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# EXPERIMENTAL VALIDATION OF CUTTING FORCES IN END MILLING USING FINITE ELEMENT METHOD

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**ABSTRACT**

*In present study, an End milling operation on AISI 304 Steel was performed with a four fluted Solid carbide end mill to predict the cutting forces using Finite Element Analysis. A numerical model is developed to find the cutting forces from spindle speed, feed rate and depth of cut. Design of experiments was conducted according to Taguchi L8 orthogonal array and analysis was performed with the cutting parameters each having two levels of operation. The effect of cutting parameters on cutting force was analysed using ABAQUS/Explicit and Minitab software.*

*Methods such as Taguchi and Analysis of Variance were used to find the optimum level of machining parameters affecting on cutting force. By using Taguchi approach, optimum levels of machining parameters for cutting force are obtained as 0.06 mm/rev feed, 0.4mm DOC and 2800 rpm speed.*

***Keywords:****AISI 304 stainless steel, finite element analysis, milling.*

## 1. Introduction

End Milling is one of the material removal processes to manufacture various parts in die and moulding of parts and also different intricate designs. In the milling process, cutting forces helps to estimate surface finish, tool wear in the manufacturing processes. The cutting forces are induced as the workpiece and cutting tool comes in contact during machining [1]. The Finite Element Method is a very useful to find the machining parameters by using machining simulations. This tool helps in reducing cost of design changes, product quality improvement and reduces the time of manufacture [1].

Mebrahitom A. et al. performed finite element simulation of Side End milling operation on Aluminum 6010 and the temperature distribution at the shear area and the chip formation at different speeds were observed. Also the effect of spindle speed, feed rate and depth of cut were studied [1]. P Palanisamy et al. developed a flexible cutting force model to predict the cutting force model in a universal milling machine for machining of AISI 1020 steel using a high-speed steel cutter. Also a study was carried out to predict quantitatively the increased temperature level in the tool with increased cutting speed which would help in designing the cutting edge shape [2].PrakashChakrapani et al. presented a 3D Finite Element Model to work on Titanium alloy Ti6Al4V in

ABAQUS software to predicts the Cutting forces, Chip formation, stress and the stain rate. He also used the Johnson - cook criteria predicts the behaviour [3].K.A. Abou-El-Hossein et al. developed the first and second order models for predicting the cutting force produced in end-milling operation of modified AISI P20 tool steel using the response surface methodology (RSM) to study the effect of input cutting parameters i.e. cutting speed, feed rate, radial depth and axial depth of cut on cutting force. Predictive models analyses were performed with the help of the statistical software Minitab [4].V. Durga Prasad Rao et al. established empirical relations to estimate the surface roughness and Material Removal Rate in terms of machining parameters by using the experimental results. The second-order regression equations for the response variables, viz., surface roughness and Material Removal Rate was fit using Minitab software. He also observed that the Material Removal Rate value due to machining with coated carbide insert is larger than that of machining with uncoated carbide insert, but the surface roughness value due to machining with coated carbide insert is also larger than that of machining with uncoated carbide insert [5].TahsinTecelli et al. developed a FEM model to predict the chip shape during metal cutting at different machining condition and the influence of fracture energy and various cutting parameters on-chip generation was explored [6]. S K Thangarasu et al developed a model for predicting the cutting force obtained from strain gauge model. Using Taguchi design and measured cutting forces are compared with the predicted forces in order to validate the feasibility of the proposed design and percentage contribution of each process parameter had been analysedusing Analysis of Variance [7]. M. Balaji et al. studied the effect of cutting parameters namely cutting speed, feed rate and helix angle on the tool life which was performed on drilling of AISI304 steel with carbide drill bits and found optimum levels of cutting parameters for surface roughness and acceleration of vibration using Taguchi and ANOVA methods [8]. S.P. Palaniappan et al. investigated the machining of Aluminium 6082 alloy to identify the optimal parameters for CNC turning process. By using Taguchi and ANOVA, the optimum combination of turning parameters i.e; spindle speed, feed rate and depth of cut for the responses of surface roughness and material removal rate were obtained and also the temperature on chip was compared with experimental condition [9].N. Gupta et al. found optimal Cutting parameters in the turning of EN 31 48HRC with differently coated carbide inserts for different cutting conditions. Taguchi optimization of cutting forces with indigenous developed Carbon Nano tubes based Nano coated tool tip was done using ANOVA and S/N ratio [10].Srinivas D et al. worked on optimization of the cutting parameters for improving machinability of Aluminum Alloy (AA1100) Boron Carbide(B4C) composites by considering surface roughness and cutting forces as response variables. Taguchi's method is employed to determine optimum process parameters for dry turning of AA1100- B4C and it was observed that reinforcement percentage by weight and cutting speed are most influencing parameters [11].Gary Styger et al. describes a finite element evaluation of the effect of different constitutive models on machining induced residual stresses for Ti6Al4V titanium alloy. Residual stress and Temperature distribution in the workpiece was evaluated with respect to different elastic-viscoplastic constitutive models at certain cutting speeds and feeds [12].

## 2. Finite element analysis of end milling

### 2.1 Constitutive model material : Johnson-Cook Material model

The material behaves differently under the application of different loads and the plasticity of substance can be expressed using one of material models called as Johnson Cook model. The values Johnson Cook model are established by using experiments and the data is adjusted using curve fitting techniques. This model have five constants, that expresses the functioning of material at higher temperatures, strains and strain rates and is generally applied in finite element machining simulations. These models values can be used to find cutting forces.

Using this model, the flow stress [15] is given by

$$\sigma=(A+B\varepsilon^n)[1+c\ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}})][1-(\frac{T-T_{room}}{T_{melt}-T_{room}})^m] \quad ....(1)$$

where $\sigma$ the material flow stress, $\varepsilon$ is the equivalent plastic strain, $\dot{\varepsilon}$ is the strain rate and $\dot{\varepsilon_0}$ is the reference strain rate, T is the workpiece temperature, $T_{melt}$ is the material melting temperature, and $T_{room}$ is the room temperature. A, B, C, n, m are the material constants.

The value of parameters of Johnson Cook material model for AISI 304 Steel is shown in TABLE 1.

TABLE 1 : JC Material model parameters for AISI 304 Steel [13]

| A (MPa) | B (MPa) | C | n | m | $T_{room}$ (°C) | $T_{melt}$ (°C) |
|---|---|---|---|---|---|---|
| 280 | 802.5 | 0.0799 | 0.622 | 1 | 25 | 1400 |

### 2.2 Chip separation criterion : Johnson-Cook damage model

In the damage model when a parameter specific to an element attains the critical value then it will fail which enables the chip formation. Material model and damage model both together help for the formation of chips during finite element simulation. Damage initiation and damage evolution are both critical parameters for the formation of the chips in metal cutting process.

Johnson-Cook damage model is given as

$$\epsilon_f=[D_1+D_2\exp\ (D_3(\frac{\sigma_m}{\sigma_{eq}}))][1+D_4\ln\ (\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}})][1+D_5(\frac{T-T_{room}}{T_{melt}-T_{room}})^m] \quad ....(2)$$

where D1 to D5 are the damage model constants, $\epsilon_f$ is the equivalent strain to fracture is, $\sigma_m$ is the average stress of normal stresses in all directions and $\sigma_{eq}$ is the VonMises equivalent stress and remaining values denotes the same as that in Johnson Cook Material Model.

The value of parameters of Johnson Cook damage model for AISI 304 Steel is shown in TABLE 2.

TABLE 2 : JC Damage model parameters for AISI 304 Steel [13]

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ |
|---|---|---|---|---|
| 0.69 | 0 | 0 | 0.0546 | 0 |

2.3 Materials and Design of simulation

AISI 304 steel is one of the most widely used of all stainless steels in metal cutting applications. The combination of various properties such as resistance to corrosion, various properties and composition of AISI 304 steel is available at less cost. This material has the following applications. The combination of various properties such as resistance to corrosion, various properties and composition of AISI 304 steel is available at less cost. This material has many applications in manufacturing Medical devices, Fuel tanks, Structural components, nuts, bolts, screws, Buses and truck chassis, Exhaust systems, Food processing equipment, Heat Exchangers, Home appliances, Chemical containers etc.The chemical composition of AISI 304 Steel is represented in TABLE 3.

TABLE 3 : Composition of AISI 304 Steel [13]

| AISI Designation | % C | % Si | % Mn | % P | % Cr | % Mo | % Ni | % Cu | % V | % Fe |
|---|---|---|---|---|---|---|---|---|---|---|
| 304 | 0.03 | 0.528 | 1.53 | 0.02 | 18.7 | 0.06 | 8.59 | 0.1 | 0.02 | 70.2 |

A solid carbide end mill cutter with the diameter 12 mm is used in this study. End milling operation was performed for various cutting speeds, feeds and depth of cuts (Refer TABLE 4 & 5). The spindle speeds are 1400 rpm and 2800 rpm, feeds are 0.06 and 0.12 mm/rev and depth of cuts are 0.4 mm and 0.8 mm. According to design of experimentation, 8 combinations of cutting parameters were designed and numerical simulation was performed using ABAQUS.

TABLE 4 : Specifications of the Tool

| Tool Specifications | |
|---|---|
| Description | Specification |
| Material of Cutter | Uncoated Solid Carbide End Mill |
| Number of Flutes | 4 |
| Diameter of Cutter | 12 mm |
| Axial Rake angle Of Cutter | 18 ° |
| Radial rake angle of Cutter | 12 ° |
| Nose Angle | 0.4 mm |
| Shank Length | 70 mm |
| Helix Angle | 30 ° |

TABLE 5 : Process Parameters & their levels

| Variable Parameters | Level 1 (-1) | Level 2 (1) |
|---|---|---|
| S (rpm) | 1400 | 2800 |
| F (mm/rev) | 0.06 | 0.12 |
| D (mm) | 0.4 | 0.8 |

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## 2.4 Simulation Results

A finite element model was generated using FEA software ABAQUS to simulate the end milling process. The modelling of the end mill cutter is done in CATIA V5 software and imported to ABAQUS 2017. The workpiece is assigned with the mechanical properties of AISI 304 Steel. The properties of the workpiece& tool materials are assigned accordingly. The dry milling condition is considered, and the tool is considered as a rigid body. The Johnson Cook plastic and damage models are used in this model to define the workpiece deformation as it mostly used for higher strain rate problems .The parameters of the failure criteria are shown in the TABLE 1 & 2.

The finite element analysis is performed in ABAQUS Dynamic as during machining of metals they produces chips due to plastic deformation and strain hardening with larger strain rate. Simulation is performed according to eight different combinations of depth of cut, feed rates, and cutting speeds as shown in the TABLE 6.

TABLE 6 : Simulated results for cutting forces

| Exp. No. | Machining Parameters | | | Experimental Results [14] | Simulated Results |
|---|---|---|---|---|---|
| | S (rpm) | F(mm/rev) | D (mm) | Crossfeed force (N) | Crossfeed force (N) |
| 1 | -1 | -1 | -1 | 172.26 | 141.74 |
| 2 | 1 | -1 | -1 | 79.21 | 126.4 |
| 3 | -1 | 1 | -1 | 174.28 | 160.12 |
| 4 | 1 | 1 | -1 | 80.24 | 128.63 |
| 5 | -1 | -1 | 1 | 216.61 | 128.3 |
| 6 | 1 | -1 | 1 | 128.74 | 153.74 |
| 7 | -1 | 1 | 1 | 218.21 | 191.24 |
| 8 | 1 | 1 | 1 | 126.12 | 178.92 |

The average cutting force for different combinations of machining parameters is analyzed as shown in TABLE 6. It can be seen that with the increase in cutting speed there is reduction in cutting force. Hence inorder to reduce cutting force we can increase the cutting speed.

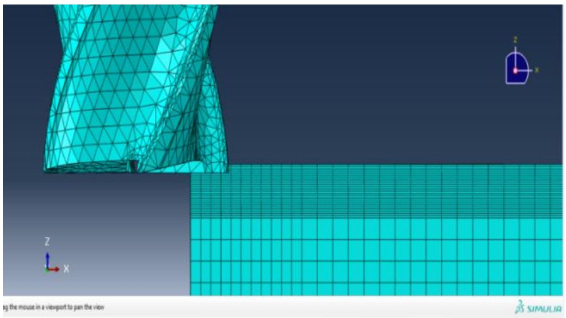

Figure 1.Meshed model of tool and Workpiece in Abaqus

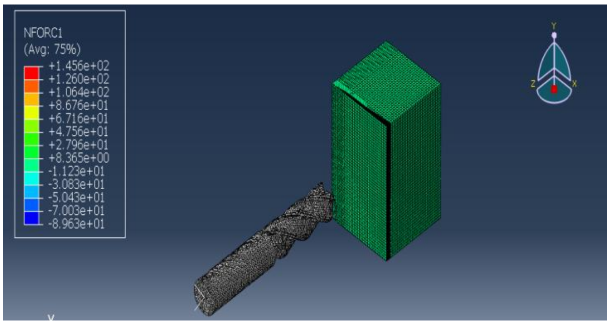


Figure 2.Model showing cutting force value

In the FE simulation the same trend is observed i.e. the cutting forces decreases with increase in cutting speed as compared to experimental results. The simulated results produced in this paper are compared with experimental results obtained from reference [14].

The difference between experimentally obtained and numerical values of cutting force at spindle speed of 1400 rpm and DOC of 0.4mm is found to be 18% and 8% in experiments 1 & 3 respectively. Also the difference in cutting force at feed rate of 0.06 mm/rev and DOC of 0.4mm is found to be 18% and 59.58% in experiments 1 & 2 respectively. Similarly the difference between experimentally obtained and numerical values of cutting force at feed rate of 0.06 mm/rev and spindle speed of 1400 rpm is found to be 18% and 40% in experiments 1 & 5 respectively. And the average error of experiments is found to be 30%. Hence it can be said that Finite Element Method is viable to predict the cutting forces. This variation in the results is present because the thermal effects were neglected during the simulation of process.

## 3. Statistical Analysis

The Taguchi and Analysis of Variance methods are used to analyze the data to find out the optimum combination levels and contribution of cutting parameters. Cutting force is taken in this work for evaluation of tool life.

### 3.1 Taguchi Method

A specially designed orthogonal array of Taguchi is used in this work to find the effects of the different machining parameters by small number of experiments as it takes less time for the experimental investigation. Taguchi method uses S/N ratio to measure the variations of experimental design. S/N ratios were calculated for cutting forces using smaller is the best characteristic for the effect of machining parameter on the cutting force.

Using Taguchi ,the S/N ratio of cutting force for the machining parameters were analyzed and results shows that the feed rate has more influence on the cutting force from TABLE 7.

TABLE 7 : Response Table for Signal to Noise Ratios

| Level | Depth of Cut (mm) | Feed rate (mm/rev) | Spindle Speed (rpm) |
|---|---|---|---|
| 1 | -42.84 | -42.74 | -43.73 |
| 2 | -44.15 | -44.24 | -43.25 |
| Delta | 1.31 | 1.5 | 0.48 |
| Rank | 2 | 1 | 3 |

Distribution of S/N ratios to the levels of cutting parameters is shown in Fig.3. Using smaller is the best characteristic, optimum levels of cutting parameters are obtained as 0.06 mm/rev feed, 0.4mm DOC and 2800 rpm speed.

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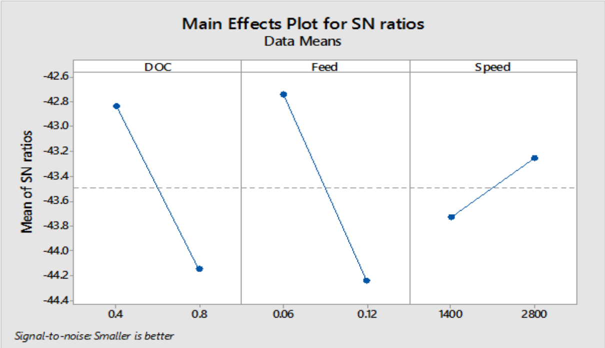


Figure 3.Main Effect Plot for SN Ratios

Using Analysis of Variance of the simulated results it is found that the contribution of feed rate is found to be 35.21%.

## 4. Conclusion

A Finite Element model and orthogonal array is developed and the cutting forces are determined under different parameter settings using Finite Element Analysis and optimum combination of process parameters is found. In this work, eight trials were performed with two levels of cutting parameters on AISI 304 steel. Effect of cutting parameters on cutting force is analysed with the help of Taguchi and ANOVA analysis. Feed rate is found to have more influence on cutting force followed by depth of cut and spindle speed. Optimum levels of cutting parameters for cutting force are obtained as 0.06 mm/rev feed, 0.4mm DOC and 2800 rpm speed.

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