Studying the Implementation of Finite Element Models in the Orthogonal Cutting Processes with Uncoated Tool and TiN, TiCN and Al_2O_3 Coated Tool

Nguyen Kien Trung*, Truong Hoanh Son
Hanoi University of Science and Technology - No. 1, Dai Co Viet, Hai Ba Trung, Hanoi, Viet Nam
Received: June 18, 2018; Accepted: November 26, 2018

Abstract

The metal machining is the most popular process used in the machinery part manufacturing. Therefore, machining process needs to be controlled by properly selecting of cutting condition, tool materials and coating to obtain the best machining time, good surface finish and low machining cost at the same time. To understand the effects of various cutting condition, tool and coating materials, it is useful to simulate the machining process using finite element techniques. This paper presents the preliminary investigation on the implementation of two dimensional finite element modeling (FEM) with two approaches, Lagrangian mesh description and Arbitrary Eulerian-Lagrangian (ALE) mesh description, to simulate the stress and cutting temperature in the orthogonal cutting processes. The influence of various tool and coating materials (TiN, TiCN and Al_2O_3 carbide coated tool, Polycrystalline Diamond - PCD) is also studied in comparison with uncoated tool. Titanium alloy Ti-6Al-4V and AISI 1045 steel is selected as *work materials in these FEM models. The results show that the FEM model with ALE approach are adequate to simulate the stress and temperature distribution with a high accuracy while the FEM model with Lagrangian approach is capable in simulate chip formation.*

Keywords: Finite element modeling, Machining simulation, AISI 1045 steel, Ti-6Al-4V, Coating

1. Introduction

The stress and temperature distribution are not only commonly used criteria for the evaluation of machinability but also play a very important role in identifying not only the main tool wear mechanisms but also chip formation in the cutting process. Both mechanical wear and thermochemical wear (including dissolution and diffusion wear) are functions of the stress and temperature. On the other hand, the stress and temperature distribution on the chip are determined to explain the chip morphology and geometry which mainly are influenced on the stress and temperature distribution on the chip. The temperature on the tool and chip can be obtained by experimental techniques (thermocouple, infrared camera, temperature indicating liquid, etc.). However, these techniques only measure in-situ local temperatures. In another aspect, the stress on the chip and the tool is hardly obtained by experiment. Therefore, computer-aided engineering tools especially Finite Element Analysis (FEA) software was utilized to perform the simulation of both temperature and stress on the tool and chip. Many researchers have been using FEA simulation to study machining processes. Ansys, AdvantEdge, Abaqus, Deform, ThirdWave and FORGE are popular types of finite element software have been focused in the simulation the cutting process of steels and other alloys. A lot of research conducted with the Finite Element Modelling (FEM) simulation on the cutting processes for carbon steels, alloyed steels and other alloys such as Titanium alloys, Nickel alloys have been published. In general, the simulation results of FEM show a good agreement with the experimental data during the machining process. Borsos et al. [1] studied a 2D orthogonal turning model of AISI 1045 steel with Abaqus. By the comparison of result from the experiment and a simulation using Johnson-Cook damage model, he proved that the tangential forces obtained from simulation model are well adequate for various cutting conditions. The average difference between the tangential forces achieved in experimental measurements and those from computational analyses was about 23%. Arrazola et al. [2] using 2D cutting model with FEA software Abaqus/Explicit to understand the thermal phenomena in the cutting process of AISI 4140 steel with different tool geometries and tool coatings. He found that experiment and simulation both showed the temperatures on coated tools were less than those on uncoated tool. The temperatures on workpiece were higher than those on cutting tool. The tool geometry had significant effects to cutting temperatures. Wu et al. [3] conducted a simulation of

* Corresponding author: Tel.: (+84) 904.999.422
Email: trung.nguyenkien@hust.edu.vn

orthogonal cutting process of titanium alloy (Ti-6Al-4V) using ABAQUS software. The parameters for simulation were achieved by the compress experiment. The results of the simulation model well-presented cutting characteristic of the machining process. The orthogonal cutting finite element model showed adiabatic shear bands which is common cutting mechanism of Ti6Al4V. A 3-dimensional (3D) model was implemented in DEFORM 3D^{TM} by work of Klocke et al [4] in order to predict of chip formation and chip breakage in turning AISI 1045 steel. The results from FEM model correlated well to those in experiments.

The present paper outlines a preliminary investigation to study the implementation of 2D FEM with two approaches in orthogonal cutting model for AISI 1045 steel and Ti-6Al-4V with carbide and PCD tool respectively to obtain stress and cutting temperature. Furthermore, in the model of AISI 1045 steel, the temperature and stress in cutting zone with uncoated carbide tool (WC) are compared with those with TiN, TiCN and Al_2O_3 single layer coating in cutting process.

2. Simulation of machining using FEM

In industries, it is necessary to know if a new product or new design is adequate in working. Any possible failure and error in working condition are inevitable to be predicted, analyzed and controlled. In research, any new material also went through a lot of experimentation and testing at different working condition before applying in the industries. Therefore, the simulation of product in working environment is common used before testing in real process. Finite element modeling is most well-known as a numerical simulation method. FEM is an effective technique which uses a discretize model equations for engineering problems. It is a utilized platform for researchers to investigate for complex problem. Besides that, FEM can also provide relatively accurate results without carrying a lot of experiments which reduces cost and time. In machining process, FEM is frequently used to improve cutting processes which mainly included reducing cutting forces and cutting temperature; improving cutting time and surface finish by investigating various cutting condition regraded to cutting speed, feed rate, depth of cut, tool paths respected to workpiece material, tool materials and tool geometry. In spite of few limitations, the FEM permits to reduce the cost of manufacturing in terms of selecting right cutting condition; predicting chip formation, cutting forces and the tool life; and saving money and time by estimating physical phenomena in cutting simulation which could be happen in the real machining process.

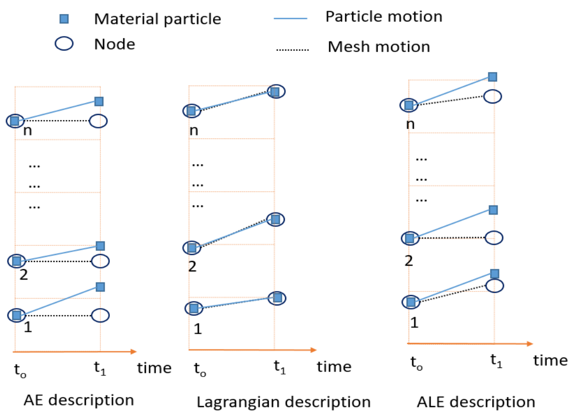

Fig. 1. The mesh and material description for 1D problem in three approaches.

In order to assigning elements of the plastic material flow in FEM modeling, there are three descriptions of motion: (1) Arbitrary Eulerian (AE) mesh description, (2) Lagrangian mesh description, and (3) a combination of Arbitrary Eulerian and Lagrangian (ALE) mesh description. The classical Lagrangian and Eulerian technique are both introduced by Boothroyd and Knight [5]. In AE technique which is widely used in fluid dynamics, the elements of the computational mesh are fixed in the space and do not distort throughout a simulation and the material is allowed to flow through elements. At the beginning of calculation, the material is contained within an element then passes through adjacent elements as calculation proceed. In Lagrangian technique which is mainly used in structural mechanics, the material is attached to elements that move with the flow. The material is contained and remained within an element throughout the simulation. Therefore, the mesh is tangle and experiments large distortions in region with high shear leading to numerical errors in the calculation. In an attempt to combine the advantages and minimize drawbacks of each individual formulation, ALE method was first proposed and developed in 1960s. In fact, there are classes of complex problem, for example a problem consists both structural components and fluids. The analysis of this type of the problems is not easily obtained using either a purely Eulerian or purely Lagrangian algorithms, while ALE has been applied successfully. In ALE approach, the movement of element is prescribed independently to that of material particles. In ALE, part of mesh may can be moved with the continuum in normal Lagrangian description, part of mesh be held fixed in Eulerian manner, and remainder will move in an arbitrarily specified way, thereby a mesh with large distortion can be handled with Lagrangian algorithms while AE method can afford for a mesh region needed higher resolution. The descriptions of mesh and material in three formulations for 1D problem are presented in Fig. 1.

2.1 Material constitutive modeling: Johnson and Cook constitutive model

To modeling the material strength, the phenomenological Johnson Cook (JC) model [6] is mostly used. The flow stress constitutive equation for the JC model is shown in Equation (1). The JC model presents the flow stress (σ) of a material as function of the plastic strain ε, the strain rate $\dot{\varepsilon}$ (s^{-1}) and temperature with the Johnson-Cook coefficients A, B, C, n, m (A [MPa] - the initial yield strength (quasi static yield strength) of the material at room temperature and a strain rate of l/s; fitting constant B [MPa] - the hardening modulus; C - the strain rate sensitivity coefficient; m - thermal softening coefficient; n - hardening coefficient; T_m [°C] melting temperature of material; and T_0 [°C] - room temperature).

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

In order to run the simulation correctly, first and foremost, the JC coefficients, the high stress and strain rates with a high adiabatic shearing were obtained from the experiment with Split Hopkinson bar compression tests. The sets of these parameters of example materials is given in Table 1. The set of JC parameters from study of Borsos et al. [1] and Meyer et al. [8] is used for the cutting simulation of AISI 1045 steel and Ti-6Al-4V, respectively in this study.

Table 1. Johnson-Cooks plasticity coefficients for AISI 1045 steel and Ti-6Al-4V

Material	AISI 1045 [1]	AISI 1045 [7]	AISI 1045[9]	Ti6Al4V[8]
A [MPa]	553.1	553	553	862.5
B [MPa]	600.8	600	600	331.2
C	0.0134	0.234	0.234	0.012
n	0.0234	0.0134	0.0134	0.34
m	1	1	1	0.8
ε_0 [σ^{-1}]	1	-	0.001	-
T_0 [°C]	25	25	20	-
T_m [°C]	1460	1460	1460	1650

2.2 Ductile damage model for chip fracture criterion (chip formation)

The ductile failure behavior of a material is very important in order to successfully simulate the chip formation (the separation between chip and workpiece) in a machining process with FEM. The ductile damage (structural failure) of a material starts to occur since the load-carrying capacity and resistance to deformation of the material are not introduced anymore. The experimental studies show that the failure behavior depends on both the loading conditions and the material properties. The material failure described by the Johnson-Cook criterion is one of the most used models to describe ductile failure in numerical simulation for metals with for high strain-rate deformation only. The JC failure model follows a cumulative damage law that the failure is assumed to occur at physical criterion when the damage parameter *D* exceeds 1. This is the criterion for chip formation. The expression of damage parameter *D* in the JC ductile failure model is introduced in the Equation (2) with $\bar{\varepsilon}_f^{pl}$ and $\Delta\bar{\varepsilon}^{pl}$ are the equivalent plastic strain at failure and the increment of equivalent plastic strain. The strain at failure, $\bar{\varepsilon}_f^{pl}$ is calculated by Equation (3) from dimensionless stain rate $\dot{\bar{\varepsilon}}_f^{pl}/\dot{\varepsilon}_0$ and non-dimension pressure-deviatoric stress ratio, *p/q*, with D_1 to D_5 are failure parameters ($\dot{\bar{\varepsilon}}_0$ - reference stain rate, *p* - pressure stress, *q* - Misses stress). In the ALE formulation, the JC dynamic failure model is used in ABAQUS/Explicit. Table 2 presents the sets of JC failure parameters for AISI 1045 steel in the FEM cutting simulation on this work and other studies.

$$D=\sum\left(\frac{\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_f^{pl}}\right) \quad (2)$$

$$\bar{\varepsilon}_f^{pl}=\left[D_1+D_2\exp\left(D_3\frac{p}{q}\right)\right]\left[1+D_4 Ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left(1+D_5\frac{T-T_0}{T_{melt}-T_0}\right) \quad (3)$$

Table 2. Johnson-Cook damage coefficients for the analytical failure model for AISI 1045 steel

D_1	D_2	D_3	D_4	D_5	$\varepsilon_0[s^{-1}]$	References
0.05	4.22	-2.73	0.0018	0.55	1	Borsos et al. [1]
0.06	3.31	-1.96	0.0018	0.58	-	Duan et al. [9]

In this paper, Johnson and Cook constitutive model is implemented in both FEM model A and B while Johnson-Cook criterion is applied on FEM model A to study chip formation as well as the effects of different coating materials on carbide substrate in an orthogonal cutting process of AISI 1045 steel.

3. Simulation setup and simulation data

3.1 Geometrical model and simulation parameters

This study used 2D orthogonal cutting model to obtain the chip formation, the stress and temperature profile in cutting. Two FEM simulation models were used in this study:

FEM model A with Lagrangian approach is applied for AISI 1045 steel with uncoated and single layer coated carbide tool (TiN, Al_2O_3, and TiCN).

FEM model B with ALE method is used in cutting process with Ti-6Al-4V with PCD tool.

These tool material and coatings are currently the most common tool coatings for machining of casting and alloy steels due to high hardness, good wear-resistant characteristics and low friction coefficient. PCD is well-known tool material in cutting of Ti alloys since they showed good wear resistance to mechanical and chemical wear. The mechanical parameters of work material and tool materials used in the simulation are presented in Table **3**. The both simulation is conducted with tool geometry with the rake angle of 7°, the clearance angle of 0°. The cutting process on Ti-6Al-4V simulated at cutting speed of 61 ÷ 121 m/min and feed rate of 0.127 mm/rev while cutting speed of 100 ÷ 500 m/min and feed rate of 0.2 mm/rev were used for the simulation with AISI 1045.

Table 3. Material parameters for work material and tool materials

	AISI 1045 [1]	Ti6Al4V [10]	WC [11]	Al_2O_3 [11]	TiN [11]	TiCN [11]	PCD[12]
Density [kg/m^3]	7800	4420	4940	3780	5420	4180	3520
Elastic [Pa]	2.00E+11	1.14E+11	4.50E+11	3.40E+11	2.5E+11	3.55E+11	8E+11
Poisson's ratio	0.3	0.34	0.18	0.23	0.25	0.2	0.3
Expansion Coefficient [1/°C]	1.15E-5	9E-5	7.7E-6	8.4E-6	9.35 E-6	8.0 E-6	2.26E-6
Specific Heat [J/kg°C]	486	560000	565.15	1173	818.9	1120	600
Thermal conductivity [W/m.°C]	49.8	6.7	30.9	8.75	23	32	520
Melting Temp. [°C]	1460	1620	2780	2072	2950	2930	-
Reference Temp. [°C]	25	25	25	25	25	25	-

3.2. Boundary conditions and element meshing

The FEM simulation model A was conducted with three boundary conditions to evaluate cutting stress and temperature. The cutting tool was allowed to move in X-direction with cutting speed V_x from the right to the left while its movement in *Y*-direction is restrained. The workpiece was assumed to be fixed at the bottom. The most part of the left side of workpiece is constrained X-direction. Fig. 3 demonstrates for all boundary conditions used in this study. In orthogonal cutting configuration, un-deformed chip thickness that specified tool position is equal to the feed rate. Tool is modeled with a coating layer with thickness of 5 µm. In element meshing of model A, a workpiece with two parts is developed to facilitate for chip formation and to control the contact. Part 1 is a region with fine elements to form chip while the remainder is workpiece support which consists of bigger elements as shown in Fig. 2. The influence of mesh size in the simulation time is significant. The simulations were performed with element size ranged from 0.005 to 0.05 mm in order to reduce computing time.

The 2D-FEM model B use Johnson-Cook model and ALE formulation to obtain the temperature profile. The chip formation in model B is only generated by defined geometry because it uses ALE mesh description. In this model, the tool was fixed while the workpiece moved in *X* direction with velocity V_x. The workpiece was also fixed at the bottom as shown in Fig. 3.

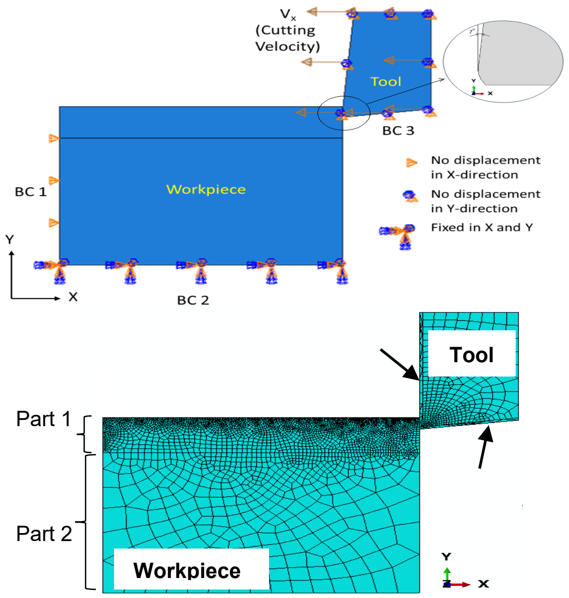

Fig. 2. Boundary conditions and element meshing for FEM model A in cutting process of AISI 1045.

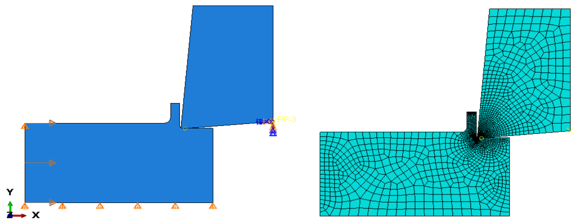

Fig. 3. Boundary conditions and element meshing for FEM model B in cutting process of Ti-6Al-4V.

4. Result and discussion

In both FEM simulation models, the stress and cutting temperature are plotted along three profiles. Profile 1 is along chip thickness, Profile 2 is along chip's length 2, and Profile 3 is along the rake face of the tool as shown in Fig. 4.

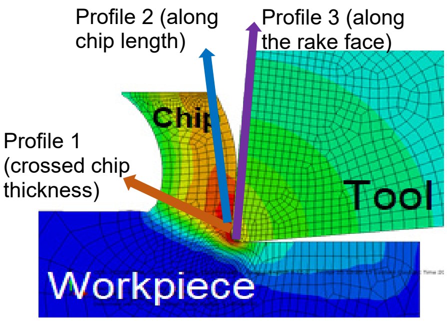

Fig. 4. The evaluated profiles of cutting stress and cutting temperature.

4.1 *The result of AISI 1045 cutting process with FEM model A*

In FEM model A with Lagrangian approach, the nodes and elements on three profiles were deflected due to the chip formation and chip breakage during cutting simulation. Therefore, the cutting process was simulated at the beginning with 0.5 mm of cutting length to minimize deflection. Although the cutting temperature at the beginning cutting stage was lower than those at the steady state process, the setup is valid to comparison purpose for cutting behavior of tool material and coatings. An example of chip formation, distribution of cutting stress and cutting temperature is demonstrated in Fig. 5 for cutting process with TiCN coating. The results of the simulation show that the simulation of the chip geometry formation was reasonable acceptable. The high stress was found at shear zone where the chip formed. In all simulations with and without the coating layers, the chip experienced higher cutting temperatures than the tool which shows a good agreement with the characteristics of real machining process.

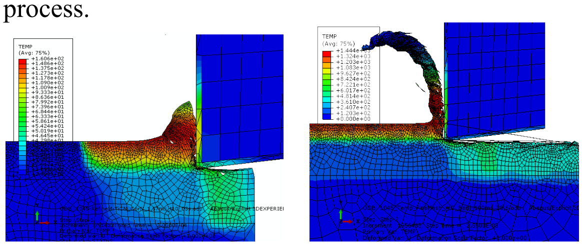

Fig. 5. The chip formation and temperature distribution with FEM models A for AISI 1045.

Fig. **6** plotted the stress with Al_2O_3 coated tool at along profile 1 and profile 2, while Fig. **7** represented temperature along these profiles.

Fig. **7** compared cutting temperature along Profile 3 in cutting process with uncoated tool and coated tools at cutting speeds of 100 and 400 m/min. In general, the higher cutting temperature and stress on workpiece were obtained at the high cutting speeds. Along Profiles 1 crossed the chip thickness, the high temperature was obtained near the contact zone for low cutting speeds, while high cutting speed showed high temperatures near the top surface of the chip. It can be declared that, at Profile 2 along chip thickness, the highest temperature is occurred near the tool tip which is common in machining of steels. The high temperature at the tool tip would lead to edge softening and fracturing off resulted in tool failure at early stage. In comparison with other researches, the results are relatively comparative with the simulation and experimental cutting temperatures reported in study of Fahad et al. [11] with $TiCN/Al_2O_3/TiN$ multi-coated tool. In his study, the maximum cutting temperature is around 170 °C at cutting speeds of 314 m/min and feed rate of 0.16 mm/rev.

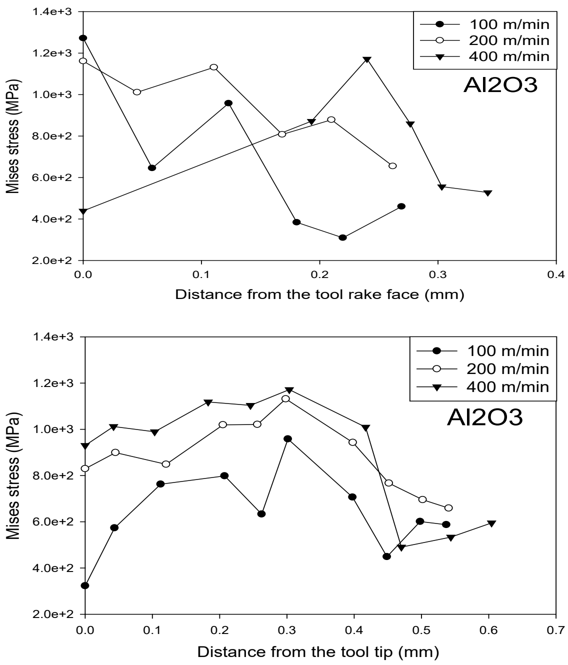

Fig. 6. Stress on profile 1 (crossed chip thickness) and profile 2 (along chip length) in cutting process of AISI 1045 with the Al_2O_3 coating.

In other view regarded to tool material and coatings, at high cutting speeds (500 m/min), the varied coatings showed slight difference in tool temperatures. However, the effect of coating to temperature on the rake face is more apparently at low cutting speed (100 m/min) as shown in Fig. 8.

The Al_2O_3 had the lowest cutting temperatures along the rake face. The highest temperatures were obtained with uncoated tool and TiCN coating. High cutting temperature contributed to significant effects to the wear rate at rake face (crater wear) in which the dissolution/diffusion wear was dominant at the high temperature zone, while abrasive wear and adhesion wear was minor. The reduction in tool hardness and edge geometric stabilization which were also very important in machining process was another consequence of the high tool temperature.

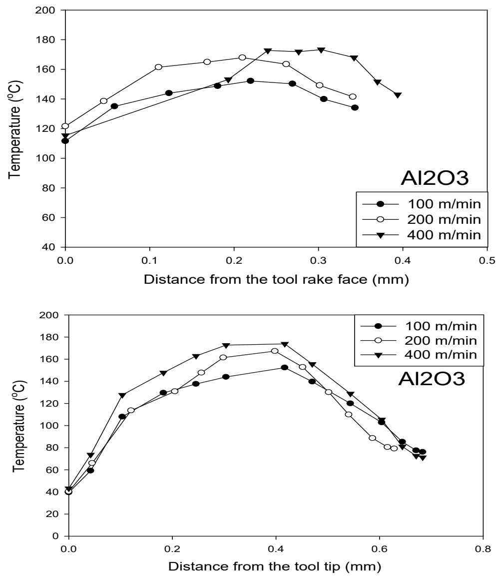

Fig. 7. Temperature on Profile 1 and Profile 2 in cutting process of AISI 1045 with the Al_2O_3.

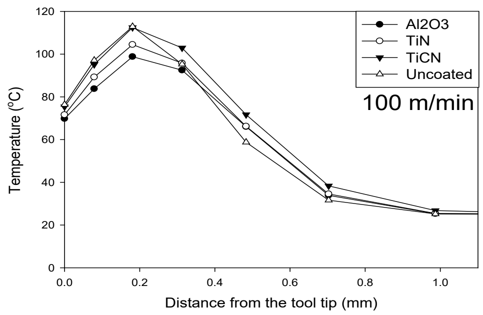

Fig. 8. Temperature on Profile 3 (along rake face) in cutting process of AISI 1045 with varied coatings at cutting speed of 100 m/min

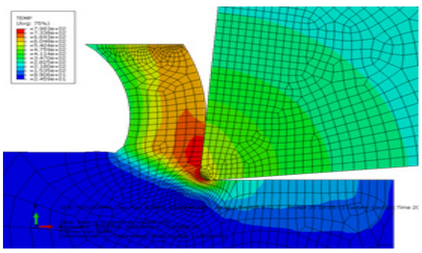

Fig. 9. The chip formation and temperature distribution with FEM models B for Ti-6Al-4V.

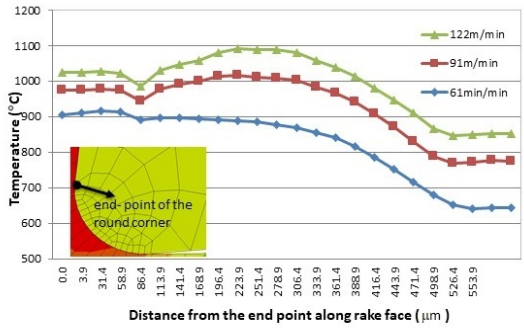

Fig. 10. Temperature on Profile 1(along tool rake face) in cutting process of Ti-6Al-4V with PCD tool.

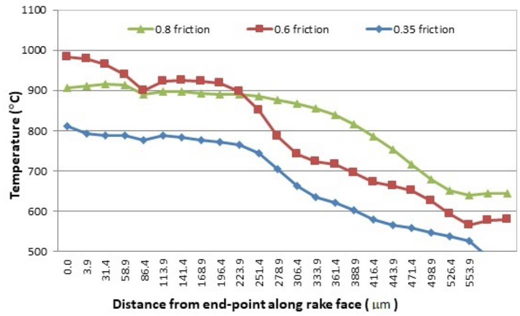

Fig. 11. The effect of tool-chip friction coefficient in cutting process of Ti-6Al-4V with PCD tool.

4.2 *The result of Ti-6Al-4V cutting process with FEM model B*

In case of FEM model B for cutting process of Ti-6Al-4V, the temperature profiles on the chip along the rake face and through the thickness of the chip were the main interest. The highest cutting temperature is happened near the tool tip (tool nose) as shown in Fig. 9. This is opposite to those in cutting of steels which was observed far from tool tip. Fig. 10 plotted temperature at Profile 3 with various cutting speeds. The effects of cutting speed to cutting temperature was more significant than those in case of AISI 1045 cutting. Titanium alloy are classified as difficulty-to-machine cause of their low thermal conductivity leading very high temperate at cutting zone. The simulation results are accepted in comparison with experiment data. The research work of Khanna et al. [13] on cutting of Titanium alloys at feed rate of 0.15 mm/rev showed that cutting temperatures are in the range of 600 °C ÷ 800 °C and 800 °C ÷ 1000 °C for cutting speeds of 40 m/min and 80 m/min. In addition, although the majority of heat generated was from plastic deformation, the simulation results proved that the friction has some impact on the temperature profile as shown in Fig. 11. To determine a reasonable friction coefficient to be used, a comparison of chip-tool contact length between experiment data and those of simulation model is needed to be carried out in future work.

5. Conclusion

In this work, two 2D FEM simulation models are conducted with Abaqus software to study stress and temperature distribution in orthogonal cutting process The cutting process of AISI 1045 steel with uncoated and single layer coated carbide tool (TiN, Al_2O_3, and TiCN) is simulated with the model A by Lagrangian approach while the cutting of Ti-6Al-4V with PCD tool is conducted in the model B with ALE method. The effect of Al_2O_3, TiN and TiCN coatings on carbide tool in cutting process of AISI 1045 steel and their differences were also studied. The result of the both simulation models is acceptable in term of predicting chip formation, stress and temperature distribution. However, the findings of simulation model need to be verified with the experimental results for confirmation. From this investigation, some of outcomes are:

The simulation of mechanical-thermal behavior of cutting process is acceptable for both models. The simulation of the chip geometry formation with FEM model A is capable with a reasonable accuracy. The limitation in chip formation of FEM model B makes this approach only suitable for study the stress and temperature distribution.

In comparison of cutting process of AISI 1045 steel and Ti-6Al-4V, the Titanium alloy is obtained the highest temperatures closer to the tool tip than those of the steel. This phenomenon is needed to be aware to avoid fracturing of tool edge.

In comparison of different coatings in cutting process of AISI 1045, the Al_2O_3 showed the highest reduction in tool temperatures at low cutting speed in comparison with TiN and TiCN coatings, although its influence is not strong at high cutting speed.

With extra verification work, this study can be developed as a useful reference for investigating cutting conditions, tool materials, coating materials; and explaining cutting properties of machining process.

6. Acknowledgements

This study was conducted with financial support from Hanoi University of Science and Technology (HUST) under project number T2016-PC-062. The School of Mechanical Engineering at HUST is also gratefully acknowledged for providing guidance and expertise.

Reference

[1] Borsos, Benjámin, András Csörgo, Anna Hidas, Bálint Kotnyek, Antal Szabó, Attila Kossa, and Gábor Stépán. "Two-Dimensional Finite Element Analysis of Turning Processes." Periodica Polytechnica. Engineering. Mechanical Engineering 61, no. 1 (2017): 44.

[2] Arrazola, P. J., I. Arriola, and M. A. Davies. "Analysis of the influence of tool type, coatings, and machinability on the thermal fields in orthogonal machining of AISI 4140 steels." CIRP Annals-Manufacturing Technology 58, no. 1 (2009): 85-88.

[3] Wu, Hong-bing, Chengguang Xu, Zhi-xin Jia, Xue-chang Zhang, and Gang Liu. "Establishment of constitutive model of titanium alloy Ti6Al4V and validation of finite element." In Measuring Technology and Mechatronics Automation (ICMTMA), 2010 International Conference on, vol. 2, pp. 141-144. IEEE, 2010.

[4] Klocke, Fritz, Dieter Lung, and Christoph Essig. "3D FEM model for the prediction of chip breakage." In Advanced Materials Research, vol. 223, pp. 142-151. Trans Tech Publications, 2011.

[5] Knight, Winston A., and Geoffrey Boothroyd. Fundamentals of metal machining and machine tools. Vol. 198. CRC Press, 2005.

[6] Johnson, Gordon R., and William H. Cook. "A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures." In Proceedings of the 7th International Symposium on Ballistics, vol. 21, no. 1, pp. 541-547. 1983.

[7] Nasr, Mohamed NA. "Effects of sequential cuts on residual stresses when orthogonal cutting steel AISI 1045." Procedia CIRP 31 (2015): 118-123.

[8] Meyer, Hubert W., and David S. Kleponis. "Modeling the high strain rate behavior of titanium undergoing ballistic impact and penetration." International Journal of Impact Engineering 26, no. 1 (2001): 509-521.

[9] Duan, C. Z., T. Dou, Y. J. Cai, and Y. Y. Li. "Finite element simulation and experiment of chip formation process during high speed machining of AISI 1045 hardened steel." International Journal of Recent Trends in Engineering 1, no. 5 (2009): 46-50.

[10] Calamaz, Madalina, Dominique Coupard, and Franck Girot. "A new material model for 2D numerical simulation of serrated chip formation when machining titanium alloy Ti–6Al–4V." International Journal of Machine Tools and Manufacture 48, no. 3-4 (2008): 275-288.

[11] Fahad, Muhammad, Paul T. Mativenga, and Mohammad A. Sheikh. "A comparative study of multilayer and functionally graded coated tools in high-speed machining." The International Journal of Advanced Manufacturing Technology 62, no. 1 (2012): 43-57.

[12] Schindler, S., M. Zimmermann, J. C. Aurich, and P. Steinmann. "Finite element model to calculate the thermal expansions of the tool and the workpiece in dry turning." Procedia CIRP 14 (2014): 535-540.

[13] Khanna, N., and Sangwan, K. S. "Machinability analysis of heat treated Ti64, Ti54M and Ti10. 2.3 titanium alloys." International Journal of Precision Engineering and Manufacturing, 14(5), (2013): 719-724.