Development of Cutting Force Model by FEM Approach and Experimental Investigation of Tool Wear for CNC end Milling in Machining of Titanium alloy Ti-6Al-4V

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Abstract**-- This paper presents the development of a cutting force model for end milling process under various cutting conditions and the tool wear is measured by Scanning Electron Microscope (SEM).This novel approach combines the concept of experimental design and finite element modeling of the cutting process which allows for a fairly accurate prediction of cutting forces with a significantly lower computational cost. The milling experiments are performed by CNC milling machine with tungsten carbide tools. The test sample made of titanium alloy Ti-6Al-4V is prepared for testing. The cutting conditions are selected based on the toughness of the work piece with in the tool manufacturer's recommended range for the work piece and tool geometry configuration. The cutting forces are measured by using dynamometer and compared the simulated results. In this modeling, the cutting tool and work piece are defined as per Taguchi design of experiments (DOE). In cutting approach, Deform 3D v 6.1 software is used to simulate the milling process.**

Index Term**-- End milling, Cutting force, Tool Wear, Machining, Metal cutting, Modeling.**

INTRODUCTION

Titanium alloy Ti-6Al-4V is known as a difficult to machine material because of its poor thermal conductivity and high cutting force in the conventional milling process. Large cutting forces are detrimental to tool life and surface integrity of work pieces and should be avoided in the machining process. Milling operation is widely used to fabricate miniaturized components with complex three dimensional (3D) geometries and shapes in bio medical, optics and electronics industries [1,2]. Tsao [3, 4] used the Taguchi method to optimize the drilling parameters (drill diameter ratio, fed rate and spindle speed) based on the core saw drill and step core drill in the drilling of CFRP; the results showed that when the feed speed was 8mm/min, spindle speed was 1200rpm diameter ratios were 0.55 and 0.74 and the axial force and hole defects came to a minimum value. Lliescu., et al. [5] Estimated and evaluated the axial force in the drilling of carbon fiber composites with coated and un coated tools and found that the main factors affecting the axial force were feed rate, cutting speed and tool wear. Alauddin et al. [6] experimentally investigated the influence of machining conditions on the average cutting forces in the end milling of inconel 718 in dry conditions using uncoated carbide inserts. It was observed that the cutting forces decrease as the cutting speed increases (11-25 m/min) for up and down mode end milling. Nevertheless the cutting speed range in the study by Alauddin et al. was relatively low. Choudhury and El baradie [7] it was reported that the tool life of coated tools was not better than that of the uncoated tools through a series of machining experiments of cutting inconel 718 using coated and un coated carbides.

Modeling of the cutting forces in end milling is important for process planning and optimization. The cutting edge in roughing or ploughing the work piece rather than cutting, causing a significant increase of cutting forces as the frictional forces are increased. The strong size effect makes more challenging [8]. It is therefore important to study the mechanics of micro cutting processes and develop comprehensive cutting force models. There have been extensive research efforts on understanding the mechanics in end milling process and developing comprehensive cutting force. Different approaches for the determination of the cutting forces exist in the literature, such as analytical, mechanistic and Numerical [9].The analysis of cutting forces in milling operation is dated back to Martelloti [10]. Saberwal., et al [11] correlated the local normal cutting force coefficients. Tlusty and Macneil [12] presented analytical expressions for cutting forces in end milling operations in which the tangential component of the cutting force was considered to be proportional to the cutting load and the radial force is empirically related to the tangential force. Kline., et al

[13] proposed a mechanistic cutting force model by considering the helix face of the cutter as an aggregation of small discrete disks along the axis. Bao and Tansel [14] introduced an analytical cutting force model for micro milling operations based on the model for conventional milling [12].Vogler., et al [15,16] have developed a cutting force model for micro milling that included both the minimum chip thickness and the micro structure effects. Zaman [17] developed a three dimensional analytical cutting model for micro end milling operation ,which determines the theoretical chip area at any specific angular position of the tool cutting edge by considering the geometry of the path of the cutting edge and relates this with tangential cutting force. Lee [18] developed a mechanistic cutting force modeling in micro end milling with cutting condition independent of cutting force coefficients. Lai [19] presented an analytical micro scale milling force model based on the FE simulations using the cutting principles and the slip line theory. Malekian [20] investigated a mechanistic modeling of micro milling forces, with consideration of the effects of ploughing, elastic recovery, run out and dynamics.

It should be noted that inspite of the extensive research efforts, it is still difficult to model machining, especially micro machining, due to the fact that there are too many variables that need to be taken into account [9].Mechanistic model is effective in predicting the cutting forces in micro milling provided that the cutting force coefficients are accurately identified from experiments. For new combinations of tools and materials without testing data, the cutting forces cannot be predicted using this approach. Theoretically the cutting forces can be obtained directly from FE simulation. Nevertheless, finite element method (FEM) requires a considerable amount of computational power to minimize accurate results. If the analysis using FEM is to consider 3D, special care is needed for simulating a micro milling process. The degree of complexity and the computational powers are increased, which adds considerably to computational time [9], and thus makes FEM not a practical approach for industrial users.

This paper presents the development of a cutting force model for end milling process using a FEM approach to enable reliable and physically sound prediction of cutting forces in end milling without the burden of heavy computational power or experimental work. The proposed cutting model for end milling is developed based on a mechanistic cutting model presented in [21] which was originally for conventional milling processes. In order to expand the mechanistic cutting force model into FEM model is employed to predict the cutting forces in end milling. Based on the FEA simulation, Deform 3D predicts the cutting forces and cutting conditions. The tool edge deterioration during metal cutting operation has a great impact on the surface quality and dimensional accuracy of the machined parts. In addition, the tool wear can directly affects the overall operation cost, as it dictates either a more frequent tool change to meet the requirements of a surface finish properties or longer machining times by using conservative data to prevent rapid tool edge degradation [22, 23]. Balla Srinivasa Prasad., et al.[24] presents the correlation of vibration signal feature that is displacement due to vibration(microns) during the machining and three dimensional finite element simulations in tool wear monitoring of a metal turning operation. This work demonstrates the three dimensional finite element analysis is used to predict the work piece displacements in feed direction and corresponding tool wear with the help of induced vibrations in face turning under dry machining conditions. Bao Hai, W.,et al [25] studied a new analytical based method for the prediction of cutting tool temperature in end milling. They claimed the dramatic tool temperature variation in end milling can cause excessive tool wear and shorten its life especially in machining of difficult to machine materials. Storchak, M., et al [26] presents the results regarding the creation of the FEM models for the cutting processes of the titanium alloy Ti-1023. Bian, X., et al [27] use Discrete element method (DEM) can simulate the motion and interaction of particle materials. This method is widely used to simulate the working process of ball mills, which yields many research valuable outcomes. In this the simulation results of particle behavior mill torque and power consumption obtained from DEM simulation is compared with experimental results in detail to validate the correctness of the simulation results. Zhang,W., et al [28] analyzed the temperature change of the sinusoidal surface milling process is simulated by using 3 dimensional modeling software, Mat Lab and finite element software. According to the finite element simulation and experimental results, the range of temperature field of sinusoidal surface modeling is similar. Specifically, the research tasks include generation of appropriate experimental data and correlate the results with a 3D FE simulation model look into the influence of cutting forces into various cutting conditions. The_implementation of machining models in the commercial FEM code Deform 3D V6.1 relates the cutting forces and tool wear during machining to the predicted process variables. The results show the good degree of agreement between experimental and simulated values in predicting cutting forces at different cutting conditions. The main objective of this work is to experimentally investigate the cutting forces and tool wear during milling of titanium alloy Ti-6Al-4V with carbide end mills under dry machining condition.

MATERIALS AND METHODS

Titanium alloys are widely used in aeronautics that demands a good combination of high strength, good corrosion resistance and low stress. The mechanical properties lead to challenges in machining operations such as high process temperatures as well as rapidly increasing tool wear. In this work, tungsten carbide end mills have been used in machining of titanium alloy Ti-6Al-4V.

The work piece material used in the experiment was Ti-6Al-4V with chemical composition shown in Table I. Its mechanical properties are shown in Table II.

Table I
Chemical composition of Ti-6Al-4V

Al	V	Fe	Si	C	N	H	O	Titanium
5.6	3.86	0.18	0.01	0.02	0.023	0.01	0.17	Balance

Table II
Mechanical properties of Ti-6Al-4V

Mechanical Properties	Value
Tensile strength(MPa)	1170
Yield strength(MPa)	880
Elongation (%)	10
Modulus of Elasticity(GPa)	113
Hardness(HB)	334

The end mill cutters have been rapidly fixed to a tool holder with a nominal diameter of 10mm. Geometric parameters of the tools are given in Table III.

Table III
Geometric parameters of end mills

Diameter (mm)	10
Rake angle (°)	10
Clearance angle (°)	10
No of tooth	2
Helix angle	30

Experimental procedure

1. Each trail was started with a new end mill with one new test condition (trail) and machining was stopped at the end of each pass.
2. A Kistler type 9257B dynamometer was used to measure the three orthogonal components of the cutting force. It has a good rigidity and high natural frequency. The work piece block of Ti-6Al-4V was mounted on the dynamometer through a fixture. The dynamometer was connected to a multichannel charge amplifier and the output signal was acquired by a high speed data acquisition (DAQ) card in a computer.
3. After each pass, the end mill cutter is removed and its tool wear is measured by Scanning Electron Microscope (SEM)
4. The above steps were repeated and remained the same in the experiment with a new end mill.
5. Experimental data of 27 experiments, tool wear V_B and cutting forces along x, y and z directions are shown in the Table IV.
   The force along x is thrust force (F_T), force along y is cutting force (F_C) and force along z is radial force (F_R). The resultant force (F) of these components has been measured by root mean square of all these three component of forces.
   The cutting parameters for the experiment were chosen as follows: cutting speed (95,110 and 126m/min), feed rate (0.1, 0.2 and 0.3 mm/rev) and depth of cut as (0.3, 0.6 and 1 mm).

A total no of 27 sets of cutting tests have been carried out using a full factorial experimental design. The experiments have been carried out on Chandra BFW CNC milling machine as shown in the Figure 1. The following sequential procedure was used to carry out the experiment under dry condition without any coolant or lubricant. Once all apparatus and DAQ were set up, a position configuration process was run to rest the default position of the coordinates on the CNC machine. This positioning process was done before each set of the tests and repositioning the default **z** plane of the work piece. Some pretests were carried out to ensure that entire equipment worked properly. The cutting parameters are selected according to the tool supplier's recommendations for work piece material and tool combinations. Cutting velocity and feed rates are selected based on the tool manufacturer's (Sandvik) recommendations for work piece material and tool combination.

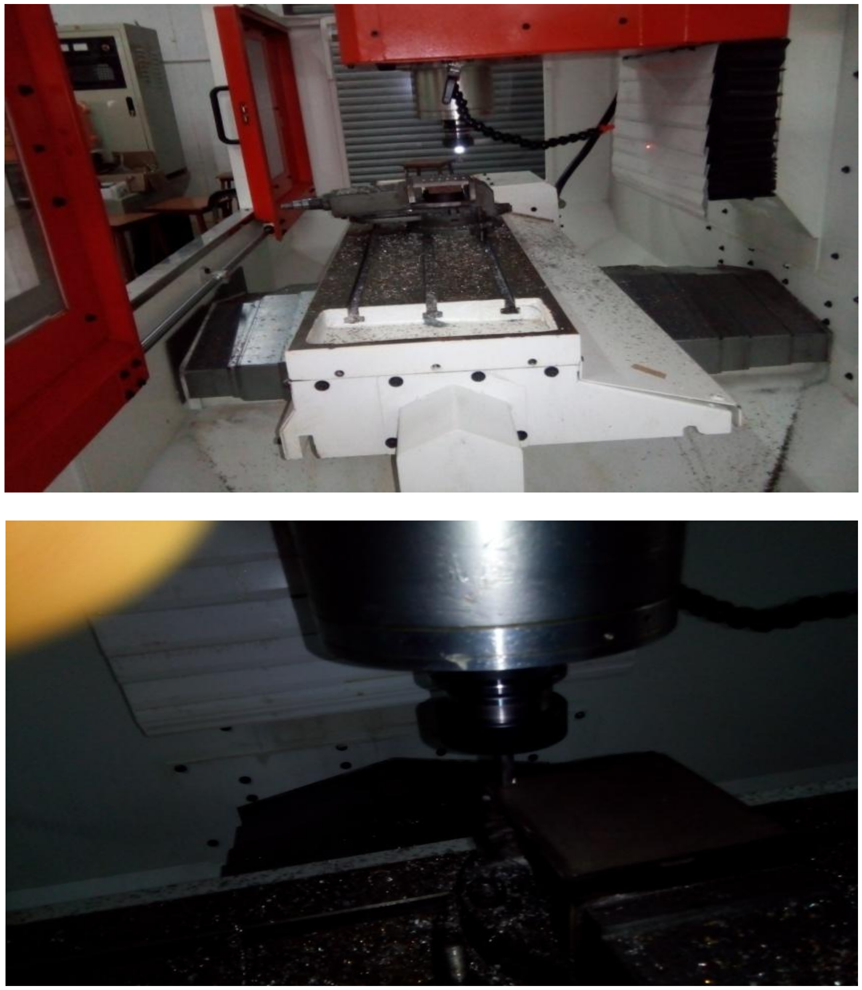

Fig. 1. a) Three axis CNC vertical milling machine b) work piece mounted on the machine table

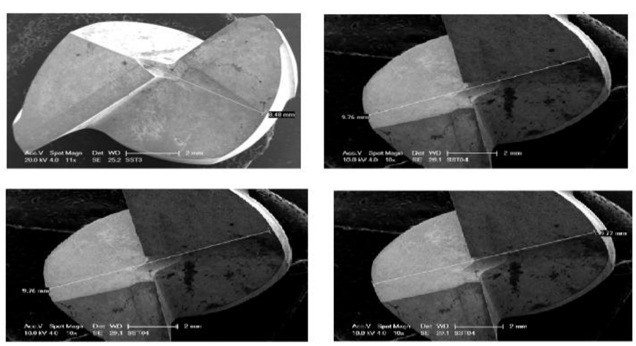

Fig. 2. The measurement of a tool wear of a two flute tungsten carbide end mill for machining of Titanium alloy Ti-6Al-4V

3. Results and Discussion

Table IV (a)
DOE with simulated and experimental results of cutting forces in x, y and z directions

Exp. No.	Design of experiments			Simulated values of Cutting Forces in (N)				Experimental values of Cutting Forces in (N)				
	C S (m/min)	F R (mm/rev)	DOC (mm)	F_T	F_C	F_R	F	F_T	F_C	F_R	F	% of Error
1	95	0.1	1.0	455	514	273	739	460	520	278	748	1.2
2	95	0.2	1.0	99	559	73	572	110	566	79	582	1.75
3	95	0.3	1.0	147	385	535	675	155	395	541	688	1.9
4	95	0.1	0.6	310	320	390	592	290	325	384	581	-1.86
5	95	0.2	0.6	370	490	510	798	376	503	515	812	1.75
6	95	0.3	0.6	440	474	615	893	451	481	623	907	1.57
7	95	0.1	0.3	190	260	420	529	195	272	431	546	3.21
8	95	0.2	0.3	310	595	820	1059	295	585	810	1042	-1.61
9	95	0.3	0.3	161	198	430	500	170	203	439	513	2.6
10	110	0.1	1.0	512	600	390	880	520	613	395	896	1.82
11	110	0.2	1.0	556	550	449	902	562	556	457	913	1.22
12	110	0.3	1.0	430	370	360	672	435	374	365	680	1.19
13	110	0.1	0.6	275	332	356	559	280	339	361	569	1.79
14	110	0.2	0.6	362	420	460	720	367	427	469	733	1.81
15	110	0.3	0.6	441	482	620	900	449	491	628	915	1.67
16	110	0.1	0.3	160	245	415	508	167	253	421	519	2.17
17	110	0.2	0.3	310	620	865	1109	308	617	859	1102	-0.631
18	110	0.3	0.3	172	150	395	456	176	159	402	467	2.41
19	126	0.1	1.0	550	630	560	1007	558	629	559	1010	0.3
20	126	0.2	1.0	614	493	502	934	621	497	508	944	1.07
21	126	0.3	1.0	602	520	495	937	610	527	503	950	1.39
22	126	0.1	0.6	180	195	340	431	187	201	347	442	2.55
23	126	0.2	0.6	380	490	560	836	384	497	565	845	1.08
24	126	0.3	0.6	450	492	620	910	455	497	627	920	1.1
25	126	0.1	0.3	160	260	410	511	167	269	413	520	1.76
26	126	0.2	0.3	110	230	385	462	115	237	391	471	1.95
27	126	0.3	0.3	170	180	420	487	178	184	427	498	2.26

Table IV (b)
DOE and Experimental results of tool wear

Exp. No.	Design of Experiments			Tool wear V_B (μm)				
	C S (m/min)	F R (mm/rev)	DOC (mm)	V_{B1}	V_{B2}	V_{B3}	V_{B4}	V_B (Avg.)
1	95	0.1	1.0	0.17	0.17	0.17	0.17	0.17
2	95	0.2	1.0	0.17	0.17	0.17	0.17	0.17
3	95	0.3	1.0	0.17	0.17	0.17	0.17	0.17
4	95	0.1	0.6	0.17	0.17	0.273	0.276	0.222
5	95	0.2	0.6	0.17	0.17	0.223	0.267	0.208
6	95	0.3	0.6	0.17	0.17	0.176	0.247	0.191
7	95	0.1	0.3	0.269	0.28	0.277	0.273	0.275
8	95	0.2	0.3	0.176	0.277	0.252	0.259	0.241
9	95	0.3	0.3	0.17	0.217	0.238	0.259	0.221
10	110	0.1	1.0	0.17	0.17	0.17	0.184	0.174
11	110	0.2	1.0	0.17	0.17	0.17	0.176	0.172
12	110	0.3	1.0	0.17	0.17	0.17	0.171	0.17
13	110	0.1	0.6	0.275	0.272	0.278	0.279	0.276
14	110	0.2	0.6	0.24	0.179	0.252	0.27	0.235

15	110	0.3	0.6	0.17	0.17	0.201	0.247	0.197
16	110	0.1	0.3	0.278	0.28	0.28	0.277	0.279
17	110	0.2	0.3	0.26	0.28	0.269	0.257	0.267
18	110	0.3	0.3	0.19	0.28	0.24	0.251	0.241
19	126	0.1	1.0	0.23	0.174	0.177	0.185	0.192
20	126	0.2	1.0	0.216	0.177	0.172	0.178	0.186
21	126	0.3	1.0	0.177	0.171	0.17	0.171	0.172
22	126	0.1	0.6	0.279	0.279	0.275	0.279	0.278
23	126	0.2	0.6	0.279	0.268	0.255	0.277	0.269
24	126	0.3	0.6	0.26	0.176	0.186	0.255	0.219
25	126	0.1	0.3	0.28	0.28	0.28	0.279	0.28
26	126	0.2	0.3	0.27	0.28	0.28	0.269	0.275
27	126	0.3	0.3	0.199	0.28	0.26	0.24	0.245

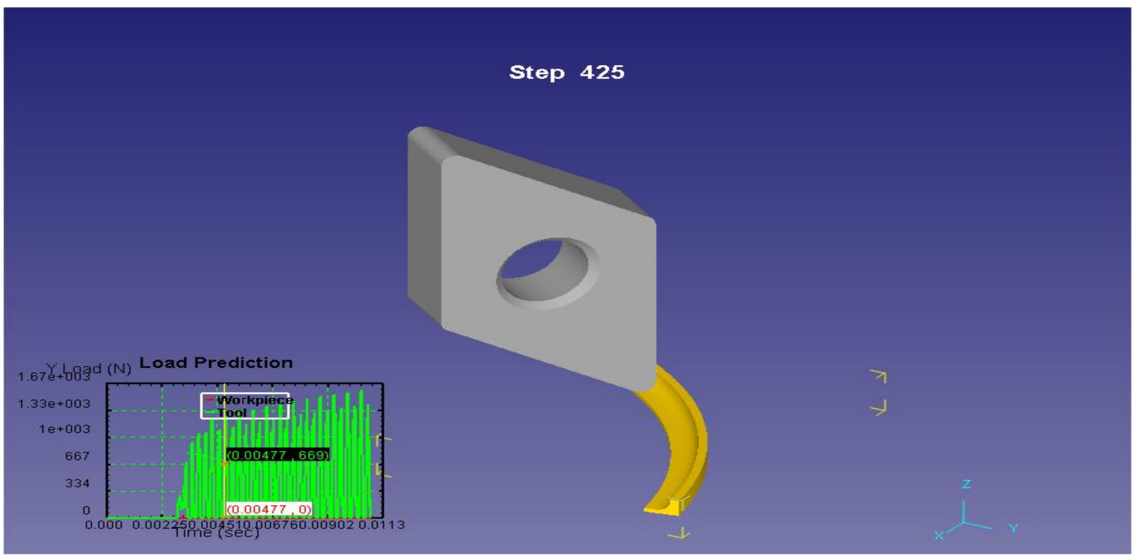

Fig 3. The measurement of cutting forces from D-form 3D software

The 3D model, implemented in DEFORM 3D v6.1 is reported in the Fig 3, where it is possible to see the cutting forces in Y direction. In the present work, the cutting tool assumed to be as rigid object meshed with more than 50000 elements is oriented according to the cutting angles set in experimental test conditions selected and it moves along a linear direction. The work piece considered as a rigid elasto-plastic object meshed with more than 25000 elements is fully constrained on the lower and lateral sides so that it cannot move. The friction is modeled considering a shear factor equal to 0.6.An adaptive re meshing scheme is implemented to optimize between the computational time and accurate prediction. The base of the work piece is constrained in all directions. The tool is subjected to move in Y direction at three different constant speeds and constrained against movements in X and Z directions. A commercial software code, DEFORM 3D v6.1 and it is an explicit dynamic ALE modeling approach is used to conduct the FEM simulation for machining by considering two flute tungsten carbide end mill geometry are successfully implemented in the model. In this approach, the elements are attached to the material, and the undeformed tool is advanced towards the work piece.

The software is used for modeling and simulating the cutting process capable of performing coupled thermo-mechanical transient analysis. The thermo mechanical FEM simulation models are related by including tool and work piece thermal and mechanical properties, boundary conditions and contact conditions between tool and work piece and one of the FEM models are shown in Fig 3. As discussed in the literature, the research is aimed to the 3D numerical prediction of cutting forces and tool wear using the knowledge acquired in 2D studies. Thus in order to validate 3D predictions for both cutting forces and tool wear has been carried out in milling.

The cutting forces are measured by using dynamometer set up and D-form 3D software. The 1000 step of operation is completed in 0.005 seconds. The values are tabulated and percentage of error between the two resultant values of forces have been calculated and found the error is within the permissible limit.

It is observed from the table that the cutting force component 'F_C' predominant at low cutting speeds like 95m/min and at the same time the thrust force component 'F_T' and radial force component 'F_R' are not predominant. The cutting speed plays a major role in increment of cutting forces.

The cutting force 'F_C' is higher when the tool operates at cutting speed of 126m/min, feed rate of 0.1 mm/rev and 1 mm depth of cut. The cutting speed plays a major role in cutting force increment. The thrust force component 'F_T' is higher at cutting speed of 126 m/min, feed rate 0.2 mm/rev and 1mm depth of cut. Probably this component minimizes the tool life and increases the tool wear. The Radial component 'F_R' is higher at the cutting speed of 110 m/min, feed rate of 0.2 mm/rev and 0.3 mm depth of cut. The total resultant force has a higher value at cutting speed of 110 /min, feed rate of 0.2 mm/rev and 0.3 mm depth of cut.

The cutting force 'F_C' is lower when the tool operates at cutting speed of 110m/min, feed rate of 0.3 mm/rev and 0.3 mm depth of cut. The thrust force component 'F_T' is lower at cutting speed of 95 m/min, feed rate 0.2 mm/rev and 1mm depth of cut. The Radial component 'F_R' is lower at the cutting speed of 95 m/min, feed rate of 0.2 mm/rev and 1.0 mm depth of cut. The total resultant force has a lower value at cutting speed of 126 /min, feed rate of 0.1 m/rev and 0.6 mm depth of cut.

The tool wear for four passes of travel of a tool on the titanium alloy Ti-6Al-4V work piece has been measured. The passes 1 and 3 are in feed direction and passes 2 and 4 are in depth of cut direction of a tool travel. The tool wear of a cutting tool for each and every pass has been measured by Scanning Electron Microscope (SEM) and then be taken as an average value for all four values of $V_{B\,1}$, $V_{B\,2}$, $V_{B\,3}$ and $V_{B\,4}$ is given in table IV (b). This has been measured based on the Taguchi design of Experiments and optimized at particular cutting speed, feed rate and depth of cut. The tool wear is higher at cutting speed of 126m/min, feed rate of 0.1 mm/rev and 0.3 mm depth of cut. The tool wear is lower at cutting speed of 95m/min, feed rates at 0.1 mm/rev, 0.2 mm/rev and 0.3 mm/rev and at depth of cut of 1mm.Based on this measured data, the feed rate has no significant effect on tool wear. The minimum tool wear is happened as 0.17 microns and maximum tool wear is 0.28 microns.

CONCLUSIONS

Based on the experimentation and simulation, the values of the cutting forces and tool wear is calculated and verified. It is concluded that

1. The mathematical model improves the machining performance by choosing the proper input variables like cutting speed, feed rate and depth of cut.
2. The tool wear is calculated and checked at particular input variables and also concluded the minimum tool wear at a specified parameters.
3. It is observed that the cutting forces and tool wear has significant relationship on each other.
4. The cutting force model and tool wear combination gives optimum cutting tool input parameters.
5. It is observed that the cutting forces and tool wear has significant relationship on each other. The cutting force model and tool wear combination gives optimum cutting tool input parameters. A comparison of the simulated cutting forces with the experimental forces indicates that the force simulation is acceptable with the cutting force model.

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