PREDICTION OF CUTTING FORCES IN TURNING OF AISI-4140 STEEL USING FEA AND EXPERIMENTAL VALIDATION

By

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ABSTRACT

Turning is one of the most widely used machining techniques. Predictions of important process variables of turning such as, cutting forces and stress distributions play significant role in designing turning process parameter and optimizing cutting conditions. The present work is focused on investigating the effect of process parameters on feed, cutting, thrust forces and prediction of forces in turning of AISI 4140 steel based on FEA method. Analysis of 3D unsteady state forces in a metal cutting process is carried out by using a Deform 3D FEA code. The cutting speed, feed and depth of cut were used as the process parameters and the cutting forces are measured and predicted. This project covers a study on modeling and simulation of cutting forces in turning of AISI 4140 steel using coated and uncoated tungsten carbide cutting tool by finite element technique and finally with experimental results. The FEA is used to analyze cutting forces, stress and strain in turning. The simulation results are compared with those of the experimental results and found that both results are in close agreement with each other.

Key words: FEA, Tungsten Carbide, AISI 4140 Steel, Tin Coating, Turning Monoxide (CO), Smoke Density .

INTRODUCTION

The turning process used widely in industry, has countless applications. Traditionally, the process is used to reduce the diameter of a cylindrical work piece, or to change a work piece of non-circular cross-section. This is done by rotating the work piece about the machine's axis of spindle and removing the material with the cutting tool, fed in the perpendicular direction. For the past fifty years, metal cutting researchers, for simulation purposes, have developed many modeling techniques including analytical techniques, slip-line solutions, empirical approaches and finite element techniques. In recent years, the finite element analysis has particularly become the main tool for simulating metal cutting processes. Finite element analysis is widely used for calculating the stress, strain, strain-rate distributions in the primary, secondary and tertiary sub-cutting zones. In consequence, in the tool, chip and work piece, as well as cutting forces, elasto-plastic deformation (shear angles and chip thickness), chip formation and possibly its breaking can be determined faster than using costly and time consuming experiments. In this work, FEA based models are developed that are able to predict the effect of various process variables on the performance measures such as cutting forces, stresses and strains.

1. Methodology

1.1 Turning Process

Turning is a very important machining process in which a single-point cutting tool removes material from the surface of a rotating cylindrical work piece. The cutting tool is fed linearly in a direction parallel to the axis of rotation. Turning is carried out on a lathe that provides the power to turn the work piece at a given rotational speed and to feed the cutting tool at a specified rate and depth of cut. Therefore, the effect of five cutting parameters, i.e. cutting speed, feed rate, depth of cut, tool geometry (nose radius) and cutting condition on the cutting forces, stress and strains need to be studied in a turning operation.

Turning process is performed to modify shape, dimension, and the surface finish of a workpiece by removing the unwanted material in the form of chips. The theory of metal cutting and chip formation are complicated, where plasticity, thermodynamic and mathematical analysis are involved.

1.2 Finite Element Analysis of Turning Process

Finite Element Analysis is a most useful and accurate approach for the determination of field variables because of the advancements in computational and processing power of computers. Thus it is almost used for all the Computer Aided Design methodologies. Applications range from deformation and stress analysis to field analysis of heat flux, fluid flow, magnetic flux, seepage and other flow problems. In this method of analysis, a complex region defining a continuum is discredited into simple geometric shapes called finite elements. The present work is based on the application of finite element for determination of cutting forces in single point cutting tool for turning operation. Once the model is developed for determination of cutting forces for single point cutting tool, it can also be implemented for other multipoint processes like drilling, milling or grinding also.

Modeling 3D cutting process using finite element technique is an ongoing research activity due to significant cost savings and offers insights into the process which are not easily measured in experiments. In particular, heat transfer and the modeling of cutting process require careful consideration in any modeling activity. This paper presents approaches for modeling the turning process for AISI-4140 type of steel. In this study, Deform 3D Finite Element Analysis software is used to study the effects of cutting speed, feed rate, and depth of cut on cutting forces. The work-piece is modeled as Elastic-plastic material to take thermal, elastic, plastic effect. Work-piece is represented by a linear model with different length for each condition. The short material length was chosen to save computational time without compromising the model integrity as heat generation in machining in small areas around the cutting zone. The work-piece shape is constructed by the DEFORM machining module, and includes geometry created by a previous tool pass, including appropriate depth of cut and nose radius details. An unstructured tetrahedral finite element mesh was generated using DEFORM's automatic mesh generation system. Re-meshing parameters, including minimum element size, and parameters for adaptive mesh definition are set within the system. For these procedures of the simulations, a minimum element size of 0.25 of the feed rate was specified. The total number of elements are 100,000 to 130,000 depending upon work-piece size. The Lagrangian calculation embeds a computational mesh in the material domain and solves for the position of the mesh at discrete points in time. An incremental Lagrangian formulation with an implicit integration method designed for large deformation simulations is used to simulate the cutting process. The solver used was the sparse matrix with a direct integration method, because the conjugate-gradient offers an improved computational speed but less stability in convergence.

Properties	AISI 4140 Steel	WC Tool
Yong's modulus (Gpa)	219	540
Density (kg/m3)	7852	12000
Poisson ratio	0.29	0.22
Thermal expansion (m/mK)	13.7e-6	4.7e-6
Thermal conductivity (W/mK)	42	40
Specific heat (J/kgK)	—	203

Table 1. Thermal and Mechanical Properties of the Work Piece and Tool Material.

1.3 Tool and Work Material

The work piece considered is AISI 4140 Steel material and the tungsten carbide cutting tool is used for machining. Thermal and mechanical properties of tool and work piece material are shown in Table 1. AISI 4140 steel has 1% chromium - molybdenum and is medium hardenability, general purpose high tensile steel, generally supplied hardened and tempered in the tensile range of 850 - 1000 Mpa.

2. Literature Review

A Review of literature describes the study of the cutting forces of turning process with the help of finite element analysis and experimental results. Typical approaches for numerical modeling of metal cutting processes is Lagrangian and Eulerian techniques, as well as a combination of both called an arbitrary Lagrangian–Eulerian formulation [1, 2]. It may be noticed that, all these methods are mathematically equivalent. The major feature of Lagrangian formulation used in this study is that the mesh attached to the workpiece.

Also, the finite element analysis was performed by Johnson-Cook's constitutive equation with three different sets of material constants (found by the application of several methods) is implemented in the FE model to study the behavior of Ti6Al4V alloy during the machining process in conventional and high speed regimes [3]. Demand for higher productivity and good quality for machining parts has encouraged many researchers to study the effects of machining parameters using FEM simulation using either two or three dimension version [4].

Finite element method by Asmaa A. Kawi [5], is a successful technique to perform analysis to estimate cutting temperatures, a possibility of developing temperature forms adequately representing metal cutting temperature as a Polynomial model of third, fourth and fifth degree with time that gives steady state temperature and for the four alloy steels used and different operation conditions. All alloys have a severe increasing temperature with increasing feed rate, while it looks less sharp with increasing cutting speed. Also the ratio of the number of nodes have maximum temperature for any operating condition and any alloy used with respect to the total number of nodes is less than 1%.

Mofid Mahdi, and Liangchi Zhang [6], considered the chip breaking and developed a 2D cutting force model with the finite element method. The variation of the cutting force was investigated carefully against both the cutting conditions and the anisotropy of the material with the following development: (a) a constitutive model of a homogeneous anisotropic elastic material under plane deformation; (b) a failure model of the work material based on the Tsai Hill criterion; (c) a contact model of the mechanisms of the cutting process. A comparison with experimental measurements showed that the constitutive model leads to a reasonable prediction.

Tugrul Ozel, and Taylan Altan [7], used a methodology to determine simultaneously (a) the flow stress at high deformation rates that are encountered in the cutting zone, and (b) the friction at the chip–tool interface. This information is necessary to simulate high-speed machining using FEA based programs. A flow stress model based on process dependent parameters such as strain, strain-rate was used together with a friction model based on shear flow stress of the workpiece at the chip–tool interface. High-speed cutting experiments and process simulations were utilized to determine the unknown parameters in flow stress and friction models.

J.C. Outeiro, et al. [8], present the influence of cutting process parameters on machining performance and surface integrity generated during dry turning of Inconel 718 and austenitic stainless steel AISI 316L with coated and uncoated carbide tools. A three-dimensional Finite Element Model was also developed and the predicted results were compared with those measured.

Johnson-Cook [9] and Zerrili- Armstrong [10] models with the material constants obtained from experiments. These material models determine the workpiece material behavior in high strain, wide range of strain rates of cutting zone. The effect of the material model constants on the orthogonal cutting simulation accuracy is also investigated in the literature [11]. Tool-chip friction model is another important input parameter for the modeling of the cutting process. Many investigations are performed to study the influence of the friction modeling on metal cutting simulation results [12-14]. AISI 4140 is used extensively in most industry sectors for a wide range of applications such as Adapters, Arbors, Axle Shafts, Bolts, Crankshafts, Connection Rods, Chuck Bodies, Collets, Conveyor Pins & Rolls, Ejector Pins, Forks, and Gears.

3. Experimental Procedure

Turning is a popularly used machining process in which, a single point cutting tool removes unwanted material from the surface of a rotating workpiece. The conventional lathe machines play a major role in machining industry to enhance product quality as well as productivity.

3.1 Design of Experiments

The modeling of parameters for an AISI-4140 steel and tool material involved a large number of other factors, such as ways of holding the workpiece, the geometry of cutting tool, etc. However to facilitate the experimental data collection, only three dominant factors were considered in

Variables Designation	Description	Low (L)	Medium (M)	High (H)
v	Cutting speed RPM (mm/min)	550	700	850
f	Feed rate (mm / rev)	0.1	0.2	0.3
d	Depth of cut (mm)	0.375	0.75	1.125

Table 2. Range of Values for Each Variable

Experiment No.	Cutting Speed	Feed rate (mm/rev)	Depth of cut (mm)
1.	L	L	L
2.	L	M	M
3.	L	H	H
4.	M	L	M
5.	M	M	H
6.	M	H	L
7.	H	L	H
8.	H	M	L
9.	H	H	M

Table 3. L9 Orthogonal Array

the planning of the experiment. The factors considered were depth of cut, feed rate, and cutting speed. The range of values of each factor was set at the three levels, namely low, medium, high, as shown in the Table 2. Based on L9 orthogonal array, a total of 9 experiments, each having a combination of different levels of factors as shown in Table 3, were carried out.

3.2 Experimentation

The experimentation was carried to measure the cutting forces at different set cutting parameters. Machining tests are carried out on AISI 4140 Steel specimen of 350 mm long and a 50 mm diameter is turned by using tungsten carbide tool (without coating and with Tin coating) on Kirloskar Turnmaster-35. All are Geared conventional lathe. The tool insert used in the process is THN SNMG 08. The variable speed upto 850 rpm can be used on the machine. The workpieces are cleaned prior to the experiments by removing 0.3 mm thickness of the top surface in order to eliminate any surface defect and wobbling. The experimental setup of the dynamometer in conjunction with tool for the measurement of cutting forces in X,Y,Z directions is shown in Figure 1. From the setup, metal cutting is carried with automatic feed and depth of cut. At different setup cutting conditions such as speed, feed and depth of cut, the cutting forces are measured using dynamometer.

4. Finite Element Modeling

The Deform-3D software is selected for the FEM simulation

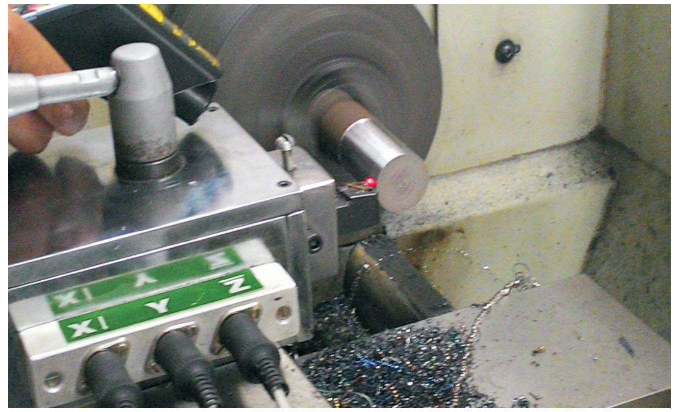

Figure 1. Experimental Setup of for Measurement of Cutting Forces

of the orthogonal cutting. The Finite Element Modeling (FEM) is considered as a very good technique to obtain the machining parameters such as cutting force, stresses, and others analysis. A typical finite element analysis in a software system requires the information procedures like, workpiece and tool is set to 30°C and simulations are carried out to reach steady state condition. The FEA is computed on Intel core i3, 2.17GHz, 4GB RAM,32 Bit computer system.

4.1 Material Modeling

Material and tool modeling by classifying (parts and properties), contact and failure laws analysis, meshing elements and boundary conditions. The effect of process parameters i.e. cutting speed, feed rate and depth of cut on the process response i.e. cutting forces, or stress, etc. can be studied. For turning of work piece, the dimensions and material data are entered in a pre-processor for creating the workpiece and tool and the data required like processing conditions of turning to analyze the simulation of forces. A simulation engine is analyzing the results by numerical calculations. Tool and workpiece material Modeling, a fully thermo-mechanically coupled implicit is considered and is shown in Figure 2. The materials and tools modeling are carried out by using Finite Element Modeling (FEM). The work-piece material dimension of 50 mm x 100 mm with machining parameters; cutting speed, v (m/min), cutting depth, d (mm), and feed rates, f (mm/tooth). Load tool holder and choose MTANR as tool holder from 'Import material from library' in workpiece material setup window.

4.2 Contact Analysis

In the finite element modeling, in addition to the cutting

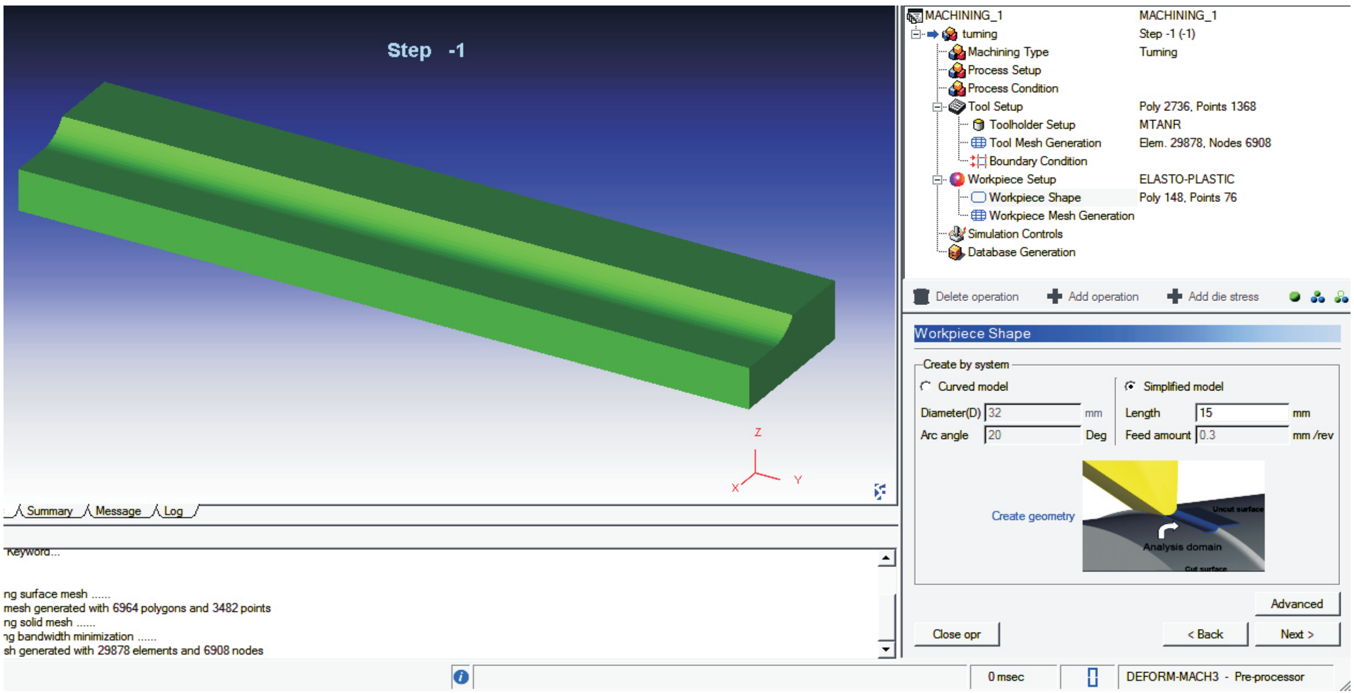

Figure 2. FEA Preprocessing Data

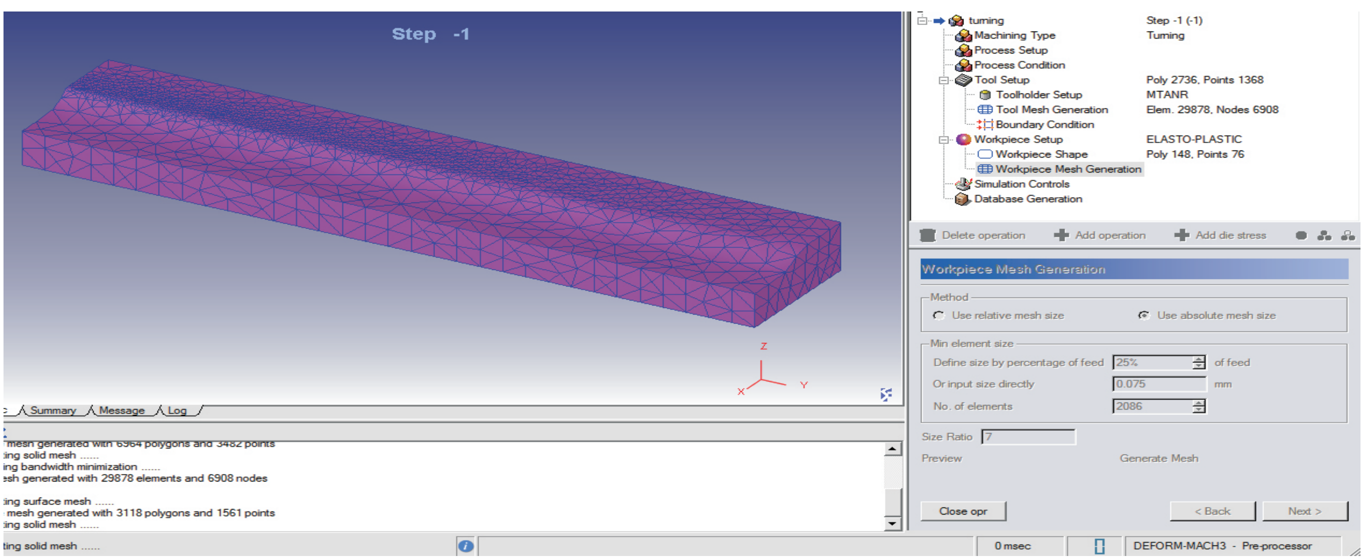

Figure 3 (a). Work Piece Mesh Generation

parameters, the following Johnson–Cook plasticity model was implemented. The material model employed is based on the Johnson Cook plasticity model. This constitutive relationship is commonly employed in modelling orthogonal cutting with use of FEM, since due to its being a strain rate dependent, it has a strong effect on the strain/stress relationship in the machining process. The Johnson–Cook parameters viz., d1 = 1.5, d2 = 3.44, d3 = - 2.12, d4 = 0.002, and d5 = 0.1 for AISI 4140 are taken from Deform-3D user manual. This model is suitable for problems where strain-rates vary over a large range (10^2-10^6). The Johnson–Cook model is capable of predicting the plastic deformation as well as damage and failure.

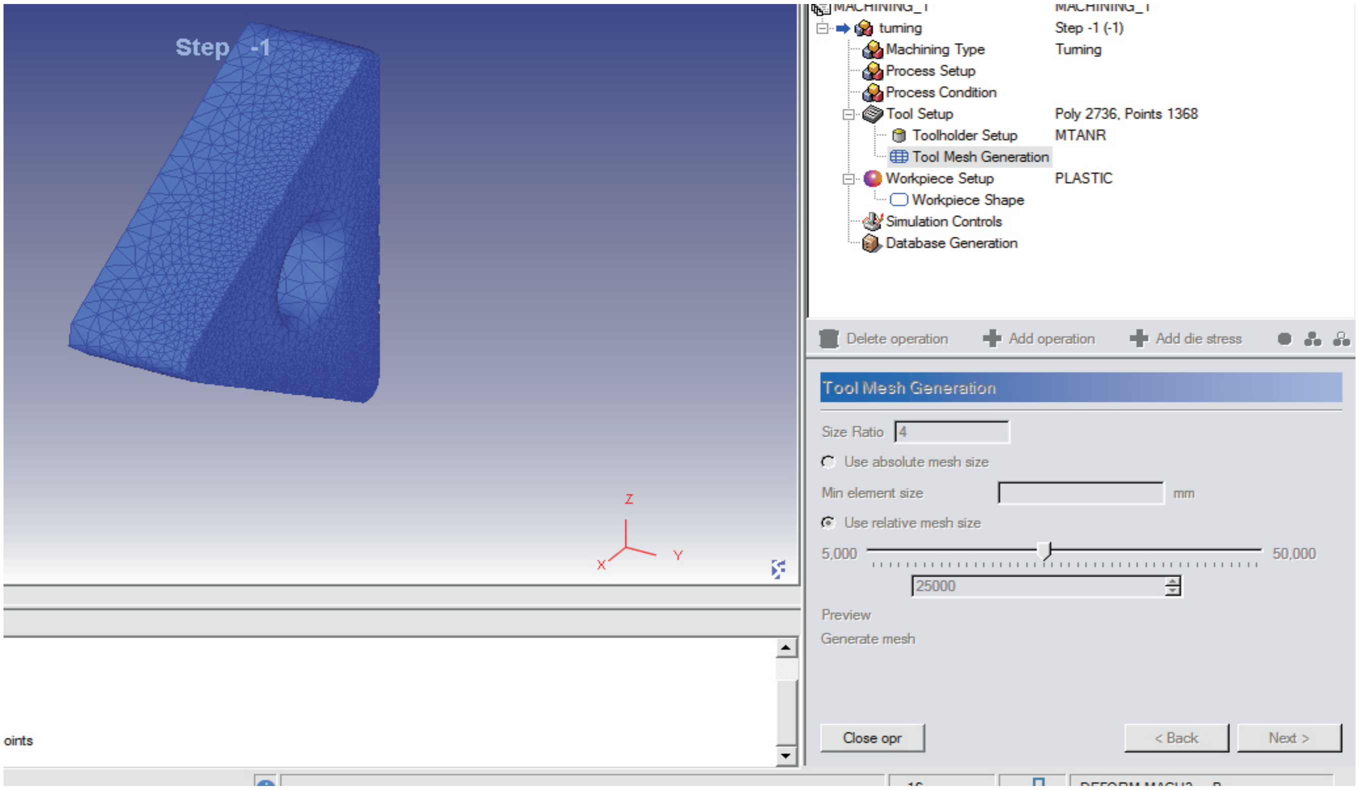

Figure 3 (b). Tool Mesh Generation

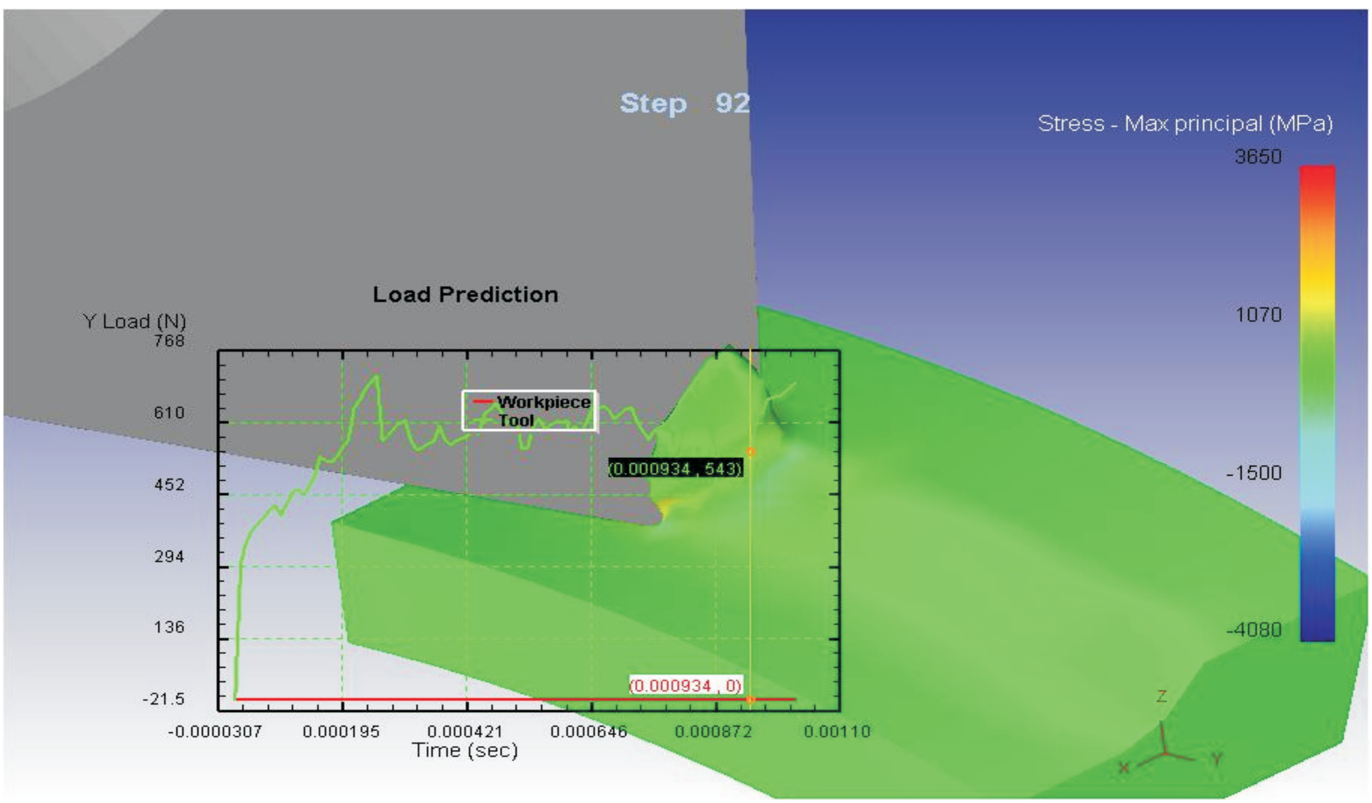

Figure 4. FEM Simulation Result for Cutting Force

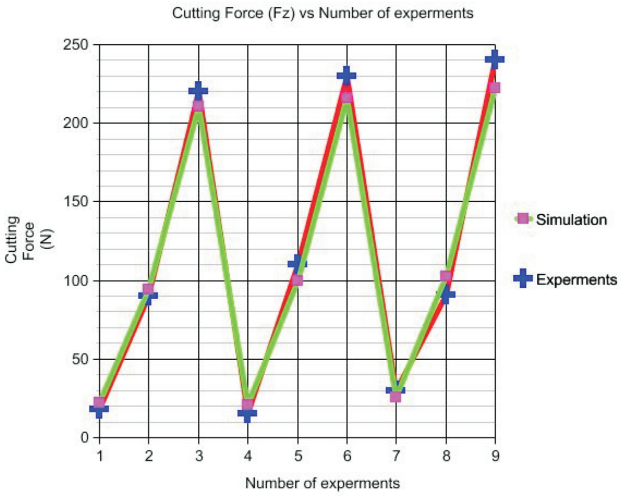

Figure 5. Comparison of Experimental and FEM Values of Cutting Force with Uncoated Tool

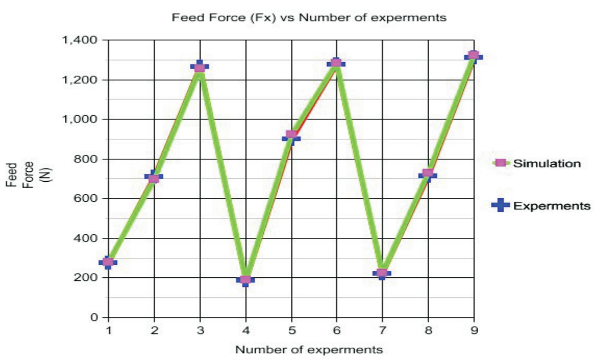

Figure 6. Comparison Experimental and FEM Values of Feed Force with Uncoated Tool

4.3 Meshing and Boundary Conditions

The mesh generation starts by creating elements along the workpiece boundary and the cutting tool. The tool mesh with minimum element size of 0.25 mm is considered and shown in Figure 3 (a). The meshing elements and boundary conditions are used at the contact surface between the

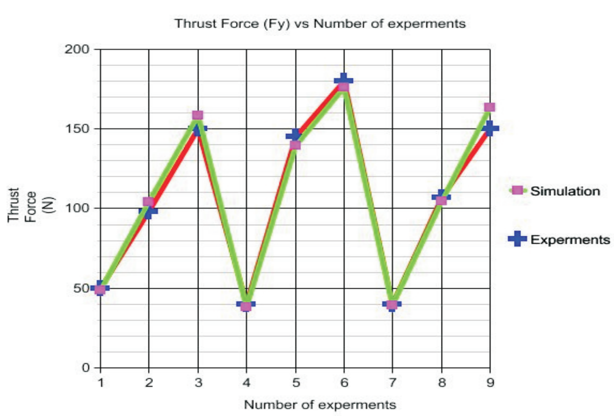

Figure 7. Comparison Experimental and FEM Values of Thrust Force with Uncoated Tool

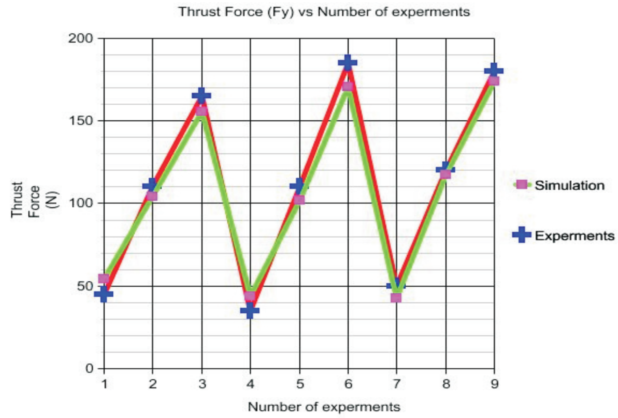

Figure 8. Comparison Experimental and FEM Values of Thrust Force with Coated Tool

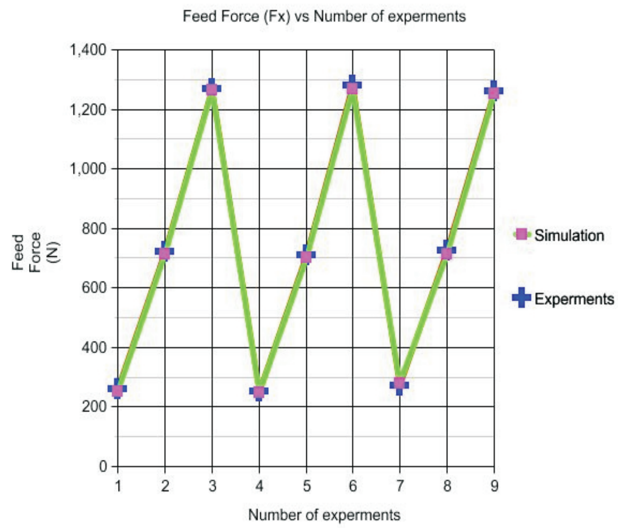

Figure 9. Comparison Experimental and FEM Values of Feed Force with Coated Tool

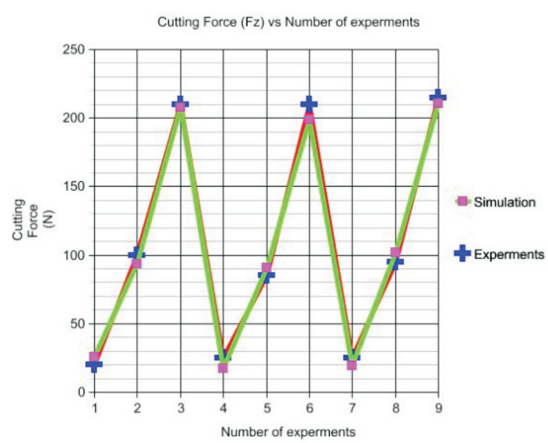

Figure 10. Comparision Experimental and FEM Values of Cutting Force with coated Tool

cutting tool edge and work piece. Total number of Tetrahedral elements generated are about 10,000 and

S No.	Cutting speed RPM (m/min)	Depth of cut mm	Feed rate mm/rev	Forces (N) Simulation values Cutting Forces (Fz)	Simulation values Feed Forces (Fx)	Simulation values Thrust Forces (Fy)	Experimental values Cutting Forces (Fz)	Experimental values Feed Forces (Fx)	Experimental values Thrust Forces (Fy)	Resultant Forces (N) Simulation	Resultant Forces (N) Experimental	%Error
1	550	0.375	0.1	21.99	281.12	48.66	18	275	50	286.14	280.08	2.1
2	550	0.75	0.2	94.1	698.46	103.99	90	710	98	712.4	722.36	1.4
3	550	1.125	0.3	210.75	1255.43	158.54	220	1265	150	1282.8	1292.7	0.7
4	700	0.375	0.2	20.49	191.23	38.01	15	188	40	196.04	192.79	1.6
5	700	0.75	0.3	99.4	923.29	139.85	110	900	145	939.09	918.21	2.2
6	700	1.125	0.1	215.96	1284.67	176.23	230	1275	180	1314.56	1308.02	0.5
7	850	0.375	0.3	25.53	225.43	39.2	30	220	40	230.23	225.61	2
8	850	0.75	0.1	102.35	728.96	104.75	91	715	107	743.5	728.66	2
9	850	1.125	0.2	222.03	1321.03	163.69	240	1310	150	1349.5	1340.2	0.6

Table 4. Forces with uncoated Cutting Tool

S No.	Cutting speed RPM (m/min)	Depth of cut mm	Feed rate mm/rev	Forces (N) Simulation values Cutting Forces (Fz)	Simulation values Feed Forces (Fx)	Simulation values Thrust Forces (Fy)	Experimental values Cutting Forces (Fz)	Experimental values Feed Forces (Fx)	Experimental values Thrust Forces (Fy)	Resultant Forces (N) Simulation	Resultant Forces (N) Experimental	%Error
1	550	0.375	0.1	25.61	250.45	54.23	20	260	45	257.5	264.62	-2.7
2	550	0.75	0.2	93.19	714.36	104.35	100	720	110	727.9	735.18	1.05
3	550	1.125	0.3	207.75	1262.53	155.61	210	1270	165	1288.9	1297.7	0.68
4	700	0.375	0.2	17.59	249.33	43.8	25	252	35	253.75	255.64	0.75
5	700	0.75	0.3	90.75	702.7	102.05	85	710	110	715.8	723.48	1
6	700	1.125	0.1	198.5	1269.98	170.66	210	1280	185	1296.6	1310.2	1
7	910	0.375	0.3	19.59	277.47	42.61	25	270	50	281.4	275.72	2
8	910	0.75	0.1	101.74	711.825	117.27	95	725	120	728.5	740.97	1.7
9	910	1.125	0.2	210.19	1251.4	174.06	215	1260	180	1280.8	1390.8	0.83

Table 5. Forces with coated Cutting Tool

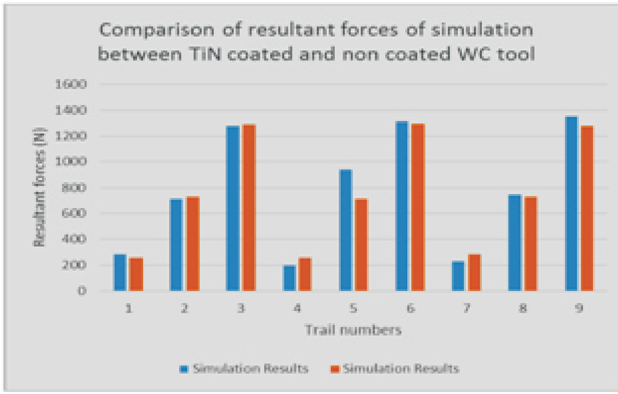

Figure 11. Comparison of Resultant Forces of Simulation and Experimental Values

20,000 nodes for work piece and tool respectively as shown in Figure 3 (b). Enter the number of simulations as 200 steps and collect the forces data after completion of simulations on Deform-3D in the post processor group as shown in Figure 4.

5. Results and Discussion

The cutting forces in X, Y & Z direction are determined from both simulation and experimental setup and are tabulated in Table 4 for uncoated cutting tool and Table 5 for coated cutting tool. Figures 5, 6 and 7 show the comparison of simulation and experimental results in turning used uncoated WC tool and Figures 8, 9, 10 show the comparison of simulation and experimental results in turning using TiN coated WC tool. The comparison shows that the forces using coated tool are lower than using the uncoated tool.

The FEM simulation results compared with experimental values are presented in Table 5. The graphs of cutting forces, feed forces and thrust forces are plotted between FEM values and experimental values respectively. Figure 8, 9 and 10 shows that, FEM values are very close to the experimental values and also they project similar trend. The FEM model is extensively useful. Figure 6 shows the feed forces of both experimental values are and FEM values are very close and their average values also very close. Both coated and uncoated cases of FEM feed force values are very close to the experimental values. Further, it is observed that with TIN coating the experimental forces are reduced in comparison with the uncoated tools. The same was reflected with simulation results in Figure 11.

Conclusion

Finite Element Method using DEFORM 3D program is found to be a successful technique to perform trend analysis to estimate cutting forces in metal cutting with respect to various combinations of design variables (metal cutting speed, feed rate and depth of cut). The simulation results of cutting forces were agreeable to the experimental results and the errors are within 5%. Starting to rise rapidly, it gradually enters the mean steady state, where the cutting force began to decline, and ultimately remained stable. Increased cutting speeds (Vc) resulted in decreased cutting tool forces. The maximum forces of the workpiece during machining is reduced to a much lower value by using TiN coated WC tool.

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