Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 1619-1628
doi:10.4028/p-be47dp

Submitted: 2021-12-08
Revised: 2022-01-31
Accepted: 2022-02-02
Online: 2022-07-22

Influence of Coulomb's Friction Coefficient in Finite Element Modeling of Orthogonal Cutting of Ti6Al4V

Nithyaraaj KUGALUR PALANISAMY[1,a*], Edouard RIVIÈRE LORPHÈVRE[1,b], Pedro - José ARRAZOLA[2,c] and François DUCOBU[1,d]

[1]University of Mons, Research Institute for Science and Material Engineering, Machine Design and Production Engineering Lab – Belgium.

[2]Mondragon Unibertsitatea, Faculty of Engineering, Mechanical and Manufacturing Department – Spain.

[a]Nithyaraaj.KUGALURPALANISAMY@umons.ac.be, [b]Edouard.RIVIERELORPHEVRE@umons.ac.be, [c]pjarrazola@mondragon.edu, [d]Francois.DUCOBU@umons.ac.be.

Keywords: Ti6Al4V; Orthogonal Cutting; ALE Model; Friction; Coulomb; Forces; Chip Morphologies

Abstract. The reliability of the pertinent parameters set of Johnson-Cook constitutive model is highly linked with the friction condition at the tool-chip-workpiece interface. In the present work, a study on the influence of Coulomb's friction coefficient on the observables such as forces, chip thickness and chip curvature by FE simulation of orthogonal cutting of Ti6Al4V alloy has been carried out. A FE model with an Arbitrary Lagrangian-Eulerian (ALE) approach is employed to simulate the cutting process for different cutting conditions. The simulated results, for a wide range of friction conditions, are analyzed and compared with experimental results. The analysis show that the Coulomb's friction coefficient has a direct link with the observables. The paper reveals that for accurate prediction of observables an optimized value of the coefficient of friction in correlation with the parameters values of the constitutive model is imperative.

Introduction

The conventional machining process generally plays an important role in the manufacturing industries. In the metal cutting process, the tool and the workpiece are subjected to thermo-mechanical loads due to chip separation and the friction between the tool-chip-workpiece [1]. During the cutting process, large elastic-plastic deformations are observed at a very high strain rate in the order of 10^3 to 10^6 s^{-1} and a significant amount of heat is generated at the tool-chip interface [2, 3]. The complexity of the cutting process further increases with Ti6Al4V alloy because of its intrinsic properties such as high chemical reactivity, low thermal conductivity, etc. [4, 5]. Due to the complexity, the direct measurements of stresses and temperature distribution in the deformation zones during machining experiments are extremely difficult. So, the Finite Elements Modeling (FEM) in particular, has been employed by the researchers for the simulation of the machining process [2, 6]. The efficiency of the FE model of orthogonal cutting is determined by the selected numerical parameters such as type of formulation (Lagrangian, Eulerian, Arbitrary Lagrangian-Eulerian, or Coupled Eulerian-Lagrangian), material models, friction models, and chip separation criterion [2, 7, 8].

The accuracy of the FE model is mainly defined by the material model and the contact condition between the tool-chip-workpiece. A reliable constitutive model is necessary to describe the deformation behavior of a workpiece subjected to machining, that is to relate the large plastic strains at the very high strain rates and temperatures observed during the machining process. For orthogonal cutting of Ti6Al4V alloy many empirical and physical-based models have been proposed and employed by the researchers. Due to the robustness and large availability of data's empirical models are highly recommended for numerical modeling of orthogonal cutting of Ti6Al4V [2, 9]. In the article [10, 11, 12] the authors employed the Lagrangian model with chip separation criteria and justifies the value of the parameters of the constitutive model is another most significant input that affects the accuracy of the simulated result. However, the author neglected the influence of friction coefficient parameters.

In the modeling of the machining process, the tool-chip friction is one of the most significant problems that need to be addressed for the accurate prediction of observables [13]. This paper particularly deals with the study on the influence of the Coulomb friction coefficient values. For this work, an Arbitrary Lagrangian-Eulerian formulation without chip separation criteria is adopted and the well-known Johnson-Cook constitutive material model [14] with the parameters set identified by Seo et al. [15] is considered. The contact condition is defined by Coulomb friction law. To study the influence of friction coefficient 20 values generated via LHS (Latin Hypercube Sampling) ranging between the values 0.0 to 1.0 are considered for simulation. The observables such as cutting force, feed force, chip thickness, and chip curvature are calculated and are compared between the 20 numerical simulations and the experimental reference to select the best friction coefficient value.

The Constitutive Model and its Parameters

The Johnson-Cook (JC) constitutive model [14] is the well-known and highly exploited empirical model for its mathematical simplicity and flexibility. The Johnson-Cook flow stress equation is represented by combining the plastic, viscous and softening term and its flow stress equation is represented by the Eq. 1:

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

The JC equation requires five material parameters (A, B, C, n, m) and their values depend on the material. These are determined by flow stress data obtained from experiments. The parameter A is the yield stress of the material, B is the modules of strain hardening, n is the strain-hardening exponent, C the strain rate sensitivity, and m is the thermal softening exponent. T is the current temperature, T_{melt} and T_{room} are the melting and the room temperatures respectively, while $\dot{\varepsilon}_0$ is the reference strain rate.

The parameters data are taken mostly from dynamic experimental material tests such as Split Hopkinson Pressure Bar (SHPB) [2, 7]. However, the observables from SHPB experiments are inadequate to represent the deformation behavior of the material so, the parameter's values are extrapolated. These extrapolations of data rise the concern which also leads to the proposition of numerous parameters sets by the researchers for the same material [11, 16]. In [10, 11] the authors conducted extensive research to justify the influence of parameters value and suggest the parameters set from the work of Seo et al. [15] can be able to produce numerical result close to the experimental ones. In this work, the parameters set for JC model is adopted from the work of Seo et al. [15] as recommended by Ducobu et al. [11] and are reported in Table 1.

Table 1. Parameter set adopted from Seo et al. [15].

Parameters	Values
A (MPa)	997.9
B (MPa)	653.1
C	0.0198
m	0.7
n	0.45
T_{room}(K)	298
T_{melt}(K)	1878

Friction Model

In addition to the material model, the friction model has a crucial impact on the simulation results of the orthogonal cutting model. Along with the material model and its parameters the contact condition or the friction condition between the tool-chip is another most important problem that needs to be addressed carefully [3, 16]. In [3] the authors conducted extensive research on the importance of friction condition in modeling the cutting process. In this article many friction models are analyzed to name a few, Coulomb's friction, Velocity-dependent friction, Sticking-sliding friction models (Zorev's model) are some notable models employed in machining process modeling.

In the study, the well-known, simple, and most extensively used Coulombs or Sliding friction model is considered. Even though it has been criticized by the researchers, the Coulombs model is still highly employed for its simplicity and the good qualitative trends it provides. Nevertheless, friction parameters of the coulombs model are difficult to be experimentally measured. Even though methods like pin-on ring friction test are available to determine the friction characteristics during the cutting process the information is uncertain due to phenomena taking place at the tool-chip contact area [3, 16, 17].

The classical Coulomb's friction model states that the frictional sliding force is proportional to the applied normal load. The ratio of frictional sliding force to the applied normal force is the coefficient of friction μ. The coefficient of friction is constant in all the contact lengths between chip and tool. The Coulomb friction law is expressed as:

$$\tau = \mu \sigma \tag{2}$$

To determine the influence of friction coefficient parameter, a sample of 20 friction coefficient parameter values in the range of 0.0 (no friction) to 1.0 is generated using the Latin Hypercube Sampling (LHS) [18].

Finite Element Orthogonal Cutting Model

A two-dimensional (2D) plane strain model with orthogonal cutting assumption was considered for the work. The finite element software Abaqus is used to model the thermo-mechanical chip formation process. In this work, an explicit Arbitrary Lagrangian-Eulerian finite element formulation is adopted to simulate the orthogonal cutting process of Ti6Al4V. This ALE formulation combines the advantage of Langrangian and Eulerian which allows to take into account the large deformations during the material flow around the cutting edge without using a chip separation criterion.

In this FE model the tool is fixed, and the workpiece moves with the prescribed velocity. The length of the workpiece is $3h$ where h is the uncut chip thickness. The area near the cutting zone (near the tool-tip) is modeled with finer mesh. In this approach, the initial geometry of the chip has to be pre-defined with respect to the uncut chip thickness (h). For the tool, the tungsten carbide is considered, and the linear elastic law is imposed. The material properties employed in the model are given in Table 2.

Table 2. Material properties considered for this study [20]

Material properties	Ti6Al4V	Tungsten Carbide
Density, ρ (kg/m^3)	4430	15000
Young's modulus, E (GPa)	113.8	800
Poisson's ratio ν	0.342	0.2
Expansion, α (K^{-1})	8.6 e^{-6}	4.7 e^{-6}
Conductivity, k (W/mK)	7.3	46
Specific heat, c_p (J/KgK)	580	203

The tool and the workpiece meshed with quadrilateral elements with reduced integration CPE4RT for a coupled temperature-displacement calculation. In this model, the inflow, outflow, and chip top surfaces of the chip are modeled as a Eulerian surface. The mass scaling was considered to artificially increase the critical time increment of the simulations.

The mass scaling factor of 1,000 was considered as it shows a significant decrease in the computational time, without affecting the results [19]. This approach is crucial to attain the steady state (6 ms is enough) for force calculations with less computation time 3h45 with 6 cores intel i7 processor. The tool geometry is defined by the cutting conditions and are given in Table 3.

Table 3. Cutting conditions

Cutting speed (m/min)	30
Uncut chip thickness (µm)	100
Rack angle (°)	15
Clearance angle (°)	2
Cutting edge radius (µm)	20

The basic geometry and the boundary conditions are illustrated in Fig. 1. The thermal properties are adopted from the reference [21]. The initial temperature for tool and workpiece is set to 298 K.

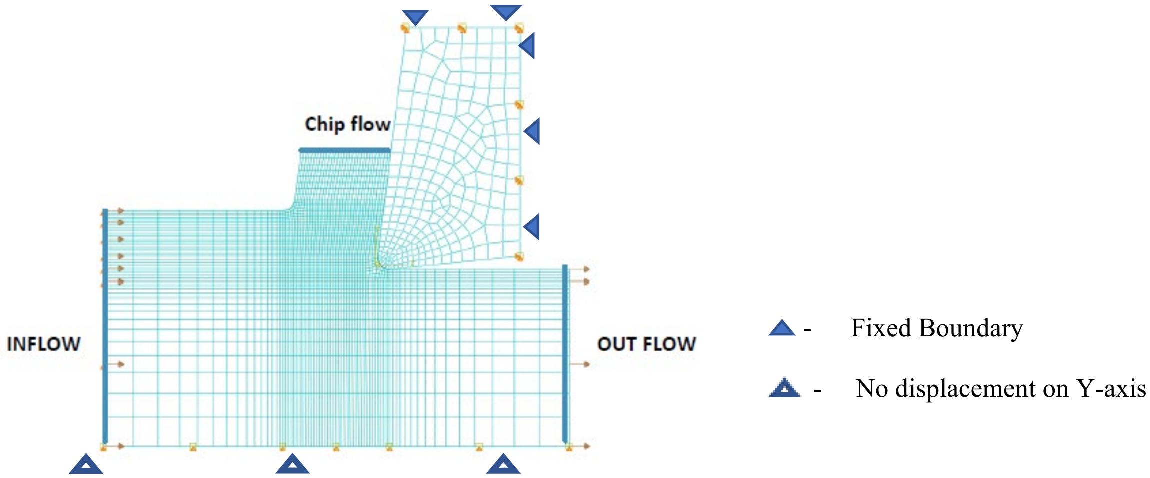


Fig. 1. Finite element model with Initial geometry, initial mesh structure, boundary conditions.

Experimental Reference

The experimental work of Ducobu et al. [22] on orthogonal cutting of Ti6Al4V with the same cutting condition is given in the Table 3 for uncut chip thickness of 100 µm is considered as a reference for this study. A continuous chip was observed from the orthogonal cutting experiment for uncut chip thickness of 100 µm. The chip observed from the experiment is shown in Fig 2.

The RMS value of cutting force (Fc) was 173 ± 2 N/mm, the feed force (Ff) was 51 ± 2 N/mm, the chip thickness (h') was 0.135±0.006 mm, and the chip radius of the curvature (R) was 0.33±0.05 mm.

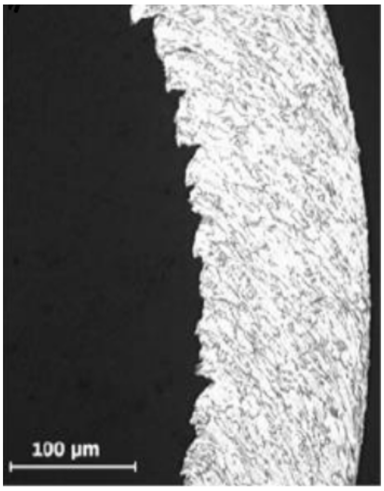


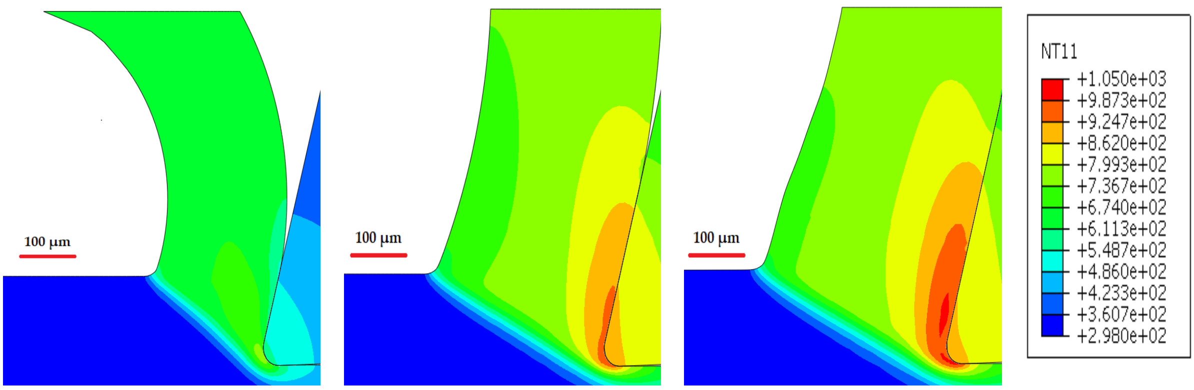
Fig. 2. Experimental reference Chip morphology for uncut chip thickness of 100 µm [22].

Methodology

To study the influence of Coulomb friction coefficient a total of 20 simulations has been carried out with the cutting condition given in Table 3. The workpiece and tool geometry, the constitutive model, and its parameters are kept constant and only the friction coefficient parameter value is updated from the values generated by LHS. To facilitate the simulation, process workflow automation for the Abaqus platform has been created to calculate the observables such as cutting force, feed force, chip thickness, and chip curvature. The result from numerical simulations is further compared with experimental results for validation.

Results and Discussion

The morphologies of the numerically simulated chips from the 20 simulations are all continuous as the experimental reference. The temperature distribution of numerical chips is given in Fig 3. The temperature difference and the plastic strain in the deformation zones of the chips are compared and analyzed. As expected, the temperature is maximum in the secondary deformation zone for all the numerical chips, and the magnitude of the temperature increases with the increase of friction coefficient value and remains almost constant after $\mu = 0.84$. In addition, a non-uniform temperature distribution is observed between the tool and the chip. These temperatures discontinuity attributes to the thermal contact resistance.



a b c d

Fig 3. Temperature contour (in K) of (a) $\mu = 0.0$ (b) $\mu = 0.53$ (c) $\mu = 1.0$ (d) Temperature scale for h= 100 µm at 20 ms of cutting time.

The maximum temperature at the secondary deformation zone of the chip with respect to friction coefficients value is given in the Fig 4.

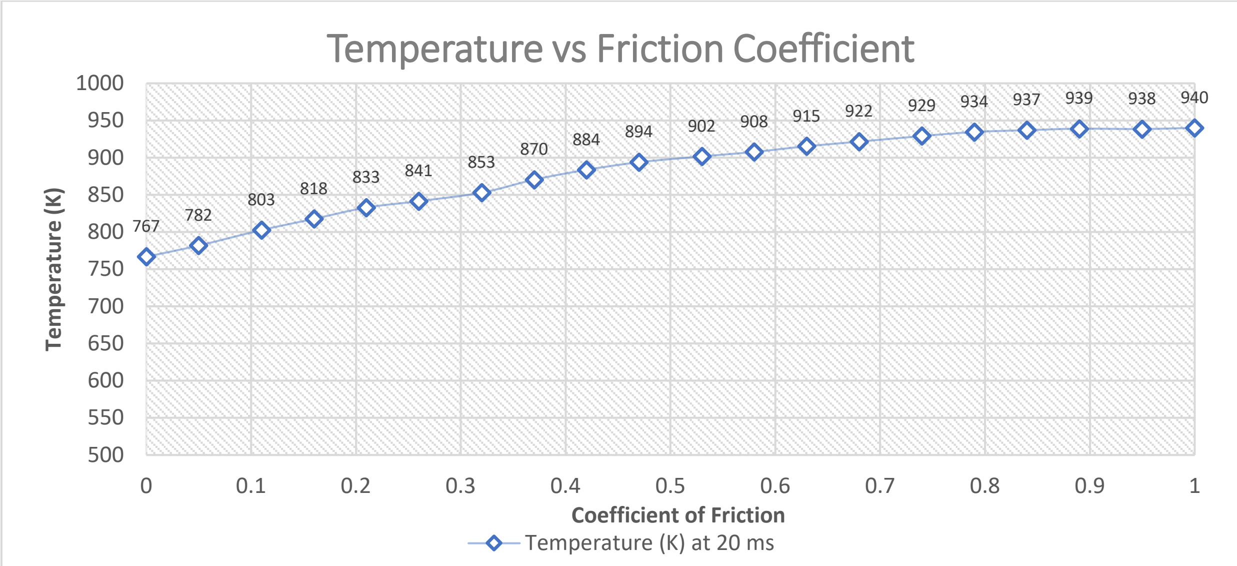
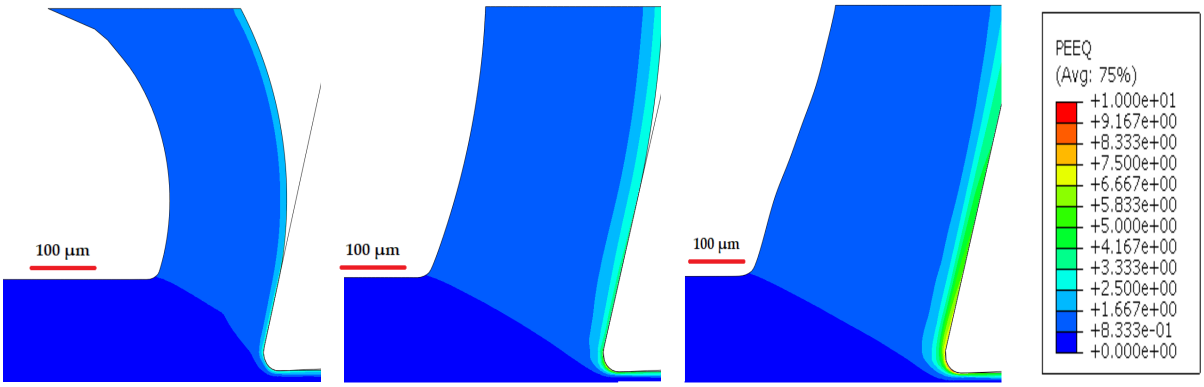


Fig. 4. Maximum temperature in the chip vs the friction coefficient.

For all the numerical chips high plastic strain is observed at the chip side in contact with the tool rake face and the Equivalent plastic strain (PEEQ) goes up to 16 for the friction coefficient of μ = 1.00. The PEEQ contour is given in Fig 5.



a b c d

Fig 5. PEEQ contour of (a) μ = 0.0 (b) μ = 0.53 (c) μ = 1.0 (d) PEEQ scale for h= 100 μm at 20 ms of cutting time.

When the temperature increases the force increases as the temperature in the deformations zones is directly linked to the forces. The RMS values of cutting force and feed force are given in Table 4.

Table 4. RMS cutting force (Fc), feed force (Ff), chip thickness (h'), chip radius of curvature (R) and Δx differences with the experimental forces of h = 100 μm

μ	Fc (N/mm)	Δ_{Fc} (%)	Ff (N/mm)	Δ_{Ff} (%)	h'(mm)	$\Delta_{h'}$ (%)	R(mm)	Δ_R (%)
EXP	173±2	-	51±2	-	0.135±0.006	-	0.33±0.05	-
0	148	14	35	31	0.158	17	0.05	-85
0.05	154	11	36	29	0.161	19	0.09	-73
0.11	163	6	35	31	0.167	24	0.13	-61
0.16	171	1	37	27	0.174	29	0.18	-45
0.21	179	3	41	20	0.181	34	0.25	-24
0.26	187	8	44	14	0.193	43	0.31	-6
0.32	198	14	50	2	0.203	50	0.39	18
0.37	208	20	57	12	0.215	59	0.42	27

0.42	218	26	63	24	0.227	68	0.44	33
0.47	228	32	70	37	0.238	76	0.46	46
0.53	238	38	79	55	0.249	84	0.51	62
0.58	244	41	85	67	0.245	81	0.61	85
0.63	251	45	92	80	0.250	85	0.69	109
0.68	256	48	97	90	0.258	91	0.78	136
0.74	265	53	105	106	0.268	99	1.09	230
0.79	269	55	111	118	0.274	103	1.33	303
0.84	273	58	117	129	0.275	104	1.35	309
0.89	277	60	123	141	0.276	104	1.50	355
0.95	276	60	124	143	0.277	105	2.05	521
1.00	277	60	125	144	0.277	105	2.36	615

The cutting force and feed force varied exactly in the same manner concerning the variations in the coefficient of friction as shown in Fig 6. The increment of cutting forces is observed till the friction coefficient value of 0.89, after which the magnitude is reduced and remained almost constant. Whereas, for the feed force the increment is observed for the friction coefficient between the value of 0.16 to 0.89 and the magnitude is almost constant between 0.0 to 0.16 and 0.89 to 1.0. The evolution of forces with respect to values of friction coefficient is given in the Fig 6.

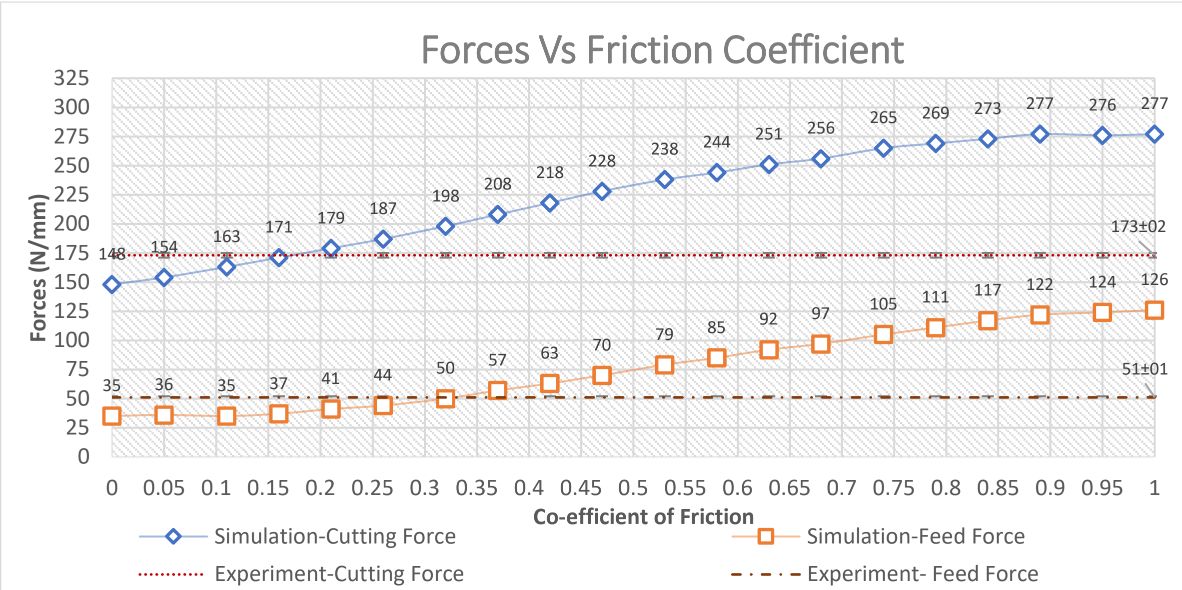


Fig. 6. RMS value of cutting forces and feed force vs the friction coefficient.

The thickness of the chip increases when the friction coefficient increases up to the value of 0.84 after which the chip thickness remains almost constant. This is due to the fact that when the friction at the tool-chip interface increases, the shear angle decreases, and the chip becomes thicker. This can be observed in the numerical chip by an increase in shear strain. In other words, due to friction the temperature between tool and chip interface increases which in turn increases plastic deformation, and to accommodate the flow of the chip, the chip thickness increases. It is also observed that there is a change in the evolution of chip thickness when the friction coefficient increases from 0.53 to 0.58, and it is not observed in the force evolutions. This may be due to the material behavior and thermal boundaries applied in the FE model. Fig 7 represents the evolution of chip thickness vs friction coefficient values. In addition, it is observed that the chip radius of curvature increases, with the increase of friction coefficient. This is because, when the friction is increasing the tool rake face provides resistance to the chip to slide. It is evident that for $\mu = 0$ chip curl increases as there is no resistance for the chip to slide. The evolution of the chip radius of curvature vs friction coefficient is plotted in Fig 8.

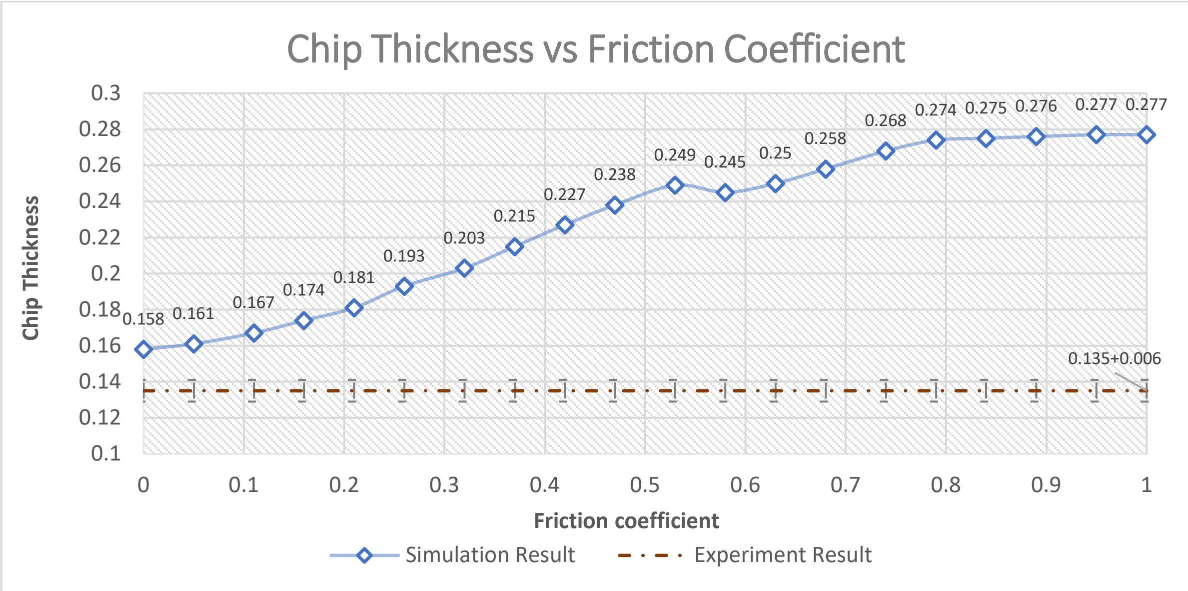


Fig. 7. Chip Thickness VS Friction Coefficient.

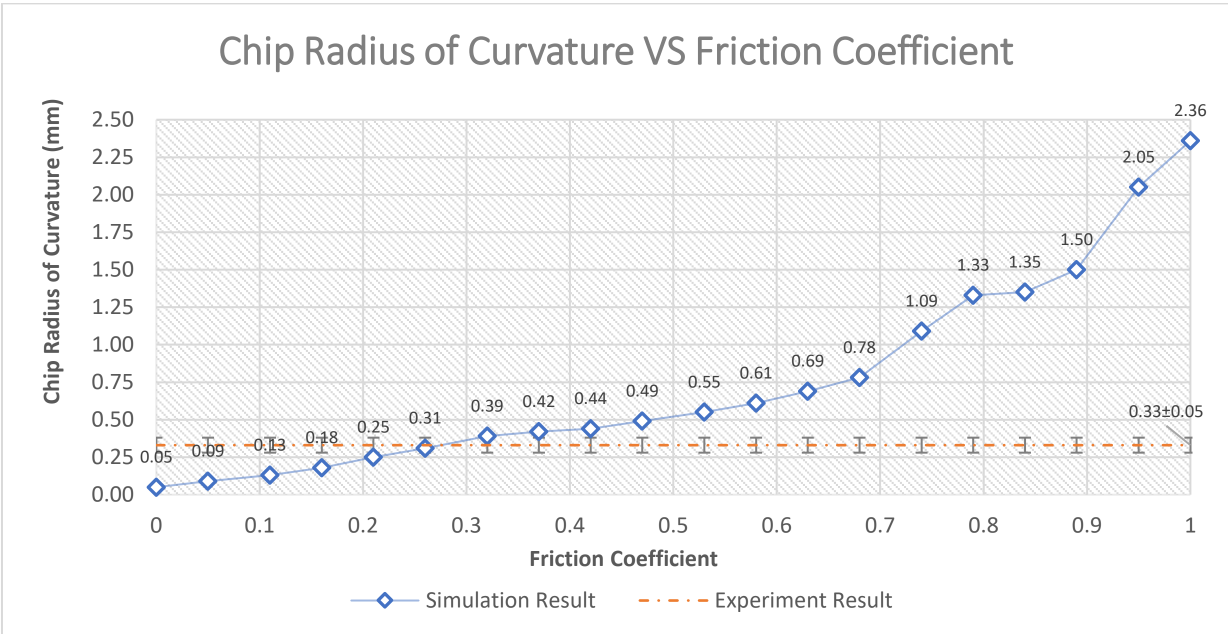


Fig. 8. Chip Radius of Curvature VS Friction Coefficient.

From the analysis, it is evident that for the particular cutting condition and with the particular parameters set for JC the friction coefficient value of $\mu = 0.16$ can predict the cutting force the, $\mu = 0.32$ can predict the feed force and chip radius of curvature near to the experimental observations. It has also been observed that feed force and chip mean curvature seem to be more sensitive to the friction coefficient value than the cutting force and chip thickness. The analysis shows that the best friction value is not unique for all the observables with the parameter set for the JC model considered in the study. To define the best friction coefficient from this particular study a cost function with equal weights ($F_C = F_F = h' = R = 0.25$) and cost function with different weights ($F_C = F_F = 0.3$ and $h' = R = 0.2$) are considered. The cost function equation is given in Eq 3.

$$\xi = \omega_1 . \left| \frac{F_C^{Sim} - F_C^{Exp}}{F_C^{Exp}} \right| + \omega_2 . \left| \frac{F_f^{Sim} - F_f^{Exp}}{F_f^{Exp}} \right| + \omega_3 . \left| \frac{h'^{Sim} - h'^{Exp}}{h'^{Exp}} \right| + \omega_4 . \left| \frac{R^{Sim} - R^{Exp}}{R^{Exp}} \right| \quad (3)$$

Where ω is the weighting factor, Sim is the simulated result, and Exp is the experimental result respectively. The cost function calculated with the equal weighting factors and the different weighting factor shows that $\mu = 0.21$ has the minimum cost function. Therefore $\mu = 0.21$ is optimal or the best friction coordinate value in this framework. But the error is still very high.

This study reveals that only modifying the friction coefficient value is inadequate to obtain accurate results for different observables through numerical simulation. A correlation between the material model parameters, the friction value and different cutting conditions should be considered to develop a predictive model. A multi objective global optimization algorithm will be a feasible choice to search the optimum value for the parameters of the material model and the friction coefficient contemplating the different cutting conditions. Considering another friction model could also be relevant.

Conclusion

In this paper, the influence of the coulombs friction coefficient in determining the forces and chip characteristics has been studied by varying the friction coefficient values with finite element simulations. The result obtained from the numerical simulations and its comparison with the experiments depict the fact that the friction coefficient parameter plays a significant role in developing a predictive model of the orthogonal machining process. The following outcomes are drawn from the above study:

- The temperature in the secondary deformation zone in the chip and the tool-chip interface increases with the increase of friction coefficient value.
- The plastic strain at the chip side in contact with the tool rake face and the tool-chip contact length increases with the increase of friction coefficient value.
- The forces, chip thickness, and chip curvatures are directly linked with the friction coefficient value μ.
- For the particular cutting condition and with the particular parameters set for the JC model, no friction coefficient value considered in this study allows to accurately predict the forces, chip thickness, and chip curvature at the same time.

From the study, it is evident that the parameters value of the constitutive model and the parameter value of the friction coefficient has a significant influence in predicting the observables. Therefore, the authors suggest optimizing the value of the friction coefficient parameter in correlation with material model parameters by taking into account on different cutting conditions to predict the observables through numerical simulations.

References

[1] Shaw MC, Metal Cutting Principles, 2nd ed., Oxford University Press, Oxford, 2005.

[2] Arrazola PJ, Ozel T, Umbrello D, Davies M, Jawahir IS. Recent advances in modelling of metal machining processes. CIRP Annals - Manufacturing Technology. 2013 Aug 12;62(2):695-718.

[3] Melkote, Shreyes & Grzesik, Wit & Outeiro, J.C. & Rech, Joel & Schulze, Volker & Attia, Helmi & Arrazola, Pedro & M'Saoubi, Rachid & Saldana, Christopher, Advances in material and friction data for modelling of metal machining, CIRP Annals - Manufacturing Technology, 2017, 66. 10.1016/j.cirp.2017.05.002.

[4] G. Lütjering and J. C. Williams, Titanium (Engineering Materials and Processes), Springer, 2013.

[5] R. Komanduri, "Some clarifications on the mechanics of chip formation when machining titanium alloys," Wear (1982), vol. 76, pp. 15-34.

[6] K. Komvopoulos and S. A. Erpenbeck, "Finite element modeling of orthogonal metal cutting," ASME Journal of Engineering for Industry (1991) vol. 113, pp. 253-267.

[7] Arrazola, P.J., Özel, T., Numerical modelling of 3-D hard turning using Arbitrary Eulerian Lagrangian finite element method, International Journal of Machining and Machinability of Materials, (2008) pp. 238-249.

[8] F. Ducobu, E. Rivière Lorphèvre, E. Filippi, Finite element modelling of 3D orthogonal cutting experimental tests with the Coupled Eulerian-Lagrangian (CEL) formulation, Finite Elements in Analysis and Design (2017) Volume 134, Pages 27-40.

[9] Kugalur-Palanisamy N, Riviere-Lorphèvre E, Arrazola PJ, Ducobu F. Comparison of Johnson-Cook and modified Johnson-Cook material constitutive models and their influence on finite element modelling of Ti6Al4V orthogonal cutting process. AIP Conference Proceedings 2019.

[10] Kugalur Palanisamy, N.; Rivière Lorphèvre, E.; Arrazola, P.-J.; Ducobu, F. Influence of Constitutive Models and the Choice of the Parameters on FE Simulation of Ti6Al4V Orthogonal Cutting Process for Different Uncut Chip Thicknesses. J. Manuf. Mater. Process, 2021.

[11] F. Ducobu, E. Riviere and E. Filippi, "On the importance of the choice of the parameters of the Johnson-Cook constitutive model 6 and their influence on the results of a Ti6Al4V orthogonal cutting model," International Journal of Mechanical Sciences 2017, vol. 620.

[12] Yancheng Zhang, J.C. Outeiro, Tarek Mabrouki, On the Selection of Johnson-cook Constitutive Model Parameters for Ti-6Al-4V Using Three Types of Numerical Models of Orthogonal Cutting, Procedia CIRP Volume 31(2015).

[13] P. Arrazola, T. Özel, Investigations on the effects of friction modeling in finite element simulation of machining, Int. J. Mech. Sci., (2010).

[14] Johnson GR, Cook WH. A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. in: Proceedings of the seventh international symposium on ballistics. The Hague, The Netherlands, 541–547, 1983.

[15] Seo S, Min O, Yang H. Constitutive equation for Ti-6Al-4V at high temperatures measured using the SHPB technique. Int J Impact Eng, 31, 735–754, 2005.

[16] Markopoulos, Angelos & Vaxevanidis, Nikolaos & Manolakos, Dimitrios,Friction and Material Modelling in Finite Element Simulation of Orthogonal Cutting, Tribology in Industry, 37, 440-448, 2015.

[17] Malakizadi, A., Hosseinkhani, K., Mariano, E. et al., Influence of friction models on FE simulation results of orthogonal cutting process, Int J Adv Manuf Technol, 88, 3217–3232, 2017.

[18] Iman, R.L.,Latin Hypercube Sampling, In Encyclopedia of Quantitative Risk Analysis and Assessment (eds E.L. Melnick and B.S. Everitt, 2008.

[19] F. Ducobu, E. Rivière-Lorphèvre, E. Filippi, On the introduction of adaptive mass scaling in a finite element model of Ti6Al4V orthogonal cutting, Simulation Modelling Practice and Theory, Volume 53(2015)1-14.

[20] D. R. Lesuer, "Experimental Investigations of Material Models for Ti-6Al-4V Titanium and 2024-T3 Aluminum", 2020.

[21] D. William Jr., Callister, Materials Science and Engineering: An Introduction, third ed., Wiley, New York, ISBN 0471581283, 1994.

[22] Ducobu F, Rivière-Lorphèvre E, Filippi E. Experimental contribution to the study of the Ti6Al4V chip formation in orthogonal cutting on a milling machine. Int J Mater Form 68 2015.