IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
PP 22-28

3D Finite Element Analysis Simulation Of Slot Milling Process For Titanium Alloy Ti6Al4V

Prakash C[1], Vijay Sekar K.S[2]
[1]*(Department of Automobile Engineering, Surya Group of Institutions, Vikiravandi – 605 652, Tamilnadu, India)*
[2]*(Department of Mechanical Engineering, SSN College of Engineering, Kalavakkam – 603 110, Tamilnadu, India)*

Abstract : *Slot milling is one of the complex metal cutting process which is to be investigated to make it cost effective and to improve the quality of the machined components by reducing or eliminating the machining induced damages. Hence, in this research work a realistic 3D Finite Element Model is developed in ABAQUS\Explicit to simulate the slot milling process. The Finite Element Model consists of real 3D shape of the tool and workpiece. Slot milling simulation is carried out under different spindle speeds and feeds. The cutting forces, stress and chip formation are predicted from the Finite Element simulation. Moreover, the cutting force profile and data are compared with the experimental results available from the literature and found to be in good agreement. The proposed FE model with the Johnson – cook failure criteria predicts the Cutting forces, Chip formation, stress and the stain rate very effectively. The results obtained from the FE model confirm the quality and capability of predicting good results.*
Keywords - 3D Finite Element Model, Chip formation, Cutting forces, Slot Milling, Ti6Al4V.

I. Introduction

The Finite Element Method is a very useful tool to investigate the machining process with the help of machining simulations. The FE tools have reduced the cost of design changes, improved the quality of the product and significantly reduced the lead time to manufacture [1]. Numerous finite element models are developed to simulate the milling process in the form of 2D, Orthogonal cutting, Oblique cutting and 3D FEM.

The ABAQUS/Explicit V6.14 FE simulation software is capable of computing the process variables such as cutting temperature, stress, cutting forces, chip formation and strain. Nowadays such simulations are very vital which replaces/ reduces the experimental procedures and testing. Most of the researchers concentrate only on 2D orthogonal machining simulations, to simplify the FE problem and to reduce the solving time. But the results obtained from these orthogonal cutting simulations are not realistic enough to compare with the 3D slot milling simulation. Hence it is mandatory to develop 3D FE models which take into account the actual dimensions and nomenclatures of workpiece & tool. However, researchers are not concentrating on developing realistic 3D FE models since; it needs more computing resources and time.

Vijay Sekar K.S et al developed a thermo - mechanical 2D FE model to evaluate the influence of JC material model parameters on chip formation, stress, strain and temperature. The JC models M1 and M2 are suggested by the authors to achieve a reliable FE simulation and to predict good results [1]. H.B Wu et al developed 3D FE model to simulate the End milling process for titanium alloy Ti6Al4V, they conducted series of milling experiments and compared with the FE simulation results for validation. The developed FE model predicts the Chip formation, cutting forces and stress and found to be in good agreement with experimental results [2]. Shivaram P.R et al studied the milling process for titanium alloy Ti6Al4V both experimental and numerically. The FE model is developed in Deform 3D software to simulate the milling process. Moreover, the influence of cutting speed and feed rate over cutting forces and chip microstructure were studied [3]. Vivek Bajpal et al developed a simplified and scaled 3D FE model in ABAQUS and studied the cutting forces, chip morphology and compared with the experimental results. The chip morphology from FE results are compared with chips obtained from experimentation and found to be good in terms of chip size and shape [4]. Guang Chen et al investigated the chip formation, chip morphology and cutting forces while performing High Speed Machining (HSM) on Ti6Al4V. The experimental results are compared with 2D FE simulation results and found to be in good [5].

Titanium and its alloys are widely used in aerospace and medical implants due to their excellent mechanical and chemical properties. Titanium is light, strong, corrosion resistant and biocompatible; however, it has poor machinability. The low thermal conductivity and high strength result in large cutting forces during machining, as well as a reduced tool life [4]. Hence it is needed to investigate the milling process with wider machinability metric to select a suitable machining parameter setting. Experimental investigation results mainly depend upon testing conditions and quality of the data acquisition systems [5, 9]. However, a numerical simulation like FEM is very cost effective and also provides the facility to investigate the machining process very effectively even for higher cutting conditions. Numerous research papers deals with orthogonal milling simulations and scaled/simplified 3D models only, whereas till date full realistic 3D FE models are not widely reported in the literature for slot milling process.

In this research work, a full 3D FE model (with original tool and workpiece dimensions) is developed in ABAQUS/Explicit with Johnson cook failure model to simulate the slot milling process for Titanium Alloy Ti6Al4V. The cutting forces, stress, strain and chip formation are predicted and correlated with the literature. The cutting forces obtained from ABAQUS simulation result is correlated with the experimental and Deform 3D software results from the literature [3]. The correlation of the results is found to be excellent.

II. Experiment Work And Results

The milling experiments were conducted on a NAMMIL XL6026AV Vertical milling machine with 2 HP spindle power and a maximum speed of 1700 rpm. A solid carbide TiAlN coated end mill cutter with the diameter 12 mm is used for experimental study (shown in Fig. 1). Slot milling operation was performed for various cutting speeds and feeds with depth of cut of 0.5 mm (Refer Table1). The cutting speeds were 13.19, 24.87 and 33.91 m/min and feeds were 60, 120 and 240 mm/min. The cutting forces are recorded using the IEICOS dynamometer and its data acquisition software [3]. The maximum cutting forces recorded by the Mill tool dynamometer during the milling process is listed in Table 4.

Fig. 1 a) Work and Tool b) Experimental Setup c) Data-acquisition system

Table 1 Machining parameters used in milling of Titanium Alloy Ti6Al4V

Milling parameters	Magnitude
Spindle speeds, N (rpm)	350, 660, 900
Cutting Speed, Vc (m/min)	13.19, 24.87, 33.91
Feed rate, f (mm/min)	60, 140, 240
Depth of cut (mm)	0.5

Table 2 Physical properties of Titanium Alloy Ti6Al4V

Specifications	Value(s)
Elastic Modulus (GPA)	120
Poisson's ratio, υ	0.27
Density (Kg/m^3)	4430
Hardness (HRC)	30

Table 3 Properties and Geometric Specifications of End Mill Cutter

Specifications / Description	Value(s)	Specifications / Description	Value(s)
Product	End Mill Cutter	Number of flutes	04
Shank type	Plain	Point angle (°)	115
Cutter diameter (mm)	10	Helix angle (°)	30
Overall length (mm)	75	Coating	TiAlN
Shank length (mm)	30	Coating Thickness	2 to 5 Microns
Flute length (mm)	40	Working Temperature	Max 900^0C
Shank Diameter (mm)	10	Coating Colour	Reddish - violet – black
Material	Solid Carbide SANDVIK H10F Grade	Coating Hardness	3300Hv
Hardness	92.7 HrC	Density (kg/m3)	11,560

Table 4 Experimental Results of average cutting force at different cutting speeds and Feed rates [3].

Cutting Speed, Vc (m/min)	Feed rate, f (mm/min)	Max. Cutting force, Fx (N)	Max. Cutting force, Fy (N)	Max. Cutting force, Fz (N)
13.19	60	48	94	39
	120	96	104	31
	240	134	109	6
24.87	60	41	59	22
	120	63	35	30
	240	74	67	18
33.91	60	33	42	12
	120	46	18	29
	240	58	41	22

III. Finite Element Model

A 3D FEM has been developed using finite element analysis software ABAQUS 6.14 – 2 for investigating the slot milling process [6]. The 3D model of the end mill cutter is created in CATIA [7] modeling software and it is imported to ABAQUS.

The work-piece model is incorporated with the mechanical properties of Titanium alloy Ti6Al4V. The physical and mechanical properties of the workpiece & tool materials are listed in the Table 2 and 3. The FE model for the slot milling process of titanium alloy Ti6Al4V consists of 86,000 C3D8R elements in the work-piece and 32,985 C3D10M elements in the end mill cutter (shown in Fig. 2). The dry milling environmental condition is considered, with the depth of cut of 0.5 mm. The tool is considered as a rigid body. The FE model parameters are listed in the Table 7.

The Johnson–Cook plasticity model is incorporated in this FEM to describe the deformation of the work-piece. Since, it very much suitable for higher strain rate problems [8]. The parameters of the failure criteria are listed in the Table 5 and 6. Adaptive meshing technique is used for this analysis to facilitate plastic deformation of the titanium alloy during machining simulation. Defining the contact between the tool and the work-piece is very vital to characterize a realistic cutting simulation. The Coulomb friction model is selected in ABQUS with penalty friction of coefficient 0.5.

The FE analysis is carried out in ABAQUS Dynamic - Explicit module since, machining of conventional metals and alloys produces chips due to plastic deformation and strain hardening with larger strain rate. Number of simulations has been carried out with the process parameters listed in Table 1. FE simulation is done based on the nine different scenarios with one depth of cut, three feed rates, and three cutting speeds as described in the Table 1 and 4.

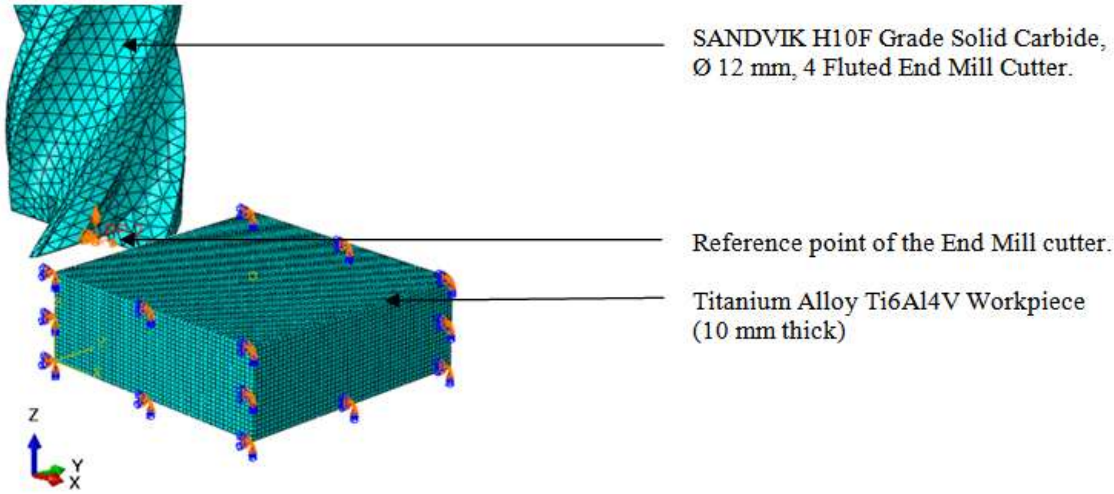


Fig. 2 Three Dimensional Finite Element Model

Table 5 The Five parameters of Johnsons – Cook constitutive equation for Ti6Al4V [8]

Specifications	Value(s)
A	1095 (Mpa)
B	780 (Mpa)
n	0.92
C	0.033
m	1.02

Table 6 Fracture parameters for Titanium Alloy Ti6Al4V [1]

Specifications	Value(s)
D_1	-0.09
D_2	0.25
D_3	-0.5
D_4	0.014
D_5	3.87
T_r	293 k
T_m	1640 k

Table 7 Finite Element Model - Input data

Specifications	Value(s)
Work Piece	Titanium Alloy Ti6Al4V
Tool	Dia. 12 mm End Mill cutter
Dimensions of FE model	25 X 25 X10 mm
Type of Element in work piece	C3D8R
Number of elements in work piece	86,000
Number of nodes in work piece	54,621
Element Size in Workpiece	0.25 mm
Type of Element in tool	C3D10M
Number of elements in tool	32,895
Number of nodes in tool	49,665
Element Size in tool	1 mm
Total Elements & Nodes in FE Model	1,04,286 & 82,895
Friction Factor	0.45
Failure Criteria	Johnson- Cook

IV. Results And Discussion

4.1 Cutting Forces

Figure 3 shows the cutting force profiles obtained from the FEM results. The FE simulation results predict that, cutting forces reduces with increasing cutting speed. The similar phenomenon of reduced cutting forces at higher cutting speeds is also observed in experimental investigation. This is evident that the proposed FEM is good enough in predicting the cutting force data.

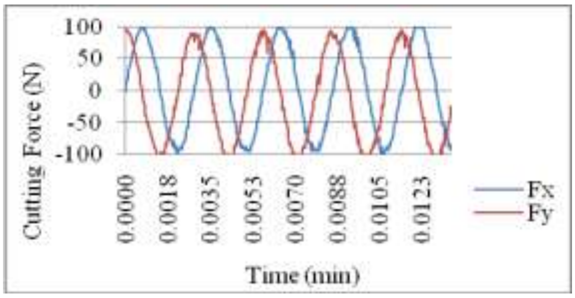


Fig. 3 a) Cutting Force Profile Fy (N) at Vc = 33.91m/min, f = 240 mm/min.

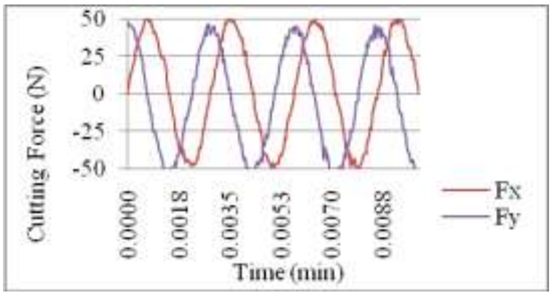


Fig. 3 b) Cutting Force Profile Fy (N) at Vc = 13.19 m/min, f = 240 mm/min.

Table 8 and 9 describes the comparison of cutting force data obtained from experimental, Deform 3D and ABAQUS softwares. The Experimental and Deform 3D results given in Table 8 and 9 are from the literature [3]. The ABAQUS FEM results are within 5 to 10 % deviation and very closer to Experimental results.

Table 8 Comparison of Cutting Force, Fy (N) for the Cutting Speed, Vc (m/min) = 13.19 m/min [3].

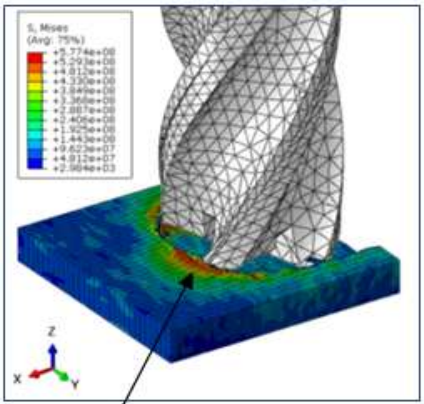
Cutting Feed, f (mm/min)	Cutting Force, F_y (N)		
	Experimental Results	Deform 3D Results	ABAQUS Results
60	94	98	95
120	104	101	96
240	109	192	101

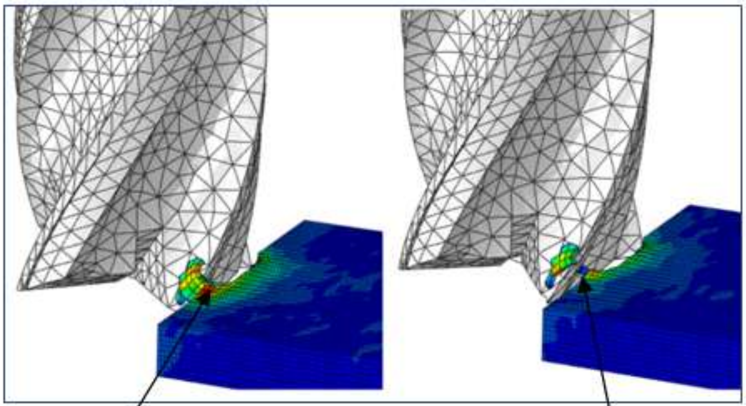
Table 9 Comparison of Cutting Force, Fy (N) for the Cutting Speed, Vc (m/min) = 33.91 m/min [3].

Cutting Feed, f (mm/min)	Cutting Force, F_y (N)		
	Experimental Results	Deform 3D Results	ABAQUS Results
60	42	37	45
120	18	12	22
240	41	40	43

4.2 Stress Plot

The Maximum Stress is developed at the tool and the workpiece interface region, due to the sliding action of the tool with the workpiece surface [10]. Figure 4 shows the maximum stressed region during chip formation in the milling operation, at Vc = 13.19 m/min, Feed rate = 240 mm/min. The stress developed during chip formation is 577 MPa (refer with Fig.4). The maximum stress is reduced from 577 MPa to 516 MPa when the cutting speed is increased.





Max. Stress Chip Formation due to plastic deformation Chip Breaking & Separation

Fig. 4 Stress Plot from FEM results. **Fig. 5 Chip Formation Process.**

4.3 Chip Formation

Chip flow directly influences the quality of the machined surface. Hence, the influence of cutting speed and feed rate over chip formation is to be observed for getting the proper material removal and dimensional accuracy of the machined components [10]. The Chip formation can be visualized from Fig. 5 which shows that chip is formed due to plastic deformation and development of stress at the cutting zone. Chips are in the form of short continuous and spiral shaped [3].

V. Conclusions

In this research work a realistic 3D Finite Element Model is developed in ABAQUS software, to simulate and to investigate the complex cutting mechanism of slot milling process in Titanium alloy Ti6Al4V.

The proposed FE model with the Johnson – cook failure criteria predicts the Cutting forces, Chip formation, stress and the stain rate very effectively. Moreover, the 3D FE model is used to simulate the slot milling process for different cutting speeds and feeds and the results are compared with the literature and it is found to be in good agreement. Hence it is evident that the FE model is reliable and efficient in predicting the required output parameters.

The cutting force profile is like sinusoidal wave form, since the workpiece material is homogeneous. The predicted thrust force data matches with experimental data and FE results (Deform 3D results) available in the literature. The maximum stress developed during chip formation is 577 MPa. The stress value reduces from 577 MPa to 516 MPa when the cutting speed is increased.

This FEM provides a platform to optimize the milling conditions and it helps to reduce the number of experimental trials required to optimize the machining process and such predictive numerical methods alleviate the cost & provide better solutions in quick time.

Acknowledgements

The authors are indebted to AICTE (All India Council for Technical Education) for the financial support in this work. The authors thank the Department of Mechanical Engineering, SSN College of Engineering for providing the Laboratory and Testing Facility.

References

[1]. K. S. Vijay Sekar, M. Pradeep Kumar, Finite element simulations of Ti6Al4V titanium alloy machining to assess material model parameters of the Johnson-Cook constitutive equation, *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 33(2), 2011, 203-211.*

[2]. Wu H.B, Zhang S.J, 3D FEM simulation of milling process for titanium alloy Ti6Al4V, *Int J Adv Manuf Technol, 71, 2014, 1319-1326.*

[3]. Shivram P.R, Sushinder. K, Nivedh Kannaa S.B, Nisrag Gupta, Vijay Sekar K.S, Experimental Investigation and Finite Element Analysis of Milling of Ti-6Al-4V Titanium Alloy by Studying Cutting Forces and Chip Morphology, *Applied Mechanics and Materials, 852, 2016, 311-316.*

[4]. Vivek Bajpai, Ineon Lee, Hyung Park, Finite Element Modeling of Three-Dimensional Milling Process of Ti-6Al-4V, *Materials and Manufacturing Processes 29, 2014, 564-571.*

[5]. Guang Chen, Chengzu Ren, Xiaoyong Yang, Xinmin Jin, Tao Guo, Finite element simulation of high-speed machining of titanium alloy (Ti–6Al–4V) based on ductile failure model, *Int J Adv Manuf Technol 56, 2011, 1027–1038.*

[6]. Simulia.D., Abaqus 6.14 User’s manual. Dassault systems, Providence, RI, (2014). Available: http://50.16.225.63/v6.14/

[7]. CATIA V5R14: User Manual, Dassault systems, Providence, RI, (2014).

[8]. Johnson R, Cook W.K, A constitutive model and data for metals subjected to large strains high strain rates and high temperatures, *The 7th International Symposium on Balistics, The Hague, 1983, 541-547.*

[9]. Khaled Giasin, Sabino Ayyar-Soberanis, Toby French, Vaibhav Padnis, 3D finite Element Modelling of cutting forces in drilling fibre Metal laminates and experimental hole quality analysis, *Appl Compos mater, 2016.*

[10]. C.Prakash, K.S.Vijay Sekar, 3D Finite Element Analysis of Drilling of Glass Fiber Reinforced Polymer Composites, *Adv. Sci. Eng. Med. 10, 2018, 308-312.*