

Three Dimensional Finite Element Modeling when Drilling of Ti-6Al-4V

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Abstract—Finite element modeling (FEM) is widely used to optimize machining processes, to predict and analyze the cutting force, cutting temperature and other related responses. Most of the FEM studies were conducted under the two dimensional orthogonal cutting. Drilling process, which involves oblique cutting is not suitable for orthogonal cutting modelling. Therefore, an attempt to simulate a three dimensional simulation of the drilling process is required. A commercially available software called DEFORM is used to accomplish the task. The value of thrust force from the simulation is compared with the experimental results and they are both in a good agreement. Comparison of the drill temperature at TC1 and TC2 are within an error margin of 12%.

Keywords—Drilling simulation, MQL, thrust force, temperature.

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I. INTRODUCTION

EXPERIMENTAL approaches to evaluate machining performances are time consuming and expensive. Therefore, mathematical simulation can be an alternative approach to predict the machining performance. The goal of constructing a finite element modeling (FEM) is to derive a computational model in predicting the deformation, stresses and strains in the workpiece, as well as the loads on the cutting tool. The main advantage of using FEM compared to other empirical models is its ability to represent workpiece material properties as a function of temperature, stress, and strain rate. Limited number of experiments need to be carried out by using FEM thus reduces the time and financial consumption as well as is cost saving.

Recent advancement in computer hardware and software leads to the enormous application of FEM for machining process. Metal cutting process consists of orthogonal and oblique cutting. The orthogonal cutting can be simulated by two dimensional simulations; meanwhile three dimensional simulations can be used for oblique cutting. The efficiency and accuracy of a simulation is depending mainly on chip separation criteria, friction descriptions and workpiece constitutive relationships [1].

There are two formulation models existed for analyzing the machining process in FEM namely Eulerian and Lagrangian. In the Eulerian model, the material flows through the FE mesh and is recommended for fluid-flow analysis. This method assumed that the chip formation is continuous and the shape of the chip is known in advanced. The unknown material variables are calculated at preset locations as the material flows through the mesh. Furthermore, the formulation is more suitable for applications where the boundary regions of the solid body under analysis are known a priori, such as in metal forming [2].

Advances in computation accessories, such as faster processors and larger memory have encouraged researchers to use Lagrangian formulation for metal cutting simulation. The principal advantages of this approach are (i) the tool can be simulated from some initial state to steady state cutting and (ii) the chip geometry together with workpiece residual stress can be predicted. In the Lagrangian analysis, the FE mesh is attached to the workpiece and the computational grid deforms together with the material. The Lagrangian calculation embeds a computational mesh in the material domain and solves for the position of the mesh at discrete points in time. Compared to Eulerian, the calculation time for Lagrangian method is much faster due to no transport material through the mesh needs to be calculated. The geometry of the material boundaries (or chip shape) does not have to be predetermined, but is developed during the course of the analysis entirely as a function of the physical deformation process, machining parameters, and material properties. Disadvantage of Lagrangian mesh is increasing time step or a stability loss when the distortion of elements is too high.

Material model is essential to solve the problem related to the material separation on the explicit algorithm and the fracture of each element. John-Cook (JC) model appears to be the best solution for machining process. It describes the material's properties such as strain-hardening, thermal softening and strain rate dependence as given in Equation 1. The first term in the bracket gives the dependence on strain, which represents strain-hardening effect. The second bracket means instantaneous strain rate sensitivity which represents strain rate hardening. Lastly, the third bracket is the temperature dependence of stress such as thermal softening effect.

$$\bar{\sigma} = \left[A + B(\bar{\epsilon})^n \right] \left[1 + C \ln \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \right] \left[1 - \left(\frac{T - T_0}{T_{melt} - T_0} \right)^m \right] \quad (1)$$

where A , B , C , n , m , $\bar{\sigma}$, $\bar{\epsilon}$, $\dot{\epsilon}$, $\dot{\epsilon}_0$, T , T_{melt} , and T_0 are yield stress constant (MPa), strain hardening coefficient (MPa), strain rate dependence coefficient, strain hardening coefficient, thermal softening coefficient, flow stress, plastic strain, strain rate (s^{-1}), reference plastic strain rate (s^{-1}), working temperature ($^{\circ}C$), and melting temperature workpiece ($^{\circ}C$), respectively.

The coefficient of friction is essential in machining simulation. It represents the contact region at the tool-chip interface, which influences by the cutting speed, chip thickness, rake angle and workpiece material. Coulomb friction law is prevalently used in machining simulation. This law can be expressed by means of Equation (2):

$$\tau = \mu \cdot \sigma_n \quad (2)$$

where τ , μ , and σ_n are friction stress, coefficient of friction, and normal stress, respectively.

Numerous FEM simulations when machining Ti-6Al-4V were performed and discussed on the shear localized chip formation. In 1996, Obikawa and Usui [3] have developed a FEM for machining of Ti-6Al-4V with an assumption that the tool is rigid and the temperature has been measured. The Lagrangian formulation is applied to analyze and predict the two dimensional elastic plastic under the unsteady state heat conduction. It shows that serrated chip was established based on the fracture strain and defined boundary condition. Umbrello [4] developed a FEM based on the Lagrangian implicit code to model the chip formation of orthogonal cutting of Ti-6Al-4V under the conventional and high speed machining. This model compared three different constitutive models proposed by previous researchers. They concluded that a good prediction of cutting force and chip morphology can be achieved only if the material constants for the John-Cook's constitutive equation were identified using experimental data obtained by the methodology which permits to cover the ranges of true strain, strain rate and temperature similar to those reached in conventional and high speed machining.

Hua and Shivpura [5] used a DEFORM software to simulate the orthogonal machining of Ti-6Al-4V. The workpiece was modeled as a rigid-visco-plastic material owing to large plastic deformation taking place in the primary and the secondary deformation zones during the simulation. Meanwhile, the tool was modeled as a rigid material in order to predict the stresses in the tool body. In addition, ductile fracture criterion was adopted to simulate crack initiation and propagation for chip segmentation. They concluded that chip formation is caused by the flow localization within the primary deformation zone, subsequently initiates crack in the primary deformation zone. Meanwhile secondary deformation zone controls the chip morphology.

Baker and his co-workers [6] have developed a two dimensional FEM to simulate the high speed machining of

Ti-6Al-4V using ABAQUS software. They assumed that chip segmentation is caused solely by adiabatic shear band formation and no material cracking occurs in the shear zone. They concluded that the chip segmentation decreases with increasing thermal conductivity. Furthermore, the elastic modulus affects the degree of segmentation. Owen and Vaz [7] have simulated two dimensional machining of Ti-6Al-4V, to evaluate the effect of cutting speed and rake angle on process evolution. However, their result does not represent the exact physical phenomenon and mechanism of chip segmentation.

Ozel and Zeren [8] have simulated the orthogonal cutting process for a meso-scale finish machining using an explicit dynamic Arbitrary Lagrangian Eulerian method. They found that very high and localized temperatures are predicted at tool-chip interface due to a detailed friction model. Prediction on the von Mises stress distribution shows that there exists a region of very high deformation rate around the edge of the cutting tool. They also found that the stress profile exhibits both compressive and tensile stresses beneath the machined surface.

Literature reveals that the aforesaid FEMs in machining have been widely applied in the two dimensional orthogonal cutting, whereby little works have been done in three dimensional simulation process due to the difficulties that arouse from the rotation of the cutting tool. Three dimensional FEM can provide more detailed information of the stress, strain and temperature distributions in the tool and workpiece.

Attanasio and his co-workers [9] conducted the three dimensional turning simulation of AISI 1045 steel. They considered that the workpiece as a rigid-plastic object meshed with more than 45,000 elements. Meanwhile, the cutting tool is assumed as a rigid object meshed with more than 100,000 elements. The friction was modeled considering a shear factor equal to 0.82. Updated Lagrangian and Eulerian formulations were combined in their analysis. The purpose is to predict the crater wear on the cutting tool. They found that the results showed good agreement with the experiments proving the reliability of the developed procedure.

Soo and his co-researchers [1] analyzed the prediction of the cutting force and temperature of a ball nose milling process. The simulation was conducted at the cutting speeds in the range of 60 to 210 m/min and at the feed rate of 0.2 mm/tooth. The workpiece was meshed with a total of 7600 elements, whereas the cutting tool was 15,800 elements. The tool is defined as a rigid model. The Coulomb friction model has been implemented with the coefficient of 0.2. They found that the predicted cutting forces were essentially constant as the cutting speed was increased from 60 to 210 m/min. Furthermore, the temperature showed a steady rise with a greater cutting velocity at both the shear zone and the tool-chip interface.

Three dimensional milling simulations have been presented by Pantale and his colleagues [10] under unsteady state machining. An Arbitrary Lagrangian Eulerian (ALE) formulation has been adopted together with the Coulomb friction law. The coefficient of friction is determined as 0.32. The cutting tool is defined as a rigid body. They found in the

simulation that the fracture occurs near the tip of the tool and propagates along the primary shear band to the surface of the chip. This result was in contrast to the continuous chip formation where the fracture propagates along a line in front of the tool tip. Li and Shih [11] simulated 3D turning using AdvantEdge 3D software to predict the cutting force and chip thickness comparable to experimental results.

Ceretti and his co-workers [12] conducted the same process using a DEFORM 3D software and the results were in a good agreement with the experimental. Arrazola and Ozel [13] also used an ALE finite element method to predict the cutting force, temperature and stresses in the 3D hard turning process. The model has been developed under the ABAQUS/Explicit software. Coulomb friction law has been adopted in the model with the coefficient of friction of 0.35. The cutting speed and feed rate were fixed at 120 m/min and 0.1 mm/rev, respectively. Generally, it can be summarized that shear friction value [14,15], strain rate model [16,17], velocity dependent Coulomb friction model [18,19] and Coulomb friction model [20-22] are the main parameters that affect the simulation performance and accuracy.

Aforesaid literatures revealed that there has not been much research done on the FE simulation of three dimensional drilling processes especially on the titanium alloy. It is due to the difficulties that arise from the rotation of the cutting tool. This study thus aimed to study the temperature distribution on the cutting tool as well as thrust force when drilling of Ti-6Al-4V using the three dimensional simulation models.

II. EXPERIMENTAL PROCEDURES

A. Finite Element Modeling Setup

The commercial software DEFORMTM 3D is used in this study to simulate the three dimensional drilling process. It is based on the Lagrangian increment formulation. DEFORM software provides an open and integrated multi-disciplinary design analysis. This software includes pre- and post-processors with analysis modeling, analysis data integration, analysis simulation and results evaluation capabilities.

A two flutes drill insert was designed by CAD software and converted into stereolithography (STL) format which is a very common format between various CAD software and FEA packages. The drawing is then imported into DEFORM software. **Figure 1(a)** shows the model of the drill insert. The drill insert is assumed to be a rigid body which is considered as a thermal transfer model to determine the cutting temperature field. In order to carry out a finite element analysis, mesh process is required to divide the solid model into a number of discrete parts as shown in **Figure 1(b)**. A high density of mesh need to be assigned at the cutting tool edge due to the large plastic deformation, while a coarse mesh density is given in the area far from the edge. In this investigation, the cutting tool was divided into 30,000 elements. Prior to meshing, the coating layer of TiAlN has been added on the drill surface with the thickness of 5 μm . As the elements are deformed at the cutting tool edge, they are automatically remeshed and a new mesh is

generated on them. The main parameters such as strain, strain rate and temperature on the older mesh is interpolated onto the new mesh and simulation continues. This technique allows the chips to be separated from the workpiece.

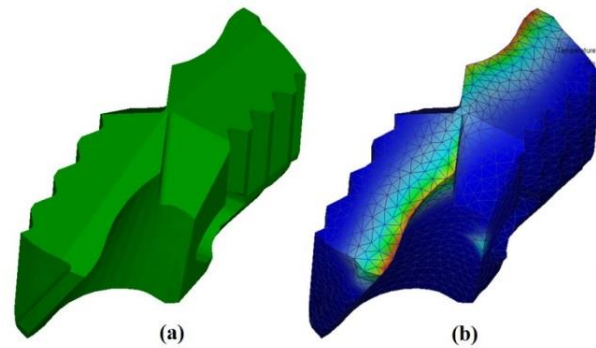


Figure 1 Drill insert (a) STL format and (b) meshed model

In order to analyze the thrust force, torque and temperature on each of the elements, the cutting edge was divided into small elements so called elementary cutting tool (ECT) as shown in **Figure 2**. Along the cutting edge composed of 9 ECTs and labeled on the cutting edge. When the drilling process begins, each ECT will sequentially engage with the workpiece until all 9 ECTs are fully engaged with the workpiece as shown in **Figure 3**.

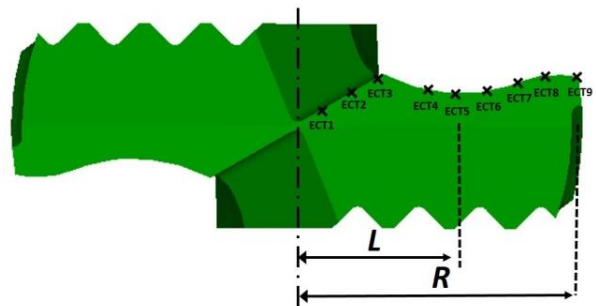


Figure 2 Solid model of drill insert with labeled of ECT along the cutting edge

The workpiece model was constructed using the primitive geometry provided in the software. The diameter and thickness of the workpiece are 20 mm and 5 mm, respectively. The workpiece is assumed as a plastic model. The number of element significantly affects the prediction accuracy of the plastic deformation process. It is recommended to apply smaller elements and large number of total elements to obtain accurate results. Therefore, the workpiece was modeled and divided into 180,000 elements. To model the behavior of Ti-6Al-4V, a John-Cook's constitutive equation was employed for which the material constants are shown in Table 1. Friction between the tool and the chip is modeled by the Coulomb friction law. Previous researches reported that the value of coefficient of friction were determined either by matching the predicted cutting force with the measured data or using an average Coulomb friction coefficient determined from the machining experiments [23,24]. Coulomb's friction model is adopted and a constant friction coefficient of 0.4 is used to

reflect the friction effect in tool-chip interface [25]. In the simulation, it is assumed that the workpiece is losing the heat into the environment. The heat transfer coefficient of $1000 \text{ kW/m}^2\text{K}$ is suitable for Ti-6Al-4V [4]. According to Gardner and Dornfeld [26], the heat transfer coefficient for convection under flood cutting condition is between 20 to $40 \text{ W/m}^2\text{K}$. In addition, smaller value of $5 \text{ W/m}^2\text{K}$ can be used for dry cutting condition. This experiment was conducted under the minimal quantity lubrication (MQL) condition. In this case, the appropriate convection coefficient value of MQL condition is taken as $10 \text{ W/m}^2\text{K}$ or 0.01 N/sec mm C. and the ambient temperature is assumed to be at 20°C . The machining parameters in this analysis are shown in Table 2. In general, the value of the critical damage (Cockroft and Latham criterion) of 0.35 is chosen based from the recommendation by [27] and [28].

TABLE 1 MATERIAL CONSTANT FOR JC CONSTITUTIVE MODEL OF Ti-6Al-4V [4, 15]

$A \text{ (MPa)}$	$B \text{ (MPa)}$	C	n	m	$\dot{\epsilon}_0$
782.7	498.4	0.028	0.28	1	10^{-5}

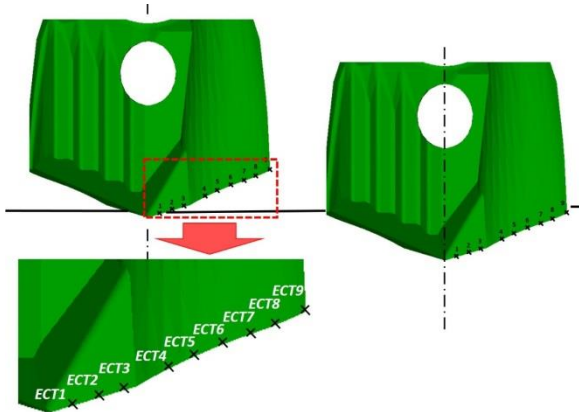


Figure 3 Early penetration engagement and full engagement during the drilling process

TABLE 2 MACHINING PARAMETERS FOR FEM AND ACTUAL EXPERIMENT

Cutting speed, $V_c \text{ (m/min)}$	60
Feed rate, $f \text{ (mm/rev)}$	0.1
Depth (mm)	5

B. Drilling setup

The drilling test was conducted on a vertical machining center and the setup is shown in **Figure 4**. The workpiece with a diameter of 20 mm is clamped on the rotating spindle. A stationary 14 mm diameter drill bit is clamped on the tool holder. The indexable carbide drill is coated with AlTiN. The overhang of the workpiece and the drill were kept constant at 5 mm and 75 mm , respectively. The tool holder assembly is mounted on the Kistler 9257B dynamometer to measure the thrust force and torque. The MQL is supplied via the atomizer unit and the lubricant used is synthetic ester. **Figure 5** shows

the K-type thermocouple wires embedded in the grooves. Both wires were located near to the cutting edge, denoted as thermocouple 1 (TC1) and thermocouple 2 (TC2). The coordinate of these locations are defined from the chisel edge of the insert.

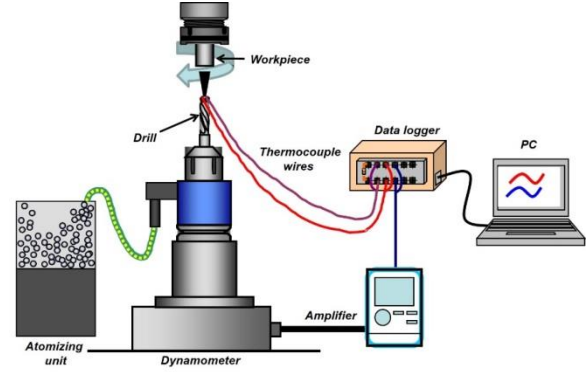


Figure 4 Drilling setup

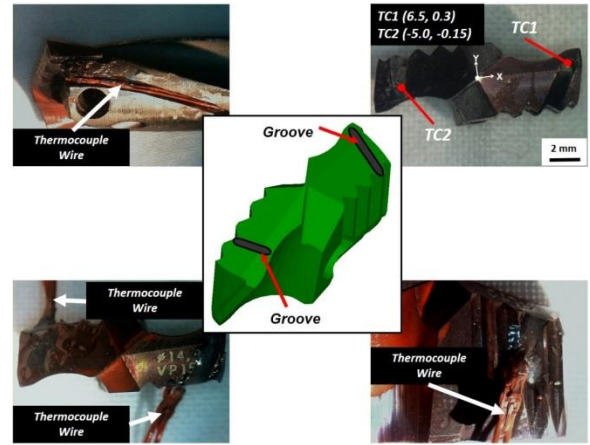


Figure 5 Embedded thermocouple setup

III. RESULTS AND DISCUSSION

A. Prediction of Thrust Force

Thrust force at the cutting speed of 60 m/min and feed rate of 0.1 mm/rev is simulated for comparison with the experimental result as shown in **Figure 6**. Thrust force is observed to increase with increasing depth of penetration. This is due to higher contact pressure on the tool-chip interface, which leads to an increase in thrust force. In the early stage of drilling process, only a small areas of chisel edge (Region 1: ECT 1 to 3) were in contact with the workpiece as the drill begins to penetrate into it. As the process continues, the contact area becomes larger (Region 2: ECT 4 to 9) as the cutting edge starts entering the workpiece.

The trends of the plotted curves for thrust force against L/R obtained by the dynamometer measurement and FEM calculation is observed to be similar. The experimental and numerical results of the thrust force do agree well, as shown in **Figure 6**. The result of FEM shows a slightly higher thrust force, especially at ECT 1 to 7. However, as the penetration becomes deeper, the measured thrust force is greater than FEM

at ECTs 8 and 9. The reason for the significant difference, especially at ECTs 8 and 9 is most likely due to the value of friction coefficient, which varies along the cutting edge. Larger contact area near to the tool periphery, where the drill required more energy to deform the chip, subsequently increases the thrust force.

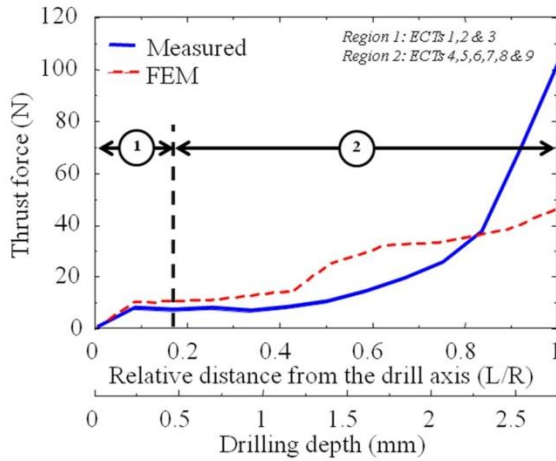


Figure 6 Comparison of thrust force of ECTs along the cutting edge

B. Prediction of Drill Temperature

For the thermal process, the workpiece and tool initial temperature are assumed to be at temperature of 25°C. During the drilling process, the temperature increases due to the plastic deformation and friction on the tool-chip interfaces. **Figure 7** shows the result of the measured drill temperature at TC1 and TC2 in comparison with the prediction result by the FEM. It can be seen that the temperature generated by the FEM calculation is in agreement with the experimental result when the cutting speed of 60 m/min and feed rate of 0.1 mm/rev are employed. It is observed that the deviation in drill temperature magnitudes between the measured and simulated is approximately 12% and 0% at TC1 and TC2, respectively. This deviation can be considered in an acceptable range, thus providing a good validation for the FEM model. It is suggested that the chips is constantly flowing via the flutes and carry the heat away, while the cutting edge is in continuous contacts with the chips. In addition, thermal conductivity and specific heat of the cutting tool and the workpiece have an effect on the temperature variance.

The graph of the predicted temperature field for the drill insert after the full engagement is shown in **Figure 8**. Meanwhile, **Figure 9** shows the evolution of the predicted drill temperature generation at all the ECTs starting from the early penetration (ECTs 1,2 and 3) until it is fully engaged (ECT 9). It can be seen that the generated temperatures are different at every ECTs. In this simulation, ECT 9 has a slightly higher temperature than that of other ECTs. The temperature distribution at the region close to the margin of the drill is relatively high. Difference of temperature values in each ECT can be attributed to the assumption of the value of rotational

velocity along the cutting edge. Generally, the value of rotational velocity near to the chisel edge is nearly zero, and it increases towards to the outer drill's diameter. Meaning that, the rotational velocity is greater at the outer diameter compared to inner diameter of the drill bit. In addition, there is a variation of coefficient of friction along the cutting edge, which is expected to increase with the temperature as well.

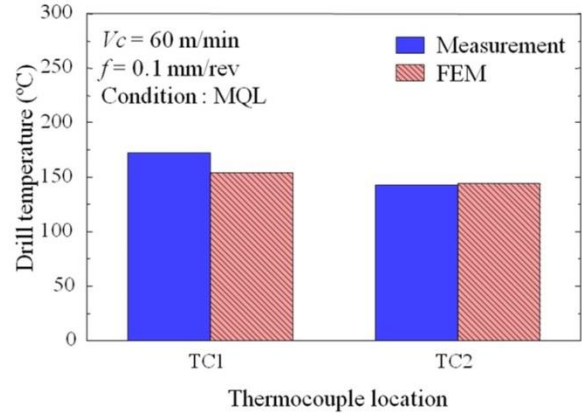


Figure 7 Comparison of FEM and measurement of drill temperature at thermocouple TC1 and TC2 after full drill engagement

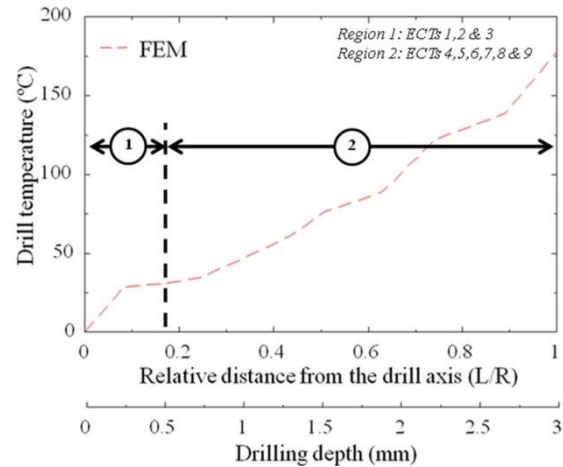


Figure 8 Temperature distributions along the chisel and cutting edges as a function of drilling depth

IV. CONCLUSIONS

Finite element approach is used to study the effect of machining conditions on thrust force and temperature distribution when drilling Ti6Al4V. A commercially available software code (DEFORM 3D) is used to accomplish the task. The simulation is carried out at the cutting speed and feed rate of 60 m/min and 0.1 mm/rev, respectively. A constant Coulomb friction coefficient (0.4) is assumed to represent the friction between the tool-chip interfaces. Results for the simulated thrust force are compared with the experimental results and they are in a good agreement. A comparison of the drill temperature at TC1 and TC2 are within an error margin of 12%.

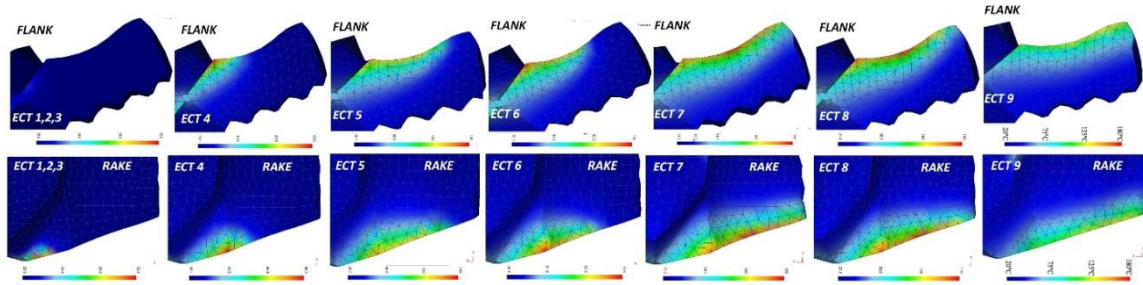


Figure 9: Temperature distributions on the flank and rake faces from ECTs 1 to 9

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