University of Birmingham
Research at Birmingham

FEM analysis to optimally design end mill cutters for milling of Ti-6Al-4V

Kumar, Vinod; Eakambaram, A.; Arivazhagan, A.

DOI:
10.1016/j.proeng.2014.12.402

License:
Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Kumar, V, Eakambaram, A & Arivazhagan, A 2014, 'FEM analysis to optimally design end mill cutters for milling of Ti-6Al-4V', *Procedia Engineering*, vol. 97, pp. 1237-1246. https://doi.org/10.1016/j.proeng.2014.12.402

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
Checked for eligibility: 08/01/2018

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

• Users may freely distribute the URL that is used to identify this publication.
• Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
• User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
• Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 30. Nov. 2021

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 97 (2014) 1237 – 1246

Procedia Engineering

www.elsevier.com/locate/procedia

12th GLOBAL CONGRESS ON MANUFACTURING AND MANAGEMENT, GCMM 2014

FEM Analysis to Optimally Design End Mill cutters for Milling of Ti-6Al-4V

Vinod Kumar[a,*], Eakambaram A[b], Arivazhagan A[c]

[a] Indian Institute of Information Technology Design & Manufacturing, Kancheepuram, Tamilnadu, Chennai - 600127, INDIA.
[b] Arunai Engineering College, Tiruvannamalai, - 606 603, Tamilnadu, INDIA.
[c] Advance Design and Manufacturing Engineering Centre, School of Architecture, Design and Built Environment, Nottingham Trent University, Burton St, Nottingham, NG1 4BU, UK.

Abstract

This paper presents an FEM analysis conducted for optimally designing end mill cutters through verifying the cutting tool forces and stresses for milling Titanium alloy Ti-6Al-4V. Initially, the theoretical tool forces are calculated by considering the cutting edge on a cutting tool as the curve of an intersection over a spherical/flat surface based on the model developed by Lee & Altinas [1]. Considering the lowest tool forces the cutting tool parameters are taken and optimal design of end mill is decided for different sizes. Then the 3D CAD models of the end mills are developed and used for Finite Element Method to verify the cutting forces for milling Ti-6Al-4V. The cutting tool forces, stress, strain concentration (s), tool wear, and temperature of the cutting tool with the different geometric shapes are simulated considering Ti-6Al-4V as work piece material. Finally, the simulated and theoretical values are compared and the optimal design of cutting tool for different sizes are validated. The present approach considers to improve the quality of machining surface and tool life with effects of the various parameters concerning the oblique cutting process namely axial, radial and tangential forces. Various simulated test cases are presented to highlight the approach on optimally designing end mill cutters.

Keywords: end mill; FEM analsyis; tool force, Ti-6Al-4V;

---

1. Introduction

The usage of Ti-6Al-4V is widespread now-a-days in automotive, aerospace and bio-medical industries due to its several inherent properties, such as low thermal conductivity, low elastic modulus, and its capability to withstand

---

* *Corresponding author. Tel.: +91- 9865449800.*
E-mail address: gsvinodkumar2@gmail.com

doi:10.1016/j.proeng.2014.12.402

varying loads at higher temperatures. Even though Ti-6Al-4V is utilized in different domains, machining Ti-6Al-4V is difficult because of its higher hardness, high specific strength at elevated temperatures. The composition and mechanical properties of Ti-6Al-4V are shown in Table 1 & 2. As most of the mechanical energy used to remove material becomes heat in machining process, high temperature is generated in the cutting region. Due to this fact, the machined chips can easily adhere to the cutting tool and on the machined surface which encounters rapid tool wear. For Ti-6Al-4V, this problem is more severe due to their low thermal conductivity as 80% of the heat generated in the cutting region goes to the cutting tool. To avoid these problems it is a well known fact that cutting fluids are used. But still the damages in the finished surface of Ti-6Al-4V can be easily noticed in case of high speed machining process. Many researchers attempted to solve the problem by adopting various optimization methods to control the process parameters and by utilizing different cutting fluids. Some suggested the usage of cutting tool materials with high hardness will reduce heat affected zones, improves the work piece quality, production rate and the tool life. Despite these efforts, the problem is encountered in many scenarios and this research attempts to resolve this issue by adopting a method of optimally designing suitable end mill tool which produces less cutting forces, improve quality of machining surface and tool life . In this paper, various cutting tool forces in the machining process are calculated by considering end mill (ball & flat) for machining Ti-6Al-4V. Later, based on the cutting forces, FEM analysis has been carried out considering Ti-6Al-4V as the work piece material to optimally design end mills. In order to have a better understanding of the problem the forth coming section provide a brief review of research work conducted in a broad domain of milling Ti-6Al-4V.

Table. 1 Composition (wt. %) of Ti-6Al-4V

Content	O	H	N	C	Fe	V	AL	Ti
Weight %	-	0.005	0.01	0.05	0.09	4.4	6.15	balance

Table. 2 Mechanical properties of Ti-6Al-4V at room temperature

Tensile Strength Mpa	Yield Strength Mpa	Elongation	Modulus of Elasticity Gpa	Hardness HRC
993	830	14	114	36

Nomenclature

Ft, Fr, Fa	Tangential, radial and axial force
Sz	Feed tooth, mm
s	Feed (mm/ minute)
Rpm	Spindle speed
As	Average value of chip thickness(mm)
Zs	No of teeth in simultaneous engagement with work
Pz	Tangential force (N)
Px	Axial force (N)
Py	Radial force (N)
P	Total force (N)
Ks	Specific cutting force(Kgf/mm^2)

2. Literature of Review

Lee and Altintas[1] applied the geometry and kinematics of the ball end milling process and predicted the cutting forces accurately in tangential, radial, and axial directions. They developed a model and measured the fundamental cutting parameters, the yield shear stress, the average frictional coefficient on the rake face and shear angle from a set of orthogonal cutting tests performed at various cutting speeds and feeds. Ahmad Yasir et.al [2] presented an approach on Minimum Quality Lubrication (MQL) and proved it to be effective in terms of tool life and surface roughness and at certain cutting speeds. They mentioned that MQL is less effective at higher cutting speeds due and higher pressure is needed to ensure that the mist particle to penetrate into the cutting zone. Puneet Tandon et.al [3] proposed a geometric model of the cutting tool from the viewpoint of shape realization. A mathematical model of the end mill is developed and the geometry of the cutting tools are expressed in terms of various bi-parametric surface patches. Finally by solving the geometry of cutting tool equations, they validated the surface models of the tool. Abbas Fadhel et.al [4] predicted that the feed rate is the most dominant on the cutting force, followed by the axial depth, radial depth of cut and then the cutting speed. Experiments were conducted to verify that the accuracy of the cutting force values using Genetic network (GN) and it was found to be 92%. Their approach proved to be a successful technique that can be used to predict the longitudinal cutting forces produced in end milling.

Dimitrov et.al [5] proposed a method to verify that the cutting speed is the most influential parameter concerning tool life. They conducted experiments and verified that the major causes of decreased tool life is due to increased thermal load and surface hardening of the work material. Later cooling modifications have been introduced and the thermal load is reduced by providing by aiding the removal of the heat generation at the cutting zone. The effect of feed rate on surface roughness has been investigated by Nagi Elmagrabi et.al [6] by comparing it other cutting parameters. They noticed that flank wear, adhesion and thermal crack at high cutting speed are the dominant failure mode when machining Ti-6Al-4V with PVD carbide tool. Experiments were performed to verify the vibration of high speed ball end milling by Lee et.al [7]. It is noted that when high-speed ball end milling is used in a cantilever-shaped thin plate, the vibration at the end part of the work piece was severe and was affected considerably by cutter orientation. Among the experiments conducted they found the most stable cutting was achieved with a vertical upward cutting orientation and at the lower part of the work piece. Pai chi chang and Wang lin [8] presented a model for evaluating the quality of the actual working profile of a taper ball-end milling cutter with a cylindrical shank. In their work, they attached the cutter to the cylindrical surface of the shank and the analysed the process by adopting the minimum circumscribed cylindrical surface (MCCS) of the shank as the datum axis. Using this concept they defined the minimum circumscribed taper surface (MCTS) and the minimum circumscribed sphere (MCS) to calculate the profile of the spiral groove on the taper part and the ball-end part of the cutter. A mathematical model to measure the edge of the roller nest mill cutter is proposed by Kuo and Wu [9]. From the calculated data of the edge, a theoretical value is compared with the measured value and a precise assessment was given for processing the roller nest mill cutter. Engin and Altintas [10] investigated a generalized mathematical model of helical end mills. In their work, the end mill geometry is modelled by helical flutes wrapped around a parametric envelope. Then coordinates of a cutting edge point along the parametric helical flute are mathematically expressed. Finally, they evaluated the chip thickness at each cutting point by using the true kinematics of milling including the structural vibrations of both cutter and work piece. Johanna Senatore et.al [11] computed the effective radius of milling cutter using the radius of curvature of the envelope curve. In their work they calculated the step-over distance and the effective radius by projecting the curvature of the envelope curve onto a plane perpendicular to the direction of feed motion. A relation was established enabling the angular interval for which the step-over distance of a torus mill is found to be greater than the step-over distance of a spherical mill. Engin and Altintas [12] presented a generalized mathematical model for inserted cutters also. The model allowed spacing different inserts on the cutter body mathematically by defining its centre from a cutter body coordinate system. The inserts are oriented by rotating them about the three axes of the cutter body. The insert geometry is defined individually in a local coordinate system by its edge dimensions and shapes. A new experimental method for force coefficients identification considering the inclination angle for ball-end finish milling has been proposed by Qingyuan Cao and Jun Zhao [13]. The start and exit radial immersion angles were modelled based on different inclination angles. In their work, they analysed that the position of the cutting element on the ball-end mill edge was the only factor to affect the cutting force coefficients in tangential, radial and axial directions. Pioneering studies on the mechanics of chip during machining of titanium alloy or Ti-6Al-4V alloy have been conducted since the early 1950s by Shaw and his co-workers [14,15] and Boston et al. [16]. It is noticed that a large proportion (about 80%) of the heat generated when machining Ti-6Al-4V is conducted into the tool because it cannot be removed with the fast flowing chip due to the low thermal conductivity of titanium alloys, which is about 1/6 that of steels [17]. Also the combination of high stress and high temperature at the tool tip promote tool wear and increase production cost. The prominent failure modes in titanium machining were investigated by W Konig [17] and Ezugwu &Wang [19]. They noticed that the failure modes in Ti-6Al-4V are notching, crater wear, flank wear, chipping and catastrophic failure which are caused by high temperatures, high pressures, chemical reactivity and the formation of segmented chips. Also Ezugwu &Wang [19] reports that tungsten carbide and PCD are the best tool materials to machine Ti-6Al-4V. They reported that it is due to a stable TiC reaction layer that is formed between the tool and the chip. Cutting speed has been proven to have the most prominent effect of tool life of all the cutting conditions [19-21]. Tool life will exponentially decrease as the cutting speed is increased. For this reason, it is common machining practice to machine titanium at a cutting speed of 60 mm/min. It has also been reported that the depth of cut influences the tool life negatively [20-22]. Tool geometry also has a significant influence on the tool life. It has been suggested that a clearance angle of 10^0-15^0 together with a high negative rake angle (-10^0 to -15^0) can yield significant improvements [20-22]. Based on the literature review it has been decided to conduct a research to optimally designing the end mill and to proceed with a FEM analysis for machining Ti-6Al-4V. In order to proceed with the analysis initially the theoretical tool forces are calculated and CAD models of end mills are created. Then using the CAD model FEM analysis has been conducted in ANSYS workbench. For ease of understanding, the rest of the paper is presented as follows : (i) Section 3 explains the tool geometry and force analysis conducted for Ti-6Al-4V (ii) Section 4 provides the details of the FEM Analysis of end mill tool for milling Ti-6Al-4V (iii) Section 5 describes the simulation and results and (iv) Section 6 on conclusions and scope for future work.

3. Tool Geometry and Force Analysis

In this research, the geometrical model already developed by Altintas and Lee [1] has been considered for calculating the forces while milling Ti-6Al-4V. Slight modifications have been made to suit the need of the present work and same is reproduced here for better understanding. A detailed geometry of a ball end milling cutter is shown in Fig.1.1-1.3.

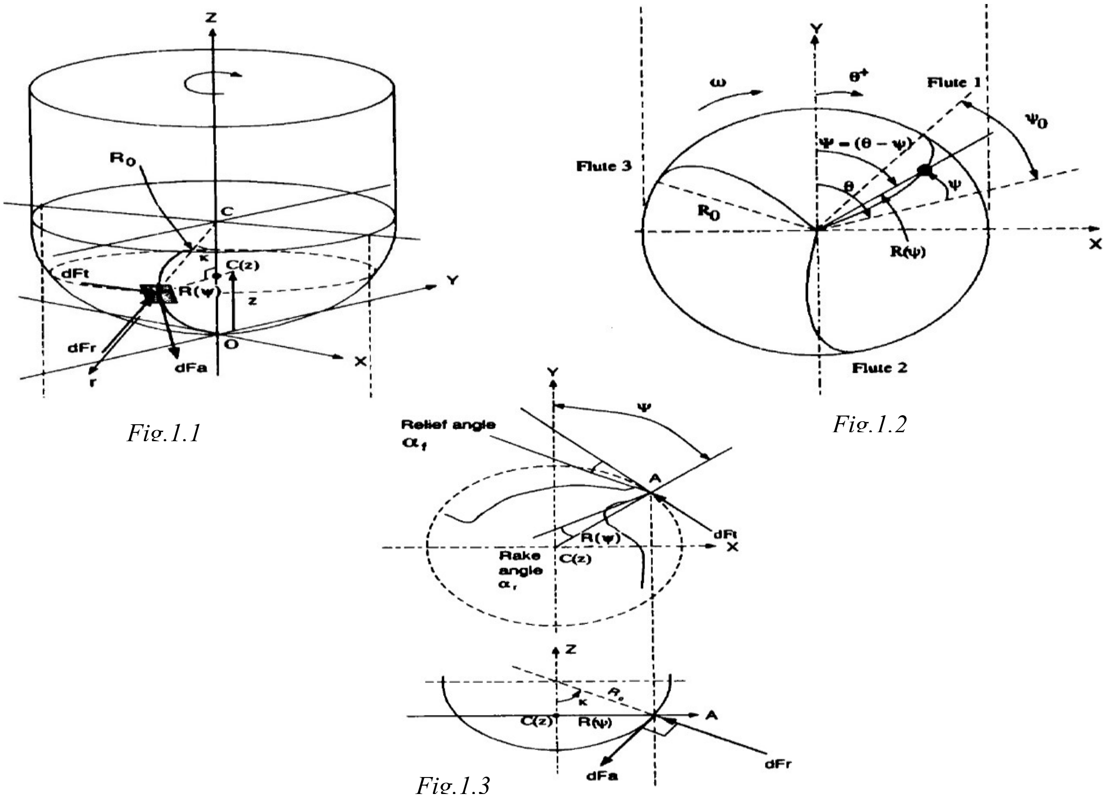

Fig.1.1

Fig.1.2

Fig.1.3

Fig.1.1 -1.3 Geometry of a ball milling cutter1,2&3

Each flute lies on the surface of the hemisphere, and is ground with a constant helix lead. The flutes have a helix angle of i_o at the ball-shank meeting boundary. Due to the reduction of the radius at the x-y planes towards the tip in the axial (z) direction, the local helix angle $i(\psi)$ along the cutting flute varies for constant helix lead cutters.

The expression for the envelope of the ball part is given by :

$X^2 + Y^2 + (R_o - Z)^2 = R^2$….Eqn (1)

Where R_o is the ball radius of the cutter measured from the centre of the sphere. The cutter radius in the x-y plane at axial location Z is $R^2(Z) = Z^2 + Y^2$….Eqn (2)And it is zero at the ball tip. The centre of the local coordinate system coincides with the global coordinate system X-Y-Z on the dynamometer shown by ball tip point 'O' in the Figure.1.1-1.3.

3.1 Force Analysis

In the milling operation, cutting tool generates tangential, radial and axial forces on the work piece. In the present work, to design the cutting tool, force calculations for different normal features (Figure.2) has been completed for different types of cutting tool geometries using MATLAB. While calculating the forces the cutting conditions (spindle speed,feed,depth of cut,average chip thickness etc) are taken based on standard handbook data [22]. Then using these conditions the cutting forces namely tangential, radial and axial forces acting on the tool are calculated. The results obtained from MATLAB is shown in Tables 3 & 4. It clearly indicates that when the spindle speed increases, the cutting force decreases which results in lower value of cutting temperature and giving an improved tool life.

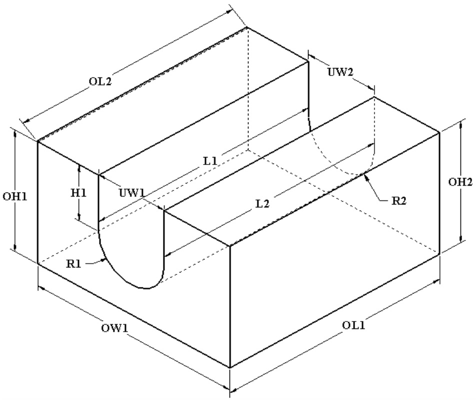

Fig.2 Ordinary through slot with curved base

Table.3 Calculation of cutting force

Rpm	Z	S	S_z	D	t	φ_s	B	K_s	Z_s	A_s	P_z	P_x	P_y	P
65	4	32	0.123	5	4	2.6	4	105.1	0.029	4.3	513.2	102.6	256.6	872.52
105	4	32	0.07619	5	4	2.6	4	117	0.029	2.6	345	69	172.5	586.5
185	4	32	0.043	5	4	2.6	4	132.6	0.029	1.5	226	45	113	384
280	4	32	0.0285	5	4	2.6	4	145	0.029	0.998	164.5	32.9	82.2	279.6
405	4	32	0.01975	5	4	2.6	4	157.3	0.029	0.69	123	24.6	61.5	209.1
725	4	32	0.011	5	4	2.6	4	178	0.029	0.385	78.2	15.6	39.1	132.9

Based on the results the graphs shown from Fig.3.1 to 3.3 have been plotted. They represent the relationship between feed tooth vs. force (Fig.3.1), force vs. speed (Fig. 3.2) and speed vs. power (Fig.3.3). The three graphs indicate that as feed increases gradually force increases and in the same way when speed increases force is decreasing (Fig. 3.2). It means forces will increase if feed and speed increases. In the last graph (Fig.3.3) it is understood that the cutting speed and power increase proportionally.

Table.4 Calculation of cutting speed and power

Rpm	Cutting speed (m/min)	Power (watt)
65	1.021	85.6
105	1.649	92.9
185	2.905	107.2
280	4.398	118.2
405	6.361	127.8
725	11.38	145.8

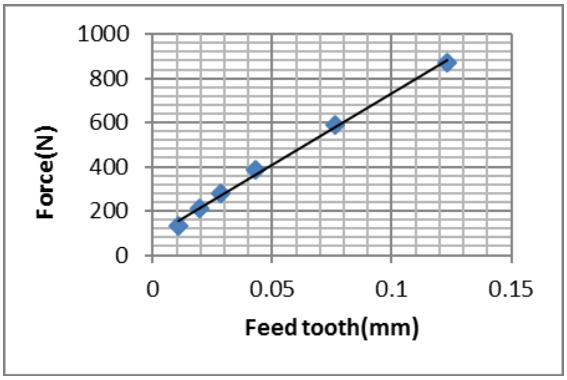

Fig.3.1 Plot between Feed tooth (mm) Vs Force (N)

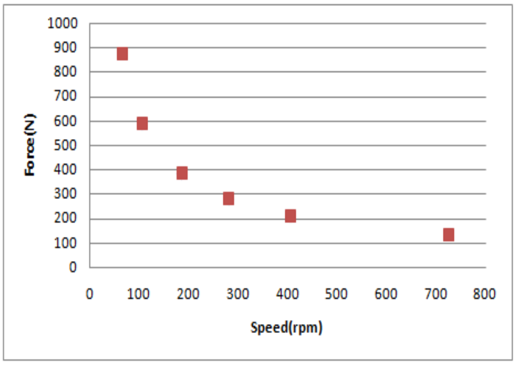

Fig.3.2 Plot between Force (N) Vs Speed (rpm)

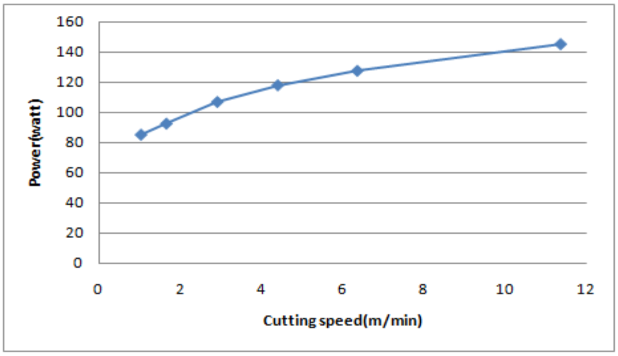

Fig.3.3 Curve of Cutting speed (m/min) Vs Power (watt)

4. FEM Analysis of End Mill Tool for Milling Ti-6Al-4V

4.1 Analysis of Tungsten Carbide End Mill Tool While Milling Ti-6Al-4V Work piece

Based on this analysis, it is decided to proceed with a simulation by optimally designing an end mill using the obtained values. The CAD model is created using Autodesk inventor software and assembled with a rectangular block (which is considered as work piece) and imported to ANSYS work bench. In ANSYS workbench transient structural analysis is considered as this type of analysis is used to determine the dynamic response of a structure under the action of any general time-dependent loads. Then the material properties are added to the imported CAD model. After attaching CAD model of the tool and work piece, settings related to part geometry, coordinate systems and reference temperature are inputted. It is then meshed as shown in Fig.4 and simulated with higher mesh density on contact surfaces to allow contact stresses to be distributed in a smoother way.

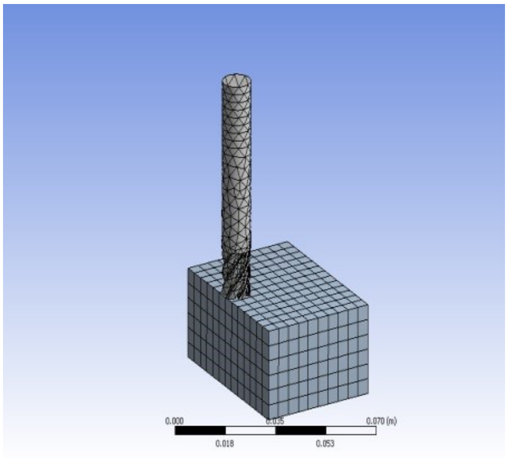

Fig.4. Meshing of end mill tool and work piece

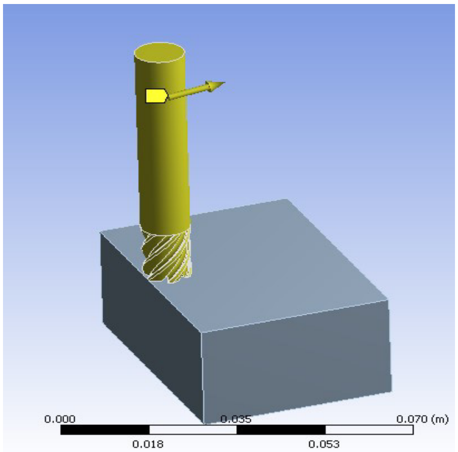

Fig.5. Applying all settings to the tool

4.2 Analysis Settings

Analysis settings include many options for finding the stress analysis. Step controls are used to control the time step size in a transient analysis. They are used to perform two distinct functions like defining steps and specifying analysis settings for each step. All these details are given from Table 5-7. Figure.5 shows a screen shot of the part after applying all the necessary settings.

Table.5 Details of analysis setting

Step controls	
No of steps	1
Step end time	1s
Auto time stepping	on
Define by	substeps
Initial substeps	1000000000
Minimum substeps	1000000000
Non-linear controls	
Force convergence	Program controlled
Displacement convergence	Program controlled
Rotation convergence	Program controlled
Line search	Program controlled

Table.6 Details of rotational velocity

Steps	Time(s)	Rotational velocity (rad/s)
1	0	75
1	1	75

Table.7 Details of velocity

Steps	Time(s)	Displacement(m)	Velocity(m/s)
1	0	0.001	0.008
1	1	0.001	0.008

5. Simulation and Results

In the present work, dynamic analysis of the tungsten carbide end mill tool on Ti-6Al-4V work piece are simulated using ANSYS workbench software. The simulation results are given in Table 8. Fig.6 and Fig.7 shows the transient structural analysis performed for the present conditions. Also the simulation analysis has been performed for 3 types of milling operations namely slot milling, hole and step milling and various graphs are plotted. Due to page restrictions only few graphs from Fig.8-10 are presented. Fig.8 represents a gradual increase in stresses of the tool with respect to time. In machining, time period is major criteria as it will affect the tool life which in turn affects the work piece quality. Also stresses acting over the tool during machining affect the tool life. Particularly in milling operations the work done by the tool must be completed within the time to optimize the stresses as both time and stresses are interrelated to each other. This has been achieved properly and in Fig.9 relationship between stresses and strain are shown (stress increases with respect to strain). Finally the Fig.10 represents the relationship between the stress and the time period. It clearly states whenever there is an increase in tool usage the stresses over the tool is increased. Based on the analysis and plotted graphs the following points are observed:

1. Stresses observed on the optimally designed tool are lesser.
2. Forces on the tool are reduced when compared with the values from the existing literatures.
3. Tool life (usage) is improved based on the new optimal design.
4. The tool life while milling Ti-6Al-4V is observed based on the calculated forces.
5. The simulated values and the calculated values are closer to each other and can be taken a potential direction for further research.

Table.8 Machining conditions and von mises stress

Speed (rad/s)	**Velocity (m/s)**	**Displacement (m)**	**VonMises Stress(pa)**
75	0.001	0.001	1.135e5
75	0.004	0.001	4.6085e5
60	0.003	0.001	4.3053e5
75	0.01	0.0015	1.1558e6
75	0.06	0.001	6.9466e6
60	0.08	0.001	9.2638e6
60	0.1	0.001	1.1064e7
65	0.4	0.001	1.4544e7
60	0.009	0.001	1.0408e6

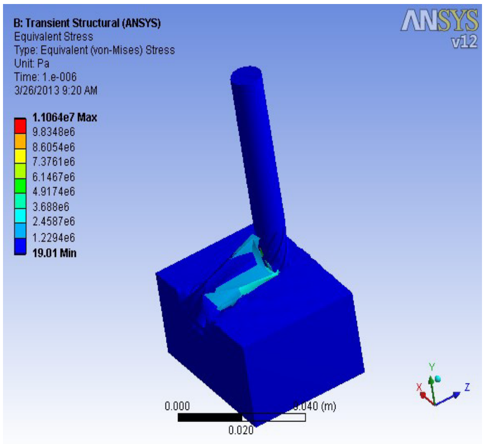

Fig.6 Equivalent stress-1

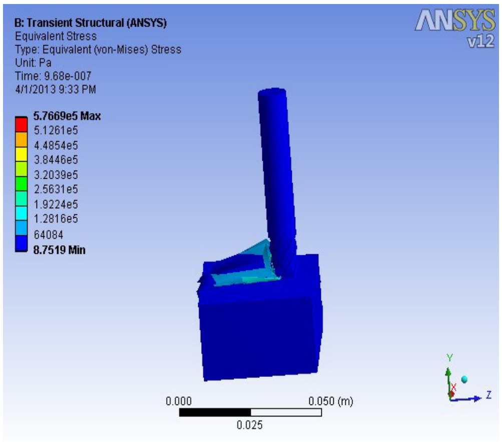

Fig.7 Equivalent stress-2

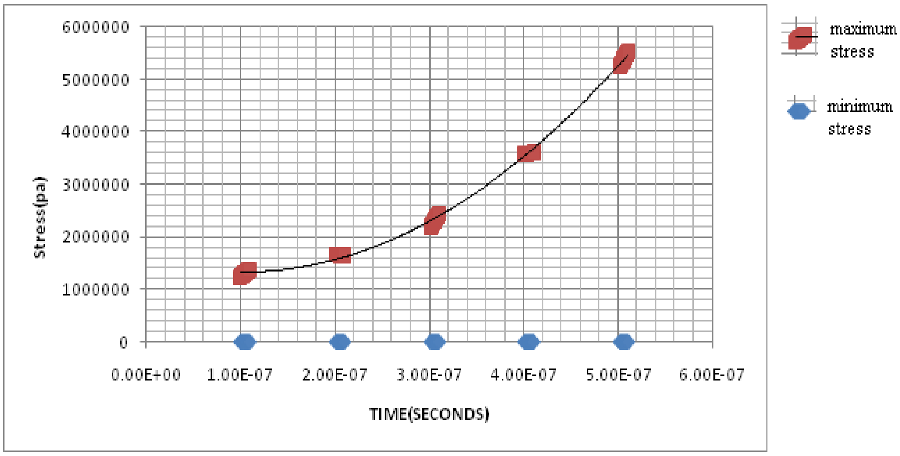

Fig.8 Relationship between Time(s) vs. minimum and maximum Stress (pa)

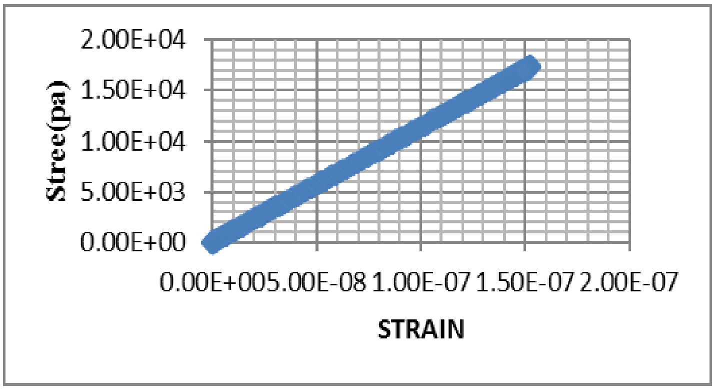

Fig.9. Relationship between Stresses (pa) vs. Strain during end mill tool analysis

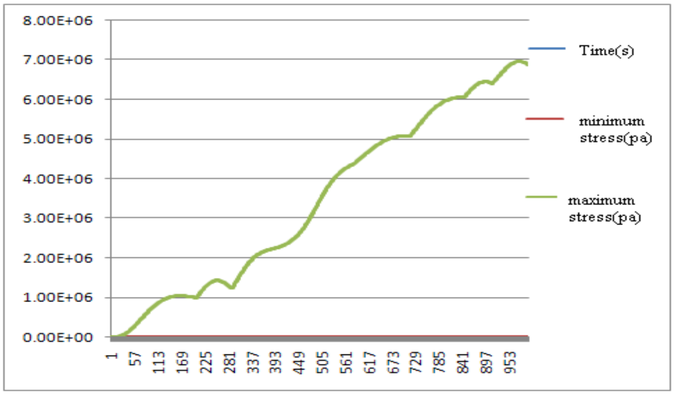

Fig.10 Relationship between Time(s) vs. minimum and maximum Stress (pa)

6. Conclusions and Scope for Future work

In this paper, an approach to calculate the end mill tool forces while milling Ti-6Al-4V has been presented by using tool geometric equations. Standard cutting conditions of milling machines are considered and cutting velocity, forces, power are calculated for the better performance of end mill. The optimal design of end mill including end mill insert are developed using Autodesk Inventor and were simulated using ANSYS. The obtained results indicate that the predicted forces and simulated forces are closer to each other. Based on these observations it is decided to carry out further work to experimentally verify the dynamic stresses and forces of end mill while milling Ti-6Al-4V considering appropriate machining parameters.

References

[1]. P Lee and Y.Altintas,(1996)"Prediction of ball-end milling forces from orthogonal cutting data”, International Journal Machine Tools Manufacturing, vol 36,pp. 1059-1072

[2]. Ahmad Yasir M., Che Hassan C.H, Jaharah A.G, Nagi H.E, Yanuar B and Gusri A.I,(2009)"Machinability of Ti-6Al-4V Under Dry and Near Dry Condition Using Carbide Tools",The Open Industrial and Manufacturing Engineering Journal,pp.1-9.

[3]. Puneet Tandon, Phalguni Gupta and Sanjay G. Dhande, (2005)"Geometric Modelling of End Mills”, Computer-Aided Design & Applications, Vol. 2, Nos. 1-4, pp 57-65.

[4]. Abbas Fadhel Ibraheem, Saad Kareem Shather & Kasim A. Khalaf,(2008)"Prediction of Cutting Forces by using Machine Parameters in end Milling Process",Engneering&Technology,Vol.26.No.11.

[5]. D. Dimitrov, D. Hammond , N. Treurnicht1and M. Saxer, (2012)" Investigation of Selected Cooling Techniques for Milling of Ti-6Al-4V", Computers and Industrial Engineering 42 Proceedings.pp.21-28.

[6]. Nagi Elmagrabi, Che Hassan C.H, Jaharah A.G, F.M. Shuaeib,(2008)"High Speed Milling of Ti-6Al-4V Using Coated Carbide Tools", European Journal of Scientific Research ISSN 1450-216X Vol.22, pp.153-162.

[7]. C.M. Lee, S.W. Kima, Y.H. Lee, D.W. Lee, (2004)"The optimal cutter orientation in ball end millingof cantilever-shaped thin plate", Journal of Materials Processing Technology, pp.153–154.

[8]. Pai chi chang and Wang lin, (2007) “Evaluation of the profile of the taper ball milling cutter with a cylindrical shank”, Journal of Materials Processing Technology, pp.407-413.

[9]. H.Kuo and L.J.Wu (2001) “A study on the evaluation of a model of the precise outside of the roller mill cutter”, Journal of Materials Processing Technology, pp.178-182.

[10]. S.Engin and Y.Altintas (2001) “Mechanics and dynamics of general milling cutter”, International Journal Machine Tools Manufacturing, pp.2195-2212.

[11]. Johanna Senatore, Stephane Segonds, Walter Rubio, Gilles Dessein(2012) “Correlation between machining direction, cutter geometry and step-over distance in 3-axis milling: Application to milling by zones”, Computer-Aided Design, pp.1151-1160.

[12]. S. Engin, Y. Altintas (2001), “Mechanics and dynamics of general milling cutters. Part II: inserted cutters”, International Journal of Machine Tools & Manufacture, pp. 2213–2231.

[13]. Qingyuan Caoa, Jun Zhao, Shiguo Han, XiaoxiaoChen (2012), “Force coefficients identification considering inclination angle for ball-end finish milling”, Precision Engineering, Vol.36,pp.252-260.

[14]. MC Shaw, SO Dirke, PA Smith, NH Cook, EG Loewen, CT Yang, (1954). Machining titanium, MIT Rep., (Contract AF 33 (600) 22674..

[15]. NH Cook (1953). Chip formation in machining titanium, In Proc. Symp. On Machining and Grinding Titanium, Watertown Arsenal, Watertown, MA, US Army Ordnance Corps. 1-7.

[16]. OW Boston, RM Caddell, LV Colwell, RE McKee, KF Packer, PR Visser. Machining titanium, Final Rep. (Production Engineering Department, University of Michigan) (US Army Contract 20-018-ORD-11918).

[17]. W Konig, (1979). Applied Research on the Machinability of Titanium and Its Alloys, Proceedings of the Forty-seventh Meeting of AGARD, AGARD Structural and Material. CP256, 1-10.

[18]. Ezugwu EO, Wang ZM, 1997,. Titanium alloys and their machinability - a review. Journal of Processing Technology. 68: p. 262 - 274.

[19]. Wang ZY, Rajurkar KP. Cryogenic machining of hard-to-cut materials. Wear. 2000; 239:p.168-175.

[20]. Rahman M, Wang ZG, Wong YS. 2006, A review on high-speed machining of titanium alloys. JSME International Journal; 49: p. 11-20.

[21]. Hong SY, Markus I, Jeong Wc, 2007. New cooling approach and tool life improvements in cryogenic machining of titanium alloy Ti-6Al-4V. International Journal of Machine Tools & Manufacture.41: p. 2245-2260.

[22]. Machinery’s Handbook, Erik Oberg, Franklin D. Jones , Henry H. Ryffel, Christopher J. McCauley, Industrial Press Inc.,U.S, 29th Revised edition, 2012.