Figure 27. The plot compares these numbers for the sharp tool and the edge radius tool. It can be seen from this plot that in the case of the edge-radius tool a higher percentage of energy is expended in the chip itself. Also a higher percentage of energy is expended in the sacrificial layer. This could be because of the compressive stresses impeding the occurrence of fracture thus requiring more energy to be used to cause fracture leading to chip formation. There is no considerable difference in energy expended in friction for the two tool edge conditions. There is an increase in percentage of energy expended in sub-surface deformation with the edge radius tool. This can be expected because of the extra effort needed to stretch the material, based on the hypothesis presented earlier, and cause fracture to occur.

5. Summary and Conclusions

This paper investigated the presence of ductile fracture ahead of the cutting tool in the presence of a finite edge radius. Orthogonal cutting experiments were performed on Al2024-T3 with tools of different edge radii and several uncut chip thickness values. A quick-stop device was employed to freeze the chip-root. Instead of examining chip-root in the traditional of polishing the cross-section, chip-roots were viewed without any polishing in an SEM and the chip-workpiece interface was viewed directly to detect the presence of ductile tearing. Based on the observations from these set of experiments, a hypothesis was presented for presence of the interface zone of metal and its different fracture regions. Using a finite element model that uses a

sacrificial layer for material separation based on a J-C damage model, the stresses and energy distribution were studied. Some of the main conclusions of this paper are as follows:

1. The chip-workpiece junction consists of an interface zone of metal when cutting with an edge-radius tool. Such an interface is absent in the case of an up-sharp tool (with edge radius much smaller than the uncut chip thickness).
2. The interface zone of metal is seen to fracture at three locations: one, at the upper edge closer to the chip, two, in the middle of the zone, and three, at the lower edge closer to the workpiece surface.
3. In the case of the up-sharp tool, material separation happens only at the lower boundary of the chip where it leaves the workpiece surface.
4. Based on observation, it can be hypothesized that an element of metal approaching the tool edge radius will get wrapped around the edge and then be stretched in opposing directions: in the direction of the chip flow and in the direction of workpiece surface movement. Depending on which area is weaker and how strong these stretching effects are, the element of metal can fracture at the upper, middle and/or the lower edges of the interface zone.
5. The mean stresses in front of the tool are tensile even with an edge radius tool indicating favorable conditions for fracture to occur.
6. All stress components are consistently lower with the edge radius tool than the sharp tool indicating that a sharp tool provides a more favorable condition for fracture to occur.
7. A higher percentage of energy is spent in the sacrificial layer and the sub-surface in the case of the edge radius tool than the sharp tool.

Some implications of these research findings are in the area of improving surface properties generated in machining of ductile materials. Optimum surface and sub-surface properties are important in areas such as ultra-precision machining of optical components and in machining of micro/nano parts. The occurrence of ductile fracture is expected to influence the nature of the surface created and its sub-surface properties. Factors that promote ductile fracture leading to easy material separation and chip formation can result in better surface and sub-surface properties in ductile materials. Such factors include optimizing design of the cutting edge, improvised cutting actions and altering surface properties of the material being cut.

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Figure 1 (a) Sharp tool, and (b) blunt tool causing ploughing (adapted from [13])

Figure 2 Experimental flow field during machining [14]

Figure 3 Ductile fracture evidence: OFHC Cu low speed (left); AL2024-T3 high speed (right) [28, 29]

Figure 4 Orthogonal tube cutting

Figure 5 Sample trace of edge radius [31]

Figure 6 QSD device built: Left – sketch of operation; Right – picture of device

Figure 7 Preparing and mounting SEM sample

Figure 8 Measured cutting and thrust forces

Figure 9 Sketch of chip-root interface with finite edge radius

Figure 10 SEM micrographs of sample A1 ($t_o = 68 \mu\text{m}$, $r = 37 \mu\text{m}$)

Figure 11 SEM micrographs of sample A3 ($t_o = 37 \mu\text{m}$, $r = 37 \mu\text{m}$)

Figure 12 SEM micrographs of sample A5 ($t_o = 15 \mu\text{m}$, $r = 37 \mu\text{m}$)

Figure 13 SEM Micrographs of sample C1 ($t_o = 105 \mu\text{m}$, $r = 75 \mu\text{m}$)

Figure 14 SEM micrographs of sample C3 ($t_o = 75 \mu\text{m}$, $r = 75 \mu\text{m}$)

Figure 15 SEM micrographs of sample C5 ($t_o = 50 \mu\text{m}$, $r = 75 \mu\text{m}$)

Figure 16 SEM micrographs of samples D1, D3 and D5 (up-sharp tool, $r = 12.5 \mu\text{m}$)

Figure 17 Hypothesis of material separation in the interface zone in the presence of finite cutting edge radius

Figure 18 Illustrating the problem of element failure

Figure 19 Mesh used in the finite element analysis

Figure 20 Height of sacrificial layer should be higher than edge radius of tool. Element that has failed is shaded gray.

Figure 21 Simulation of chip formation with sharp tool ($r = 12.5 \mu\text{m}$, $t_0 = 105 \mu\text{m}$, cutting speed = 150 m/min)

Figure 22 Simulation of chip formation with edge radius tool ($r = 38 \mu\text{m}$, $t_0 = 105 \mu\text{m}$, cutting speed = 150 m/min)

Figure 23 Plot of hydrostatic stress in front of the tool tip

Figure 24 Plot of stress component σ_{11} in front of tool

Figure 25 Plot of stress component σ_{22} in front of tool

Figure 26 Plot of stress component σ_{33} in front of tool

Figure 27 Distribution of energy as a percentage of total energy expended

Table 1 Experimental conditions

	Edge Radius	Uncut chip thickness t_o (μm)				
		1	2	3	4	5
A	38	68	50	37	25	15
B	50	90	68	50	34	25
C	75	105	90	75	68	50
D	12.5	105	90	75	68	50
(Notation reference in text: Case A1 refers to a test conducted with $r = 38 \mu\text{m}$ and $t_o = 68 \mu\text{m}$); Case C3 refers to a test conducted with $r = 75 \mu\text{m}$ and $t_o = 75 \mu\text{m}$ etc.)						

Table 2 Nominal composition of Al2024-T3

Element	%
Al	93.5
Cr	0.1 max
Cu	3.8-4.9
Fe	0.5 max
Mg	1.2-1.8
Mn	0.3-0.9
Si	0.5 max
Ti	0.15 max
Zn	0.25 max

Table 3 Location of ductile fracture in interface zone for the various cases

	Edge radius (μm)	Uncut chip thickness case		
		1	3	5
A	38	L, M	L, U	L
B	50	M	L	L
C	75	M	L, M, U	U, L
D	12.5	L	L	L
(L – lower region, M – middle region, and U – upper region, of the interface zone)				

Table 4 Workpiece (Al2024-T3) Properties [40]

Density	2770 kg/m ³
Specific Heat	875.0 J/Kg.K
Thermal Conductivity	121.0 W/m.K
Coefficient of Thermal Expansion	24.7x10 ⁻⁶ /°C
Young's Modulus	73.0 GPa
Poisson's Ratio	0.33
Melting Temperature	502°C
Johnson-Cook Strength Model	A=369.0 MPa, B=684.0 MPa n=0.73, C=0.0083, m=1.7
Johnson-Cook Damage Model	D ₁ =0.13, D ₂ =0.13 D ₃ = -1.5, D ₄ =0.011, D ₅ =0.0

Table 5 Tool Properties (Diamond) [41]

Density (Kg/m ³)	3500
Specific heat (J/kg °C)	471.5
Thermal conductivity (W/m k)	1500
Coefficient of thermal expansion (µm/m °C)	2.0
Melting Temperature (°C)	4027
Young's Modulus (GPa)	850
Poisson's ratio	0.1

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