MANTECH Publications

Journal of Product Design, Quality Engineering & Technology
Volume 4, Issue 3, September-December 2019

The Development of Cutting Force Model by FEM Approach and Experimental Investigation of Tool Wear for CNC End Milling in Machining of AISI 316 Stainless Steel

A. Sreenivasa Rao[1], K Venkata Rao[2]

Department of Mechanical Engineering

MLR Institute of Technology, Hyderabad, India[1]

PBR Visvodaya Institute of Technology & Science, Kavali, India[2]

Corresponding Author: *asrao2k14@gmail.com*

Abstract

Finite element simulations have been utilized in analyses of machining process for several decades. 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 simulated results are compared against the experimental observations. The results have shown that the material AISI 316 Stainless steel has affects on cutting forces and tool wear. In cutting approach, Deform 3Dv6.1 software is used to simulate the milling process. The simulation and experimentation is performed based on Taguchi design of experiments. In this research, three dimensional finite element modeling and simulation issues for vibration assisted milling are explored in detail. Machine dynamic effects are taken into account to predict the outcomes such as tool wear and cutting forces. The model can be implemented in an online tool wear monitoring system which predicts the actual state of tool wear in real time by correlating cutting force variations during machining. The comparisons of simulations with experimental results demonstrate their predictive capability. From the results, useful conclusions may be drawn, and it can be stated that the proposed models can be used for industrial application.

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Keywords: *End milling, Cutting force, Tool Wear, Machining, Metal cutting, Modeling.*

INTRODUCTION

AISI 316 Stainless Steel has wide applications include pumps, valves, marine fittings, fasteners, paper and pulp machinery, petro chemical equipment and surgical implants that demand 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 temperature as well as rapidly increasing tool wear. In this work, tungsten carbide end mills have been used in machining of AISI 316 Stainless Steel. Literature to date has shown that limited work has been carried out to analyze the consequence of machining process variables on cutting of AISI 316 Stainless Steel.

Vasile, MJ., et al (1999) and Weule, H., et al (2001) proved that 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.

Tsao, CC., et al (2008) 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. 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, M., et al. (1998) 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

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(end milling. Nevertheless the cutting speed range in the study was relatively low.

Choudhury, IA., (1998) 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.

Ko, JH., (2008) proved that the 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. 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.

Markopoulos, AP., (2013) used different approaches for the determination of the cutting forces exist in the literature, such as analytical, mechanistic and Numerical. Martelloti, E., (1941) analyzed cutting forces in milling operation. Sabberwal, AP., (1961) correlated the local normal cutting force coefficients.

Tlusty, J., et al (1975) 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 (1962) proposed a mechanistic cutting force model by considering the helix face of the cutter as an aggregation of small discrete disks along the axis.

Afazov, SM., et al (2010) introduced an analytical cutting force model for micro milling operations based on the model for conventional milling.

Vogler, MP., et al (2003) and (2004) have developed a cutting force model for micro milling that included both the minimum chip thickness and the micro structure effects.

Zaman, MT.,et al (2006) developed a three dimensional analytical cutting model

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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 by considering the geometry of the path of the cutting edge and relates this with tangential cutting force.

Lee, HU., et al (2008) developed a mechanistic cutting force modeling in micro end milling with cutting condition independent cutting force coefficients.

Lai, XM., et al (2009) presented an analytical micro scale milling force model based on the FE simulations using the cutting principles and the slip line theory.

Malekian, M., et al (2009) 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. 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 Finite Element Simulation (FES). Nevertheless, finite element method (FEM) requires a considerable amount of computational power to reduce 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 power are increased, which adds considerably to computational time 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.

Altinas,Y.,(2000) proposed cutting model for end milling is developed based on a mechanistic cutting model presented in which was originally for conventional milling processes.

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Grzesik, W., (2008) used 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. 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 affect 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.

Bian, X., et al (2017) 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 (2017) 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.

Jiang, L., et al (2016) presents a Johnson- Cook model was used as material model of the work piece is reproduced with the Locroft and Latha model. The size of error for simulating the chip dimensions does not exceed 10% and ranges between 10% and 30% for simulating the resultant forces. In the present work, investigation primarily focuses on preparing a 3D FES based methodology to forecast the development of cutting forces and tool wear in milling operation.

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.

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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 AISI 316 Stainless Steel with carbide end mills under dry machining condition.

MATERIALS AND METHODS

The mechanical properties of AISI 316 lead to challenges in machining operations such as high process temperatures as well as rapidly increasing tool wear. The tungsten carbide end mill cutters were used for milling of AISI 316 Stainless Steel. The work piece material used in the experiment was AISI 316 with chemical composition shown in Table 1. Its mechanical properties are shown in Table 2.

Table: 1 Chemical composition of AISI 316 Stainless Steel

Elements	Percentage (%)
C	0.08 Max
Mn	2.0
Si	0.75
P	0.045
S	0.03
Cr	16-18
Ni	10-14
N	0.1
Fe	Balance

Table 2: Mechanical properties of AISI 316 Stainless Steel

Mechanical Properties	Value
Ultimate Tensile strength (MPa)	620-795
Yield strength (MPa)	206
Elongation at Break (%)	30
Modulus of Elasticity (GPa)	164
Hardness(BHN)	146

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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 3.

Table: 3 Geometric parameters of end mills

Diameter (mm)	10
Rake angle (^{o})	10
Clearance angle (^{o})	10
No of tooth	2
Helix angle	30

Machining is started with a fresh tool continued until the tool failed or the cutting teeth were severely worn, when continued cutting raised catastrophic failure. The duration of each test allowed complete stabilization of the cutting process to be attained while allowing for significant tool wear.

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 Fig 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 milling experiments are performed by CNC milling machine with tungsten carbide tools. Test sample made of AISI 316 steel 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-tooling geometry configuration. The cutting

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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 toolmanufacturer's Sandvik) recommendations for work piece material and tool combination.

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 m/rev) and depth of cut as (0.3, 0.6 and 1 mm). The force along x is thrust force (FT), force along y is cutting force (FC) and force along z is radial force (F).

The resultant force (F) of these components has been measured by root mean square of all these three component of forces.

Balla Srinivasa Prasad et al.(2016) 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 (2016) 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.

Jiang, L., et al (2016) presents the results regarding the creation of the FEM models for the cutting processes of the titanium alloy Ti-1023.



Fig 1: (a) Three axis CNC vertical milling machine

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Fig 1: (b) work piece mounted on the machine table

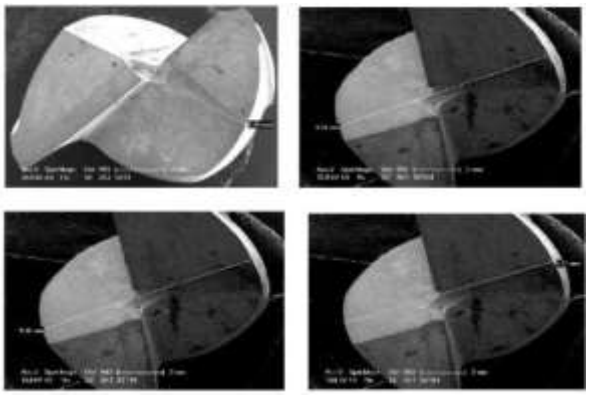

Fig 2: The measurement of a tool wear of a two flute tungsten carbide end mill for machining of AISI 316 Stainless steel. The flow chart of the present work is given below

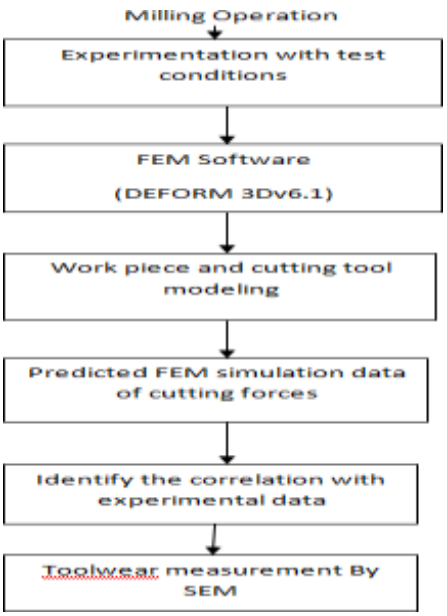

Fig 3: The flow chart of the present work for analysis of results

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RESULTS

Table 4 (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	340	240	330	531	335	235	325	523	1.5
2	95	0.2	1.0	590	720	910	1302	585	715	905	1293	0.69
3	95	0.3	1.0	220	190	181	340	210	185	176	331	2.6
4	95	0.1	0.6	295	315	525	680	300	320	530	688	-1.18
5	95	0.2	0.6	210	190	350	450	205	180	335	432	4
6	95	0.3	0.6	323	307	570	724	317	300	560	710	1.9
7	95	0.1	0.3	50	69	165	186	55	73	170	193	-3.76
8	95	0.2	0.3	230	320	615	730	220	310	610	719	1.5
9	95	0.3	0.3	110	98	270	308	115	105	265	307	0.32
10	110	0.1	1.0	120	108	100	190	125	110	105	197	-3.68
11	110	0.2	1.0	130	125	135	225	135	135	140	237	-5.33
12	110	0.3	1.0	160	150	175	280	152	145	170	270	3.57
13	110	0.1	0.6	375	410	650	855	380	415	655	863	-0.94
14	110	0.2	0.6	240	265	380	520	245	270	390	534	-2.69
15	110	0.3	0.6	250	230	350	488	240	225	335	470	3.69
16	110	0.1	0.3	60	65	165	187	70	72	170	197	-5.37
17	110	0.2	0.3	84	125	270	310	90	130	280	322	-3.87

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18	110	0.3	0.3	110	90	260	296	115	100	265	306	-3.26
19	126	0.1	1.0	305	240	290	485	300	235	280	473	2.47
20	126	0.2	1.0	390	310	490	700	400	320	495	712	- 1.714
21	126	0.3	1.0	340	410	370	650	345	415	380	660	-1.54
22	126	0.1	0.6	200	240	350	469	210	245	360	483	-2.99
23	126	0.2	0.6	220	250	360	490	230	255	365	501	-2.24
24	126	0.3	0.6	250	210	350	479	240	200	345	465	2.92
25	126	0.1	0.3	160	240	470	551	165	245	465	550	0.18
26	126	0.2	0.3	85	120	250	290	95	125	260	303	-4.48
27	126	0.3	0.3	110	100	260	300	100	95	255	290	3.33

Table 4 (b): DOE and Experimental results of tool wear

Exp. No.	**Design of Experiments**			**Experimental values of Tool wear V_B (µm)**				
	C S (m/min)	**F R (mm/rev)**	**DOC (mm)**	**$V_{B\,1}$**	**$V_{B\,2}$**	**V_{B3}**	**$V_{B\,4}$**	**V_B (Avg.)**
1	95	0.1	1.0	0.24	0.19	0.18	0.4	0.253
2	95	0.2	1.0	0.216	0.18	0.257	0.186	0.21
3	95	0.3	1.0	0.18	0.18	0.281	0.18	0.205
4	95	0.1	0.6	0.26	0.377	1.07	0.18	0.472
5	95	0.2	0.6	0.243	1.06	0.28	0.18	0.441
6	95	0.3	0.6	0.183	1.07	0.18	0.18	0.403
7	95	0.1	0.3	0.43	1.08	0.94	0.182	0.658
8	95	0.2	0.3	0.56	1.08	0.21	0.18	0.508

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9	95	0.3	0.3	0.997	1.08	0.18	0.18	0.609
10	110	0.1	1.0	0.242	0.185	0.18	1.07	0.419
11	110	0.2	1.0	0.232	0.181	0.18	0.871	0.366
12	110	0.3	1.0	0.186	0.18	0.193	0.182	0.185
13	110	0.1	0.6	0.2473	0.198	1.02	0.524	0.497
14	110	0.2	0.6	0.2397	0.187	1.08	0.28	0.447
15	110	0.3	0.6	0.186	0.183	0.604	0.18	0.288
16	110	0.1	0.3	0.35	0.48	0.842	0.338	0.503
17	110	0.2	0.3	0.273	1.08	0.738	0.318	0.602
18	110	0.3	0.3	0.192	1.08	0.24	0.18	0.423
19	126	0.1	1.0	0.232	0.181	0.18	0.185	0.195
20	126	0.2	1.0	0.21	0.18	0.18	1.0467	0.404
21	126	0.3	1.0	0.187	0.18	0.18	1.06	0.402
22	126	0.1	0.6	0.247	0.183	0.18	0.644	0.314
23	126	0.2	0.6	0.229	0.181	0.245	0.598	0.313

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24	126	0.3	0.6	0.195	0.18	1.0	0.278	0.413
25	126	0.1	0.3	0.477	0.196	0.327	0.332	0.333
26	126	0.2	0.3	0.251	0.183	0.652	0.452	0.385
27	126	0.3	0.3	0.199	0.196	0.325	0.247	0.242

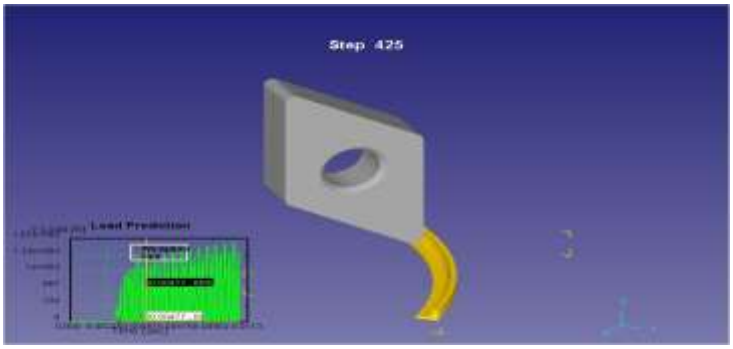

Fig 5: The measurement of cutting forces from Deform 3Dv6.1 software

The 3D model, implemented in DEFORM 3D v6.1 is reported in the Fig 5, where 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 3Dv6.1 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

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undeformed tool is advanced towards the work piece.

A commercial software code, DEFORM 3Dv6.1 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 5.

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.

DISCUSSIONS

As part of the present work, FESs have been carried out for 27 cases of experiments consisting of three different feed rates, cutting speeds and depth of cuts. The tables 4 a) and 4 b) presents results of both experimental and predicted FES values at different test cutting conditions for which simulations are carried out. In all simulations, it is made sure that steady state condition has reached and some more data are collected after some period of time.

The cutting forces are predicted by FESs. Predicted FE results are evaluated with experimental results. In FESs, the resultant field variables have been extracted after 5 ms of cutting time. This short cutting time is assumed sufficient for the field variables to reach a steady state from the literature. The displacements obtained from FE model of metal cutting process are also in agreement with the results of experiment.

It is a known fact that the friction between the tool and the work piece is little when the tool is new (sharp) and accordingly, the amplitude of

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vibration will also below. Spectrum graphs for the vibration signal are generated using Vibsoft FFT analyzer. Spectrum graphs for experimental vibration signal in every test condition are presented in Fig 6.

The measured values (experimental tests) and predicted values (FESs) are shown in Table 4 a), and correlation between tool wear and cutting forces in all conditions are presented. The affect of displacement due to vibration on tool wear is significant and clearly identified in all test conditions. Correlation between cutting forces and tool wear is observed in FESs, and corresponding measured tool wear by Scanning Electron microscope (SEM) are tabulated in Table 4 b).

The cutting forces are measured by using dynamometer set up and Deform 3Dv6.1 software. 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 'FC' predominant at low cutting speeds like 95m/min and at the same time the thrust force component 'FT' and radial force component 'FR' are not much.

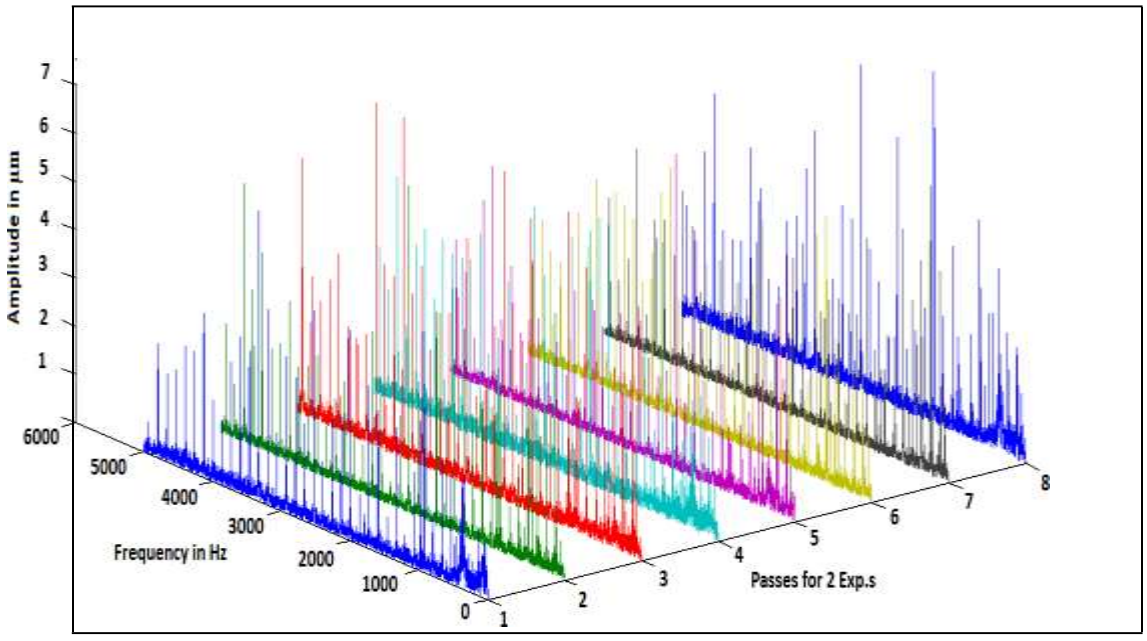

Fig 6: Frequency domains for the experiment 1 and 2

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The cutting speed plays a major role in increment of cutting forces. The cutting force 'FC' 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 thrust force component 'FT' 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 'FR' 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 m/rev and 0.3 mm depth of cut. The cutting force 'FC' 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 'FT' is lower at cutting speed of 95 m/min, feed rate 0.2 mm/rev and 1mm depth of cut. The Radial component 'FR' 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 Stainless steel specimen 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 VB 1, VB 2, VB 3 and VB
4.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 95m/min, feed rate 0.1 mm/rev and 0.3 mm depth of cut. The tool wear is lower at cutting speed of 110m/min, feed rate 0.3 mm/rev and 1.0 mm depth of cut. Based on this measured data, the feed rate has no significant effect on tool wear. The minimum tool wear is happened as 0.185 microns and maximum tool wear is 0.658 microns.

CONCLUSIONS

As the results of analysis discussed above, all the cutting forces are principally influenced by both the feed rate and depth of cut. The analysis and correlation of cutting forces to tool wear

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have been carried out. Frequency-based features correlated well with the tool wear. The correlation between 3D FESs and experimental results has proved that the approach is able to identify any existence of cutting forces in milling process and their effect on the tool wear.

Currently, the authors are undertaking well designed substantial cutting trials and simulations to further verify the approach developed potentially applied to hard materials like titanium and nickel based alloys in different machining processes, and the results will be presented in other articles in the near future. This study has shown the affects of material AISI 316 stainless steel upon the results of FE simulation of end milling.

The simulated results are compared against the experimental observations. Based on the experimentation and simulation, the values of the cutting forces and tool wear is calculated and verified. It is concluded that the mathematical model improves the machining performance by choosing the proper input variables like cutting speed, feed rate and depth of cut. The tool wear is calculated and checked at particular input variables and also concluded the minimum tool wear is defined at specified parameters.

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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