

Simulation of End Milling on FEM using ALE Formulation

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Abstract: *In end milling, cutting forces and residual stresses need to be precisely predicted in order to improve the quality of the workpiece. Numerical simulation has however not been very successful using the Lagrangian formulation in Finite Element Analysis. This is partly because there is no satisfactory and accurate separation criterion used in the modelling procedure. The results are found to be highly sensitive to the separation criterion used. End milling process simulation by the use of the Finite Element Method was investigated in this paper with an Arbitrary Lagrangian Formulation (ALE). This formulation is gaining more recognition in structural analysis nowadays, due to the combined advantages of both Lagrangian and Eulerian formulations in a single model. One major advantage is that a separation criterion is not required in the formulation. The advantages of this approach are demonstrated in the paper. The cutting forces are obtained in good agreement with experimental data.*

Keywords: *FEM Simulation of Machining; Arbitrary Lagrangian-Eulerian; End Milling; High-Speed Machining; Metal Cutting; Orthogonal Metal Cutting; Cutting force; Separation Criteria; Size Effect.*

1. Introduction

End milling is used in a wide range of manufacturing industries, due to its versatility and its high material removal rate (especially end-mills) in producing parts of desirable dimensions. Prior to production, predictions of different factors such as cutting forces, stresses, temperature etc, are important in selecting the tool material and design and can ensure an efficient machining process. Knowledge of the cutting forces allows for the prediction of tool deflection and wear, workpiece deflection, onset and/or possible regeneration of chatter and reduction of surface errors. The knowledge of temperature distribution is also crucial in material selection and research into the development of built-up edge (BUE). To this end, the aim of researchers to simulate or model the metal cutting process has grown.

2. Background

There has been an extensive research into the prediction of cutting forces in end milling, most of which have produced very good results. Majority of these are analytical based, involving quite a

number of calibration experiments used to obtain cutting force coefficients (mechanistic approach), or solving of small oblique segments along the tool's cutting edge (mechanics approach). Other studies are based on computational simulations mainly using finite element (FE) techniques. However, the stress and temperature distribution can only be predicted accurately using finite element methods based techniques. Owing to the sheer complexity and highly nonlinear nature of the end milling process, past studies using finite element methods have been mainly focused on orthogonal metal cutting.

Studies into metal cutting process began by idealising the shear zone into a single shear plane. The first model was proposed by Timme in 1870, who suggested that the chip was formed due to the brittle fracture and Tresca later assumed it to be due to plastic deformation. Much later after this, are some of the first pioneering studies carried out by Merchant (Merchant, 1945) and Lee Shaffer (Lee, 1951), still idealising the principal shear zone to a single plane extending from the cutting edge to the surface of the workpiece. Other analyses of metal cutting prior to the development of the Finite Element Method (FEM) were mainly based on these two models (Piispanen, 1948, Oxley, 1963, Fenton, 1969, Hastings, 1980).

However, with the development of the finite element method, various studies have been carried out on orthogonal and oblique metal cutting. Klamecki (Klamecki, 1973) is considered the first to introduce finite element method (FEM) technique into machining using a three-dimensional elastic-plastic model. This study was however limited to just the initial stages of chip formation. Similarly, Shirakashi and Usui (Shirakashi, 1974) applied the elastic-plastic finite element method to orthogonal metal cutting process. In this, they modified the shape of the chip until it was consistent with the plastic flow generated. K. Iwata (Iwata, 1984) also used a rigid-plastic finite element method to consider the effect of friction between the tool rake and face. In their model the shape of the model was predicted and modified repeatedly based on the distribution of flow stress. So far, the models were all based on a Lagrangian formulation. The first analysis to simulate the movement of the tool into the workpiece and continuous chip formation along a predefined "parting line" was by Strenkowski and Carroll (Strenkowski, 1985). They used a finite element program ("NIKE2D") adopting the Updated-Lagrangian formulation (ULF) and also proposed a separation criterion to simulate chip formation. This separation criterion was based on the effective plastic strain (critical limit of 0.5) at the tool tip region of the workpiece. Lee and Wilkening (Lee, 1982) were however the first to attempt chip formation by the use of an element death option in the model, but this model was not realistic as friction in the secondary shear zone was ignored. Strenkowski and Carroll found that the separation criterion has a significant effect on the residual stress in the workpiece and little effect on the chip geometry and the cutting force.

Shih et al. (Shih, 1990) carried out a study on the effects, elasticity, viscoplasticity, temperature, strain-rate and large strain have on the stress-strain relationship and the effects large friction have on the tool-chip interface. Their study was also based on the Updated-Lagrangian formulation. The separation criterion used was based on the distance between the node connecting the chip and workpiece (crack tip) and the tool tip. This type of criterion has been adopted in a number of studies to model orthogonal metal cutting, however with different values used (Shih, 1996, Mamalis, 2001, Baker, 2002, Carrino, 2003, Rosa, 2007). Shet et al. (Shet, 2000) simulated orthogonal metal cutting using a separation criterion based on a critical stress. S. Lei, et al. (Lei, 1999) used a crack length versus time separation criterion, based on the movement of the tool. Ceretti et al. (Ceretti, 1996) used an Implicit Lagrangian FE code ("DEFORM-2D") to study

continuous and segmented chip formation. In their model, a damage criterion was used similar to that of Lee and Wilkening (Lee, 1982), where the damaged element is removed from the domain. The downside of this approach is that the removal of elements corresponds to loss of mass. The only way to minimize this would be to have very small element sizes along the tool path, which would come at a higher computational cost. The author also reported that after the deletion of damaged elements, the domain boundaries had to be smoothed otherwise subsequent attempts to re-mesh would fail. Zhang (Zhang, 1999) carried out a detailed study on the separation criteria used by different researchers in their studies. The study showed that none of the existing criteria is universal and deduced that there is the need to develop a comprehensive criterion to ensure consistency in FEM models and results.

To avoid the use of separation criteria while using a Lagrangian formulation, the cutting action can be simulated as the continuous indentation and plastic flow of the material around the tool. The tool is fed into the workpiece and as soon as the elements become distorted, a re-mesh is carried out. The point of re-mesh is determined by a set of specified criteria. This method was used by Sekhon and Chenot (Sekhon, 1993), Madhavan et al. (Madhavan, 2000) and Bil et al. (Bil, 2004). One of the main problems with this approach is its high computational cost. Frequent remeshing and a very dense mesh is required to minimize the errors (Baker, 2002). Bill et al. compared three different finite elements models of orthogonal metal cutting with experimental data. Two of these models used continuous remeshing and the third was based on a damage criterion. While it was noted that the friction parameter drastically affects the results, it was also noted that even though the re-meshing approach produced better results, there was still the need for a better separation criterion.

Contrary to the Lagrangian formulation, is the Eulerian formulation where the mesh is spatially fixed. It is more suitable for fluid flow problems, which involves a control volume. It has been used to model metal forming process. However, its first application to metal cutting was reported by Usui et al. and Lajczok (Lajczok, 1980). In the study by Lajczok, the tool forces and geometry obtained experimentally were applied to the workpiece surface, thereby omitting the chip in the model. The residual stress and plastic deformation zone in the workpiece were validated experimentally. A similar approach was used by Natarajan and Jeelani (Natarajan, 1983) in modelling the residual stresses in the workpiece.

Strenkowski and Moon (Strenkowski, 1990) analyzed a steady-state orthogonal cutting with the capability to predict chip geometry and chip-tool contact length based on an Eulerian formulation. In their simulation, the mesh was not entirely spatially fixed as they employed a method proposed by Zienkiewicz et al. (Zienkiewicz, 1978) to obtain the shape of the chip. In this method, the free surface of the chip was calculated by adjusting its location (through an iterative process) to enforce a zero normal surface velocity component. Also based on an Eulerian formulation, Moriwaki et al. (Moriwaki, 1993) developed a rigid-plastic finite element model to examine the effects of the tool edge radius to the depth of cut in micro cutting process. Some other studies carried out with the use of pure Eulerian formulation were reported by Strenkowski et al. and Athavale (Strenkowski, 2002, Athavale, 1997).

What makes the Lagrangian formulation very attractive in modelling metal cutting is that the mesh covers and moves together with the material. Therefore, no a priori assumption of the chip is required because the chip develops as the tool progresses through the workpiece. Moreover, the

analysis can model indentation, incipient stage and the steady state of metal cutting. At the same time, this formulation also suffers some disadvantages, the most important of which is the use of separation criterion. The use of separation criterion to model chip formation is not reliable, as there exists no universal and consistent criterion as explained by Zhang (Zhang, 1999). Not only are there different types/methods of applying the separation criteria, there is also no physical indication as to what criterion value is to be used. Another factor concerning the use of separation criterion is the use of a parting line. The problem with the parting line is that as the analysis progresses some nodes are deformed and this can cause unstable simulation. This is because the separation criteria approach works best if the nodes are precisely in front of the approaching tool. A similar problem is experienced when using damage models for chip separation as explained by Bil et al. (Bil, 2004). Furthermore, the parting line restricts the types of tools used in the model to sharp edged tools (Movahhedy, 2000). Another major disadvantage of using the Lagrangian formulation is that, as the material is highly sheared on passing through the shear plane/primary shear zone, so are the elements, thereby causing highly distorted elements. The Eulerian formulation on the other hand, does not suffer the same disadvantages as the Lagrangian formulation. In addition, because the material flows into the model, the domain can be design to include only the area near the shear zone, thereby improving on computational cost. The only major disadvantage to this approach is that, knowledge of the volume of the domain (chip) and its precise boundary conditions are required a priori.

It is due to the above reasons that the Arbitrary Lagrangian-Eulerian formulation is ideal as this combines the features of pure Lagrangian and pure Eulerian formulations. Frank and Lazarus (Frank, 1964) and Noh (Noh, 1964) first proposed it, for two-dimensional hydrodynamic problems using finite difference schemes. It was at the time called, Coupled/Mixed Eulerian-Lagrangian Method/Code. It was later introduced to finite element method by Donea et al. (Donea, 1977) and has been used extensively, mainly to model processes involving large deformations (e.g. metal forming, metal cutting and metal forging). Some studies using ALE to model metal cutting are reported by Ozel (Ozel, 2005, Ozel, 2006).

All the studies reported so far have been focused on analysing orthogonal metal cutting and turning. Ozel and Altan (Ozel, 2000) modelled flat end milling using a single insert flat end mill. They had to split the tool cutting edges into two regions (primary and secondary cutting edges). The primary cutting edge was modelled using plane strain deformation and an axisymmetric deformation model was used to model the secondary cutting edge. The cutting force predictions obtained did not entirely match the experimental results. Pantale et al. (Pantale, 2004), presented a three-dimensional oblique model to simulate the milling process using damage criterion (Johnson–Cook’s). A full three-dimensional simulation was briefly reported, however it was not validated and no results were presented, as more investigation was needed.

In this paper, a new simulation approach using general FE commercial package (Abaqus/Explicit) to simulate 3-dimensional end milling process was proposed. The approach was used to predict the cutting forces for a non-helical with zero corner radius. However, the proposed approach can be applied to a non-helical or helical general tool (with or without a corner radius). The cutting force predictions were shown to match experimental data.

3. Model Formulation

3.1 Proposed Simulation Approach

The proposed approach is suitable for any general end mills. It is however demonstrated in this paper using a tool with zero helix angle and the results compared with experimental data for a tool with small helix angle. The approach involves modelling the cutting process at different angles of rotation to obtain the instantaneous cutting forces at these respective angles. The results obtained can be further used to predict the cutting forces for smaller feed-rates. When the helix angle is small, the tool would experience very little cutting force along its z axis, therefore the domain can be simulated using plane strain elements. Martellotti (Martellotti, 1941) in his study approximately defined the undeformed chip thickness, (termed instantaneous depth of cut) in terms of the angle of rotation as:

$$h = s_f \sin(\phi_j) \quad (1)$$

where s_f is the feed (μm) and h is the undeformed chip thickness (μm).

The angle of rotation or radial immersion angle ϕ_j , and undeformed chip thickness h , are shown below in Figure 1.

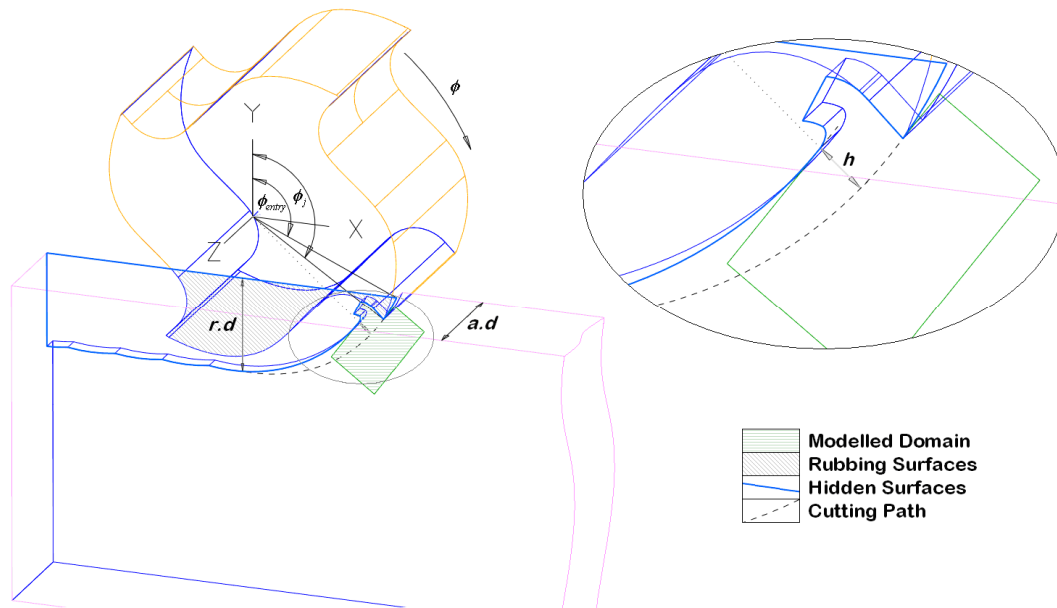


Figure 1. Undeformed chip thickness, radial and axial depth, angle or rotation.

The entry angle of the tool for downmilling is determined by the radial depth (Figure1) and the radius of the tool using:

$$\phi_{entry} = \pi - \cos^{-1}\left(1 - \frac{r.d}{R}\right) \quad (2)$$

where $r.d$ is the radial depth of cut (μm) and R is the tool radius (μm).

The exit angle for down milling is π according to the convention used in Figure1. Therefore, using the undeformed chip thickness h (for a specific angle), the cutting process is simulated and the instantaneous radial and tangential cutting forces (in cylindrical coordinate) are obtained for that angle. Finally, the cutting forces in Cartesian coordinate system (global) can be evaluated by a transformation:

$$\begin{bmatrix} dF_{x,j}(\phi) \\ dF_{y,j}(\phi) \\ dF_{z,j}(\phi) \end{bmatrix} = \begin{bmatrix} -\cos \phi_j & -\sin \kappa \sin \phi_j & -\cos \phi_j \sin \phi_j \\ \sin \phi_j & -\sin \kappa \cos \phi_j & -\cos \kappa \sin \phi_j \\ 0 & \cos \kappa & -\sin \kappa \end{bmatrix} \times \begin{bmatrix} dF_{t,j}(\phi) \\ dF_{r,j}(\phi) \\ dF_{a,j}(\phi) \end{bmatrix} \quad (3)$$

where κ is called the axial immersion angle, and is zero for a flat end tool.

The forces in the z axis will be equal to zero as a non-helical flat end tool is being used. The cutting speed, which is the relative speed between the cutting edge and the workpiece, determines the speed of the material at the inflow into the domain (Figure 3). This speed is defined as:

$$v = Spd \times \pi \times D \quad (4)$$

where Spd is the spindle speed (rev/s), and D is the diameter (μm) of the tool.

The dimensions and boundary conditions of the geometry are given in Appendix A.

4. The Finite Element Model

4.1 Finite Element Mesh

The geometry was simplified to a 2-dimensional domain to reduce its computational cost. Running it as a 3-Dimensional domain would demand large computational resources. Pednekar et al. (Pednekar, 2004) reported that a three-dimensional simulation using ALE adaptive meshing took eight days using four 1.3GHz processors. From their study, the cutting (tangential) force and thrust (radial) force obtained from three-dimensional and two-dimensional (using plane strain and plane stress elements) simulations were compared as shown in Figure2. It can be seen that the cutting/tangential forces (which is the dominant force analysis) obtained from the 3-dimensional

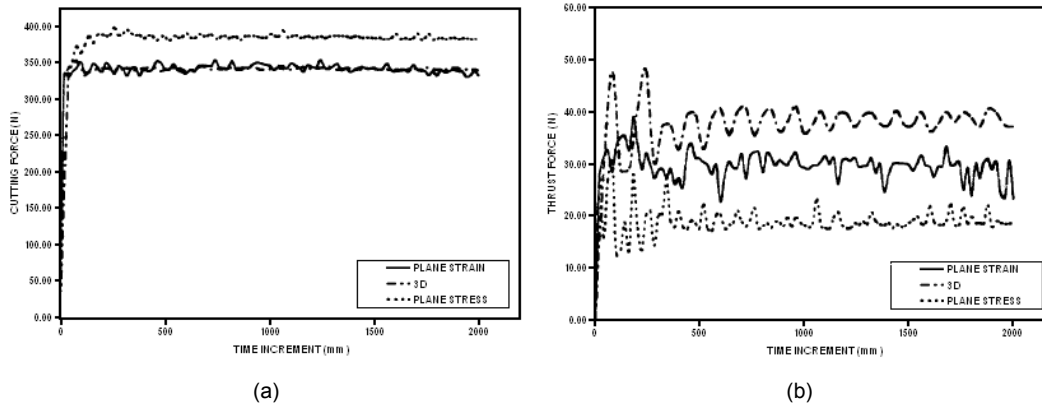


Figure 2. (a) Cutting Force and (b) Thrust force comparison between 2D plane strain and stress and 3-D models (Pednekar, 2004).

and two dimensional plane strain analysis match perfectly. There was a slight difference for the thrust/radial force.

If the tool however had a corner radius then it would have to be modelled as a three-dimensional domain or a special treatment applied to the corner. The workpiece model used four-node bilinear (CPE4R) isoparametric quadrilateral elements and a plane strain assumption for the deformations. The material properties used are given in Appendix A. The tool was modelled as a rigid body due to its relatively high stiffness. A penalty tangential behaviour was adopted in modelling the friction between the tool and the chip. A friction coefficient of approximately 0.11 was reported by Itoigawa et al. (Itoigawa, 2006) for lubricated machining and this value was used in the simulations.

4.2 Explicit Dynamic Analysis

The explicit dynamic analysis procedure used in all the simulations was originally developed for high speed dynamic problems that would rather be difficult to simulate using implicit method. It also handles complex contact and material properties very well. The equation of motion,

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{P\} \quad (5)$$

for the domain is integrated using the explicit central difference integration rule

$$\dot{u}^{(i+1/2)} = \dot{u}^{(i-1/2)} + \frac{\Delta t^{(i+1)} - \Delta t^i}{2} \cdot \ddot{u}^{(i)} \quad (6)$$

$$u^{(i+1)} = u^{(i)} + \Delta t^{(i+1)} \cdot \dot{u}^{(i+1/2)} \quad (7)$$

where u is the velocity, the superscript (i) is the increment number, while

$(i + 1/2)$ and $(i - 1/2)$ are the mid-increment values and Δt is the time increment.

These provide the nodal calculations and element calculations are performed using the strain rate to calculate the strain increments and the stress from constitutive equations.

The explicit method determines the solution by explicitly advancing the kinematic state from the previous increment as opposed to an iterative process.

Dynamic equilibrium is ensured using,

$$\ddot{u} = M^{-1} \cdot (P^{(i)} - I^{(i)}) \quad (8)$$

The explicit was the preferred method as it has the advantages of computational efficiency when dealing with large deformation and highly non-linear problems such as machining. In addition to its efficiency, the ALE adaptive meshing used in the simulation was mainly designed for use with the explicit method (Abaqus User Manual, 2006).

4.3 Arbitrary Lagrangian-Eulerian (ALE) Adaptive Meshing

The ALE adaptive meshing feature was used in all the simulations, to maintain a high-quality mesh through out the analysis. In ALE adaptive meshing, the mesh can be converted to a pure Eulerian or pure Lagrangian formulation or can be assigned a different motion, at which point it is termed “Sliding” (Abaqus Analysis User's Manual, 2006). The ALE adaptive meshing performs two steps:

1. Meshing. During this stage, a new mesh is created at a set number of increments intervals. This frequency was set to one by default due to the Eulerian region defined (Figure 3) and also spatial mesh constraints. To improve the mesh quality of “Sliding regions” a mesh sweep was performed three times.

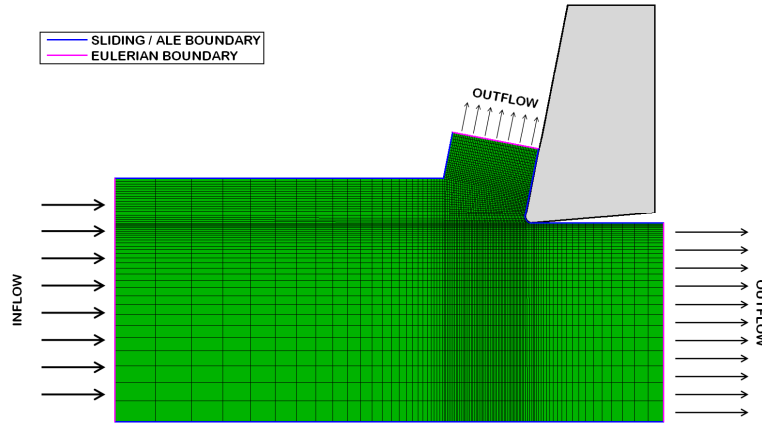


Figure 3. The Eulerian and sliding region boundaries.

2. Advection step. At this stage, the material and element variables from the previous mesh are remapped/transferred to the new mesh. The second-order advection based on the work of Van Leer (Leer, 1977) was employed by default for the simulations. First, a linear distribution of the variable, ϕ in each old element is obtained and then an element variable from the old mesh is remapped to the new mesh. During the mesh motion, the state variables are conserved including the mass and energy.

$$\frac{D\phi}{Dt} = \frac{\partial \phi}{\partial t} + \hat{v} \frac{\partial \phi}{\partial x} = 0$$

where $\hat{v}_i$ is the mesh velocity.

4.4 Modelling Assumptions

During machining as explained earlier the tool and workpiece experience different vibrations, which can grow significantly in what is called regenerative chatter. This in turn affects the undeformed chip thickness. In the simulations, it was assumed that the whole cutting process was stable and the vibrations were negligible. This criterion is also required when conducting experiments to calibrate the tool using the mechanistic approach.

The actual tool modelled has a helix angle of 30 degrees, however due to such a small axial depth of cut of 0.5mm it was assumed to be zero. In order to model a tool with helix angle, a three-dimensional domain would be required.

When simulating the end milling cutting process as a two-dimensional domain, the friction experienced on the face rubbing against the machined surface perpendicular to the tool axis (Figure1 highlights the area of friction) is not included in the simulations. This can also contribute to some force in the axial direction. To include this in the simulation would also require using a three-dimensional domain and calculating the friction using a contact condition on the surfaces. To capture a considerable amount of frictional effect (due to its relative magnitude), a fairly good mesh density would be required in this region.

The cutting edge was modelled as perfectly round with a radius of 5 μm . The actual edge radius of the tool can only be obtained by measuring it directly from the tool or obtaining it from the manufacturers. Strenkowski et al. measured an average edge radius of 50 μm (Strenkowski, 2002), while Ranganath et al. (Ranganath, 2007) measured radiuses ranging from 15 μm to 72 μm . This however can quickly create errors in the result as shown in the discussions section. Moreover, during machining, the edge is eroded very quickly as the tool wears.

Finally, the tool flutes were assumed to be perfectly identical, which it never is in practice (due to its manufacture). The changing edge radius also produces difference amongst the flutes. If there were any know differences amongst the flutes (for example tool runout) the flutes would each have to be modelled separately.

5. Results and Discussions

The simulations were conducted successfully and an example of the steady stress state of the workpiece is shown in Figure 4. The primary and secondary shear zones are seen with the highest stress area and the residual stress is seen trailing further along the machined surface. From these simulations the cutting forces in directions 1 and 2 (refer to Figure 4) in the local coordinates which correspond to the tangential and radial cylindrical coordinates respectively are collated and shown in Table 1. Figures 5a and b show the convergence of the cutting forces in the simulation $h = 10.602\mu\text{m}$.

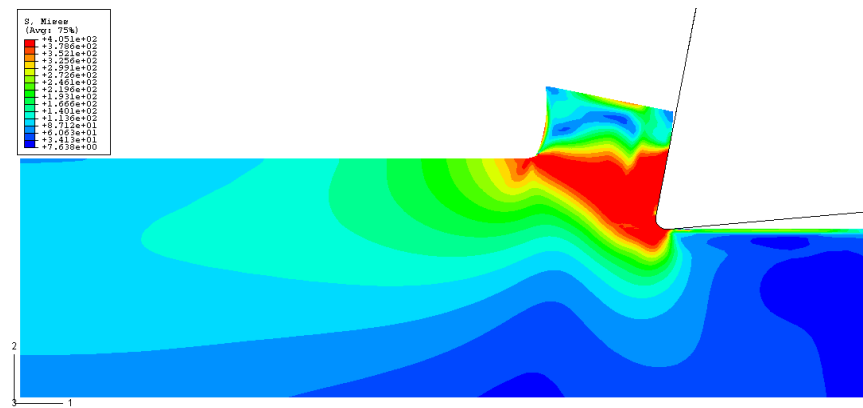


Figure 4. von Mises stress distribution for the milling simulation.

A plot of these forces against the undeformed chip thickness, h gives an indication of the effect the edge radius has on the cutting force (Figure 6 a and b). The edge radius creates additional force known as the ploughing force. To further show the influence the edge radius has on the force, it was changed from $5\mu\text{m}$ to $7.5\mu\text{m}$. Plots of cutting force against undeformed chip thickness are also shown in Figures 6 a and b) for tangential and radial forces. The influence of the larger edge radius can be seen to have increased with the increase in the radius.

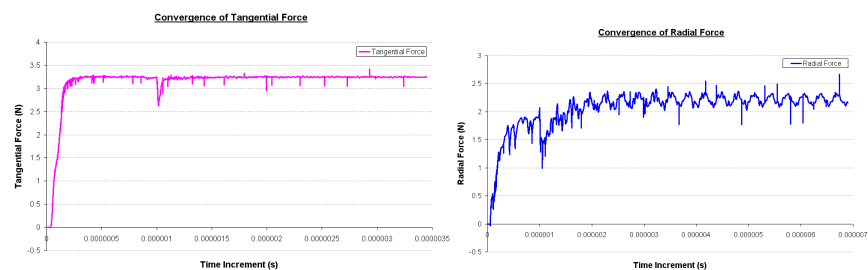


Figure 5. Convergence of tangential and radial forces on FEM

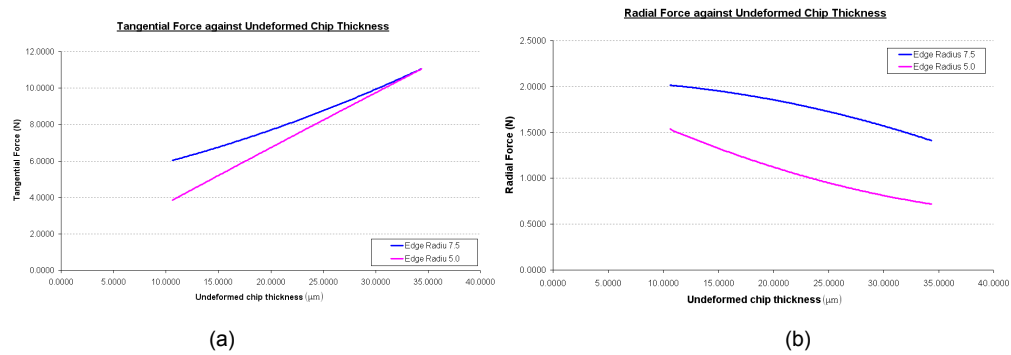


Figure 6. (a) Tangential and (b) radial forces showing effects of edge radius

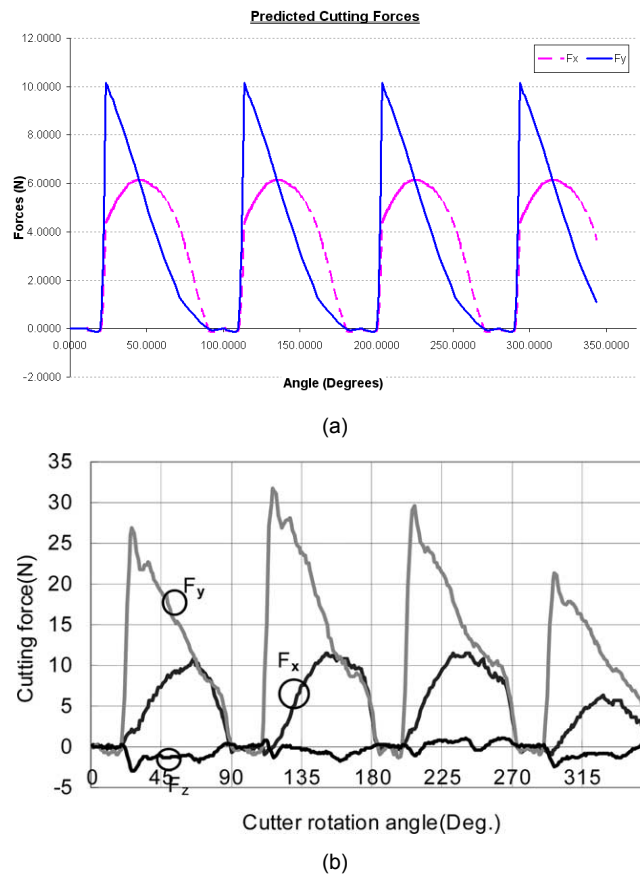


Figure 7. (a) Predicted cutting forces and (b) Experimental cutting forces (Ko, 2002)

The cutting forces in the cylindrical coordinates are transformed to the global coordinates as given in Table 1 and a plot of these is shown below in (Figure7a). As assumed previously the flutes were assumed to be identical therefore the forces predicted would be the same for each flute. The geometry and cutting conditions of the study by Ko et al. (2002) were used for the simulations and the result by Ko et al. (2002) is shown in Figure(7b). The force predicted in the simulations is seen to be very low compared to the experimental results. This could have been due to the edge radius.

The edge radius of the tool used in the experiment is unknown, however it is the authors postulation that it must have been higher than $5\text{ }\mu\text{m}$ (value used in simulations). This is because a larger edge radius (hence blunter tool) would increase the cutting force, as shown in the predicted cutting forces for tool with an edge radius of $7.5\text{ }\mu\text{m}$ (Figures6 a and b). Moreover, Ranganath et al. (Ranganath, 2006) reported various edge radii for different tools ranging from $15\text{ }\mu\text{m}$ - $72\text{ }\mu\text{m}$.

Other reason for a low cutting force prediction could be due to the presence of helix angle of 30° on the tool used in the experiment (Ko, 2002).

Finally, comparing the trend of the predicted and experimental cutting forces (Figure7a), it can be seen that there is a slight deviation in the trend (Figure7b). This is at the section close to the exit angle, which corresponds to the small undeformed chip thicknesses of the tool exiting the

Table 1. FEA and calculated results for cutting forces.

$\Delta\phi$	ϕ (rads)	h (μm)	Tangential Force, F_t (N)	Radial Force, F_r (N)	F_x (N)	F_y (N)
0	5.12	34.369	11.047	0.719	4.419	10.125
1	5.14	34.102	10.960	0.721	4.559	9.967
2	5.16	33.825	10.873	0.724	4.694	9.807
3	5.18	33.537	10.784	0.729	4.825	9.644
4	5.19	33.239	10.694	0.735	4.951	9.479
5	5.21	32.931	10.604	0.742	5.072	9.312
7.5	5.25	32.117	10.369	0.764	5.353	8.881
10	5.30	31.242	10.121	0.790	5.598	8.432
12.5	5.34	30.308	9.855	0.818	5.804	7.965
15	5.39	29.316	9.568	0.846	5.966	7.480
17.5	5.43	28.268	9.256	0.874	6.082	6.977
20	5.47	27.166	8.920	0.901	6.149	6.462
25	5.56	24.810	8.187	0.957	6.139	5.417
30	5.65	22.265	7.403	1.027	5.957	4.395
35	5.73	19.550	6.604	1.114	5.635	3.443
40	5.82	16.687	5.787	1.206	5.182	2.575
45	5.91	13.696	4.892	1.308	4.554	1.787
50	6.00	10.602	3.843	1.536	3.686	1.086

workpiece. This also corresponds to the small undeformed chip thicknesses in the Figures 6 a and b. Due to the small undeformed chip thickness the tangential and radial cutting forces are low, and the influence of the ploughing force is more. Hence, the deviation of the trend of predicted cutting force plot from that of the experimental cutting force plot, close to the tool exit angle.

6. Conclusion

In this study, high-speed flat end milling was simulated using commercially available FEM software, Abaqus. A new approach was proposed and used to predict the cutting forces. It was shown that the domain can be simplified to a 2-dimensional domain when simulating a non-helical flat end milling. However, the proposed approach can still be used to simulate machining with the use of general tools, including tools with a corner radius. The cutting forces predicted were shown to agree with experimental data and it was found that an accurate measurement of the edge radius is very crucial in modelling end milling using FEA.

This approach (being FEM based) can be used in all manner of analysis to be carried out on end milling process including study of the residual stresses and temperature distribution and tool deflection.

7. Acknowledgements

The authors acknowledge support given EPSRC for funding this project and also the support given by Airbus.

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9. Appendix

9.1 Model Geometry

The geometry of the domain according to the study carried out by Ko et al. (Ko, 2002) is given in Tables 2 and 3.

Table 2. Tool geometry

HSS end mill with four flutes	
Tool diameter, D (μm)	10000.0
Rake angle (Deg.)	11.0°
Helix angle (Deg.)	0.0°
Clearance angle (Deg.)	5.0°
Edge radius, r_{edge} (μm)	5.0
Spindle speed, (rev/min)	1000.0

Table 3. Workpiece

Aluminium 2014-T6	
Axial depth $a.d$ (μm)	500.0
Radial depth, $r.d$ (μm)	3000.0
Entry angle (rads)	1.97
Exit angle (rads)	μ
Feed, s_t (μm)	37.5

9.2 Boundary Conditions

The boundary conditions applied to the material and also to the mesh are shown below in Figure8.

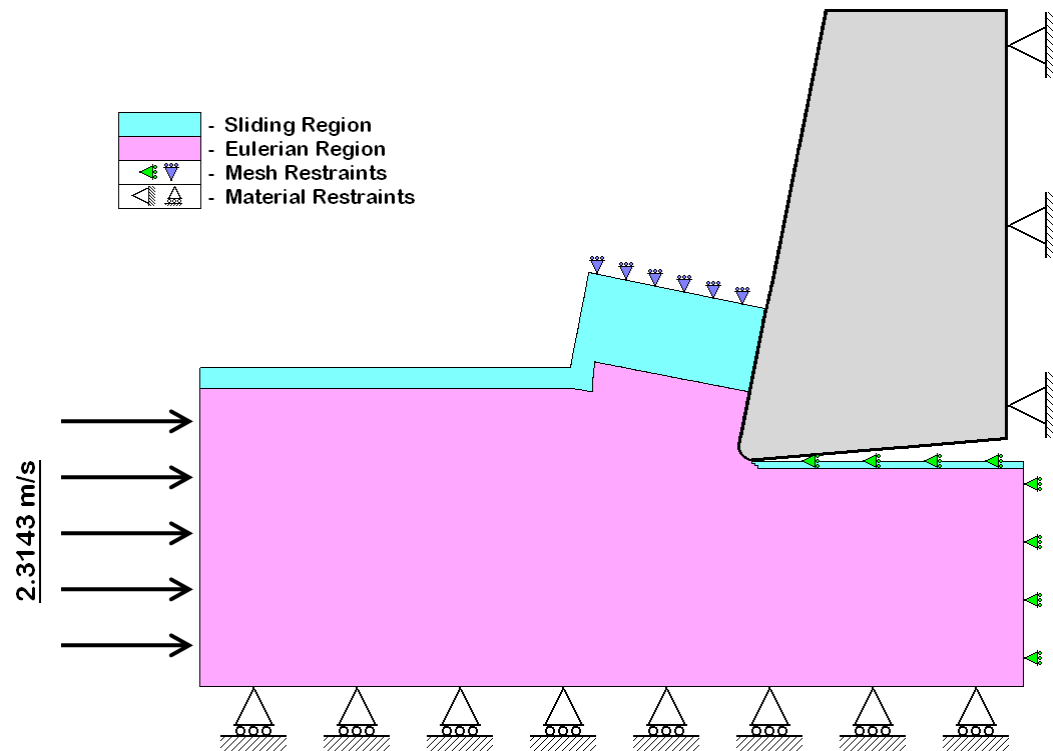


Figure 8. Boundary Conditions

9.3 Material Properties

The material used in the simulation was Aluminium 2014-T6 and its properties are given in Table 4.

Table 4. Material Properties

Density, ρ (Kgm^{-3})	2800
Young's Modulus, E (Pa) e+10	6.98203
Poisson	0.33425

Yield Stress, Se+08 (Pa)	Plastic Strain, $\mathcal{E}$
3.2400	0
3.5370	0.00056
3.6887	0.00096
3.7714	0.00136
3.8404	0.00176
3.8611	0.00216
3.8818	0.00236
3.9024	0.00276
3.9300	0.00316
3.9507	0.00336
3.9748	0.00376
3.9921	0.00416
4.0231	0.00456
4.0334	0.00496
4.0472	0.00536
4.0507	0.00576