

# A Coupled Eulerian Lagrangian Finite Element Model of Drilling Titanium and Aluminium Alloys

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## ABSTRACT

Despite the increasing use of carbon fibre reinforced plastic (CFRP) composites, titanium and aluminium alloys still constitute a significant proportion of modern civil aircraft structures, which are primarily assembled via mechanical joining techniques. Drilling of fastening holes is therefore a critical operation, which has to meet stringent geometric tolerance and integrity criteria. The paper details the development of a three-dimensional (3D) finite element (FE) model for drilling aerospace grade aluminium (AA7010-T7451 and AA2024-T351) and titanium (Ti-6Al-4V) alloys. The FE simulation employed a Coupled Eulerian Lagrangian (CEL) technique. The cutting tool was modelled according to a Lagrangian formulation in which the mesh follows the material displacement while the workpiece was represented by a non-translating and material deformation independent Eulerian mesh. The performance of the CEL based simulation was also benchmarked against an equivalent pure Lagrangian model (both tool and workpiece mesh deforms with the material). The geometry of commercially supplied twin-fluted twist drills utilised in experimental validation trials were imported into the model. Cutting speed (m/min)/ feed rate (mm/rev) combinations were 50/0.08 and 150/0.24 for the aluminium alloys while 10/0.07 and 30/0.21 were used when drilling Ti-6Al-4V. Predicted cutting forces from the CEL model were within 3-14% of the experimentally measured values while the simulated entrance and exit burr height deviated by 6-17.5% and 9-16% respectively, compared to experimental results. Additionally, the model indicated that hole surface residual stresses were typically compressive, with values of up to -344 and -711 MPa for aluminium and titanium workpieces respectively.

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## INTRODUCTION

Advanced titanium and aluminium alloys with their combination of high strength, corrosion resistance and low density characteristics currently form ~35-40% (by weight) of latest generation airframe components [1]. The assembly of such parts is principally carried out via mechanical fastening which necessitates the drilling of high tolerance/quality holes in order to prevent premature structural failure, particularly in sections subject to extreme operating stress/loading conditions. The determination of appropriate process parameters and drill geometry to achieve required hole integrity is generally based on results from cost intensive experimental trials. While the use of finite element (FE) modelling as a process analysis and verification tool has gained wider industrial acceptance in recent years, the numerical simulation of metal cutting processes remains highly challenging due to the need to consider aspects including severe metal deformation, highly non-linear coupled parameters, complex tool/chip contact conditions and workpiece material damage [2, 3, 4].

The FE simulation of large deformation problems has usually involved either Lagrangian or Eulerian mesh formulation. In traditional Lagrangian analysis, the nodes and elements are fixed to the workpiece material and follow the material deformation, however, severe mesh distortion and subsequent convergence difficulties are common problems. Techniques such as re-meshing have been developed to alleviate complications relating to mesh distortion, where the shape of the affected elements and the position of associated nodes are re-adjusted when pre-defined criteria are met. Previously calculated variables such as stress and strain are transferred to the new mesh via an interpolation scheme, which is generally a time-consuming process and subject to some loss of accuracy [3, 5]. There are 3 main methods commonly employed to initiate chip separation/deformation in Lagrangian based models, which are element deletion, nodal separation on a predefined plane or automatic re-meshing. A geometrical (such as a critical distance between the tool nose and nearest node on the cutting plane or critical penetration rate of the workpiece nodes to the rake face), or

physical (critical value of a field variable such as stress or strain) criteria is generally required to trigger the method for chip separation. However, the magnitude of the criteria also influences the degree of mesh distortion and hence the stresses predicted in the machined surface [6, 7, 8]. The procedure for determining the critical value of the chip separation criteria remains subjective, with no current consensus amongst the research community [9].

In an Eulerian formulation, the elements are spatially-fixed and independent of material deformation and therefore no mesh distortion occurs. However, the Eulerian approach suffers from difficulties in modelling the flow of material at the free surface, unless employed in tandem with an algorithm capable of handling unconstrained flow at the free boundaries. The Eulerian formulation has normally only been used to study the steady state cutting process with predefined chip geometry [10, 11, 12, 13], in order to avoid problems associated with material deformation at the free boundary. Pioneering studies by Benson [14] as well as Benson and Okazawa [15], introduced volume fraction as a field variable in order to determine the free surface of the workpiece material. Their work enabled the prediction of initial serrated chip formation in orthogonal cutting without a specification of a predefined geometry. The principal benefit of the Eulerian formulation is the reduced computation time as fewer elements are required to specify the chip and workpiece. Al-Athel and Gadala [3] applied the Eulerian formulation in a bespoke FE code to predict cutting forces when orthogonal cutting AISI P20 steel using blunt, chamfered and perfectly sharp tools. The results showed good agreement with experimental results to within 15%. The simulation also supported the theory relating to the presence of 'dead metal' in front of the chamfered/blunt tools. In addition, increasing the cutting edge chamfer angle was found to have a pronounced impact on thrust force. More recently, modern commercial finite element packages have developed capability to exploit the combined benefits of Eulerian and Lagrangian formulations, where Eulerian material can interact with Lagrangian elements through a hybrid Eulerian-Lagrangian contact. Models based on such contact conditions are often referred to as Coupled Eulerian Lagrangian (CEL) analyses.

Research on the simulation and prediction of burr formation following machining operations initially began in the late 1990s. Park and Dornfeld [16, 17], developed a 2D Lagrangian based finite element model using ABAQUS/Explicit to investigate the influence of drill geometry and backup material on burr formation when orthogonal cutting of AISI 304L stainless steel. An iterative procedure was employed to determine suitable ductile damage criteria values for successful modelling of chip separation and subsequent burr formation. It was shown that the burr formation mechanism consisted of four stages (initiation, development, pivoting, and final development), which progressed due to geometry evolution and changes in strain contours.

Although advances in computing technology have relieved some of these difficulties, the transition from 2D to 3D configurations involves more complex geometrical and contact conditions as well as increased analysis times [18]. Sartkulvanich et al. [19] developed 2D

and 3D models to study burr formation in orthogonal cutting and face milling of aluminium AA356.0-T6 using DEFORM software, involving a Lagrangian formulation and integrating a continuous re-meshing technique. The effect of tool condition (new and worn) on chip and burr formation was simulated; however results showed poor agreement with corresponding experimental data (error levels of between 50-100%). Deng et al. [20] similarly utilised DEFORM-2D to model burr formation in orthogonal cutting of mild steel. Burr size was shown to decrease with lower exit surface angle, tool rake angle, feed rate and tool cutting edge radius. Further research by Deng et al. [21] involving a 3D Lagrangian FE model of a rectangular groove cutting operation showed that the predicted burr profile and cutting forces were generally in line with experimental data. Long and Guo [22] utilised a 3D Lagrangian FE model developed using ABAQUS/Explicit to simulate burr formation when orthogonal cutting Ti-6Al-4V titanium alloy, AISI 4340 steel and AA2024-T3 aluminium alloy. In all three materials, a pivoting point at the exit surface formed during initiation of burr formation with either a positive or negative burr (edge breakout) developing depending on the properties of the individual material.

Workpiece edge breakout following orthogonal cutting Ti-6Al-4V alloy at varying cutting speed, cutting edge radius, tool rake angle and depth of cut was evaluated by Lu et al. [23] using a 2D FE model with an element re-meshing procedure. The predicted maximum length-to-width ratio of the edge breakout was  $\sim 0.2$ , which was significant smaller compared to values observed when machining brittle materials (1.05). It was also shown that smaller edge breakout could be obtained by reducing the cutting edge radius and depth of cut, or through increasing cutting speed and tool rake angle. Unfortunately, details of burr size and experimental validation were not given by the authors.

Guo and Dornfeld [24] developed a 3D FE model using ABAQUS/Explicit to examine the mechanism of burr formation when drilling AISI 304L stainless steel. The simulation highlighted the dominant roles of shearing and plastic bending in burr formation, which was characterised by the development of a 'plastic hinge' on the unconstrained bottom edge of the workpiece. Further work to improve the model was carried out by Min et al. [25], who defined a layer of uncut material ahead of the drill where the burr was expected to form. The critical thickness of this layer was dependent on the cutting conditions as well as the eventual burr type and size. Uniform burrs were typically predicted when machining under low cutting speed and feed conditions, with crown burrs prevalent at high drilling speed and feed operation, although the results were not experimentally validated.

Saunders [26] developed a 2D Lagrangian FE model using ANSYS software to predict the influence of feed rate on exit burr size when drilling AA2024-T3 aluminium alloy. The deviation in predicted burr height when compared to experimental results however ranged from 68% at low feed rates to 15% when operating at higher feed rates. Isbilir and Ghassemieh [27] presented a 3D model for drilling of

Ti-6Al-4V titanium alloy using ABAQUS/Explicit incorporating a Lagrangian formulation with material damage for element removal and chip separation. Although the reported discrepancy between measured and predicted thrust force and torque was less than 10% and 20% respectively, the predicted exit burr height was underestimated by 50-75%.

It can be summarised from the literature that accurate prediction of drilling burr formation remains a major challenge even for current state-of-the-art FE models. While Eulerian based simulations generally lead to faster solutions/convergence compared to Lagrangian models, they are generally only employed in 2D configurations. The present paper details development of a 3D FE model based on a Coupled Eulerian Lagrangian formulation for the drilling of aerospace alloys. Predicted responses include thrust forces, torque, entry and exit burr formation together with workpiece residual stresses.

## EXPERIMENTAL WORK

Three different workpiece materials were evaluated comprising an annealed Ti-6Al-4V titanium alloy having a tensile/ultimate yield strength of 825/895 MPa, together with 2 different solution treated and aged aluminium alloys; AA7010/7050-T7651 and AA2024-T351 with tensile/ultimate yield strengths of 450/520 and 290/430 MPa respectively. The cutting tools used were twin fluted, 6.35 mm diameter solid tungsten carbide (WC) twist drills supplied by MAPAL having geometry and coatings as detailed in Table 1. Drill overhang was 57 mm in all trials with corresponding run-out of < 10  $\mu$ m.

Table 1. Drill geometry and coating details.

| Factors           | Workpiece material                     |                                        |
|-------------------|----------------------------------------|----------------------------------------|
|                   | Ti-6Al-4V                              | AA7010/AA2024                          |
| Drill point angle | 135°                                   | 120°                                   |
| Drill helix angle | 34°                                    | 34°                                    |
| Point geometry    | Split point with gashed/thinned chisel | Split point with gashed/thinned chisel |
| Tool coating      | Uncoated                               | CVD diamond coated                     |

The experimental validation trials were carried out on a Matsuura FX5 high speed machining centre having a maximum spindle speed of 20,000 rpm rated at 15 kW, with variable feed rate control of up to 15 m/min. The workpiece specimens (120 × 17 × 7 mm) were held in a bespoke fixture mounted on a Kistler drilling dynamometer (model 9273) connected to charge amplifiers, with data recorded and processed on a computer using DynoWare software.

Trials were undertaken wet utilising Hocut 3380 water based emulsion (7% mineral oil concentration) delivered externally (flood) at a flow rate of 52 l/min. Entrance and exit burr height were measured using an Alicona InfiniteFocus G5 optical microscope at 8

equally-spaced positions around the hole periphery, according to the procedure detailed in a previous publication [28]. Two levels of cutting speed/feed rate combination were employed for drilling each workpiece material, which are outlined in Table 2.

Table 2. Variable factor levels for drilling Ti-6Al-4V and AA7010/AA2024 alloys.

| Factor                                     | Workpiece material | Low     | High     |
|--------------------------------------------|--------------------|---------|----------|
| Cutting speed (m/min) / Feed rate (mm/rev) | AA2024 and AA7010  | 50/0.08 | 150/0.24 |
|                                            | Ti-6Al-4V          | 10/0.07 | 30/0.21  |

## FINITE ELEMENT MODEL FORMULATION

The general purpose, commercial FE software ABAQUS/Explicit 6.14 was used for the simulation trials. Model input constraints comprised tool/workpiece physical properties and geometries, tool/chip contact characteristics and boundary conditions.

### CAD Modelling of Drill Geometry

The key geometrical features of the two drills employed in the experimental trials were measured using an Alicona G5 InfiniteFocus microscope. The data was subsequently used in SolidWorks 2015 SP3 computer aided design (CAD) software to create 3D solid representations of the drills, including the various geometrical surfaces. Comprehensive details relating to geometrical modelling of drills can be found in relevant literature [29, 30, 31, 32]. Figure 1 shows the CAD models of the drill used for aluminium and titanium alloys respectively, which were imported into the ABAQUS FE pre-processor environment. The principal geometrical difference relates to the larger point angle used for drilling the titanium alloy.

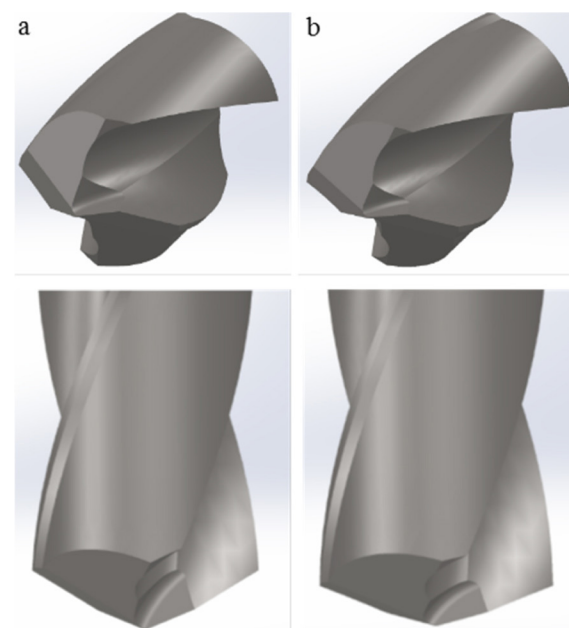


Figure 1. The CAD models of drills used for machining (a) aluminium and (b) titanium alloys.