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Finite Element Method Simulation of Turning Process with Single Point Cutting Tool: A Numerical Study

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ABSTRACT

The aim of this study is to numerically simulate to turning process in real time environment with FEM explicit software. Three input factors (depth of cut, cutting speed and rack angle) and two responses (stress and strain) are selected for simulation work. DOE technique (Taguchi) is used for making relationship among factors and responses. Surface response methodology is used for this study using MINITAB software to identify most or less significant input factors after that apply regression modeling to develop relationship between input parameters and output results in form of linear model equations based on regression modeling. Signal to noise analysis is performed to predict the effect of changing of factors according to their levels to find effect on product quality. On the basis of simulation work stress is dependent on Depth of cut and rack angle.

Key words: Turning, Single point cutting tool, ANOVA, Taguchi, FEM, explicit dynamics

INTRODUCTION

Turning is a material removal process, used to create rotational parts that have a many features, such as holes, grooves, tapers, threads, various diameter steps by cutting the unwanted material. It involves with high stress and strain which must be known to improve all of the process. The geometry of single point cutting tool mainly depends on the tool material and the work piece material. In single point cutting tool, the most important angles are the rake angles, end relief and side relief angles. Due to effects of the back rake angle the tool shear on work material and form the chip [3]. The rake angle is normally chosen for this study as to see the geometrical effects on turning process. The cutting tools are used as a rigid body and it moves horizontally with the variable speed into the work piece. It also set a suitable cutting condition like cutting velocity, and depth of cut. The cutting velocity, feed rate and depth of cut are from the three dimensions of the turning process and their products are used to obtain material removal rate.

In recent years Finite Element Method (FEM) based on Eulerian and updated Lagrangian formulation has been developed to analyse the Machining process [2]. Finite Element Method (FEM) is a powerful tool to predict cutting process variables which are difficult to obtain with experimental methods and used for conventional machining process and it predict the chip formation, strain rate and stress on the cutting edge. ANSYS EXPLICT DYNAMICS 14.5 is highly developed FEM code and used for various type of problems. Every feature in this code is described by top to bottom steps. Various material models are used by this code according to problem statement for solving expensive and time consuming experimental tests and predicting measure variables such as stress, strain and machining temperature. It also determines result with higher accuracy as compared to the any analytical model.

MATERIAL PROPERTIES OF PLATE AND TOOL

In this study two engineering materials were used for analysis from them one was used by punch and Die and another was used by plate (SS-4304). Table 1and 2 show material properties of tool and work piece.

In this study orthographic material properties were used so that FEM results are predicted more perfectly with real world environment. Tool material is only elastic material and this problem can resolve by converting it to rigid body.

Impact analysis was dependent on equations of state of materials and here these equations were used for accurate simulations of impact (Impact of Punch on plate), these equations were used for change of states of material after impact and simulate effect of impact like impact of punch and solution after punch impact on plate was shown clearly.

Table -1 Properties of Structural Steel (used for Tool)

Property	Value	Unit
Density	7850	Kg/m^3
Young's Modulus	2E+11	Pa
Poisson's Ratio	0.3	
Bulk Modulus	1.66E+11	Pa
Shear Modulus	7.692E+10	Pa
Sp. Heat	434	J/kg C

Table 2 Properties of SS 4340

Property	Value	Unit
Density	7900	Kg/m^3
Sp. Heat	423	J/kgC
Steinberg Guinean Strength		
Initial Yield Stress	3.4E+08	Pa
Max Yield Stress	2.5E+08	Pa
Hardening Constant	43	NA
Hardening Exponents	0.35	NA
Derivative dG/dP	1.74	NA
Derivative dG/dT	-3.504E+07	Pa/C
Derivative dY/dP	0.007684	NA
Melting Temperature	2106.9	C
Shear Modulus	7.7E+10	Pa
Shock EOS Linear		
Gruneisen Coefficient	1.93	NA
Parameter C1	4570	m/s
Parameter S1	1.49	NA
Parameter Quadratic S2	0	s/m

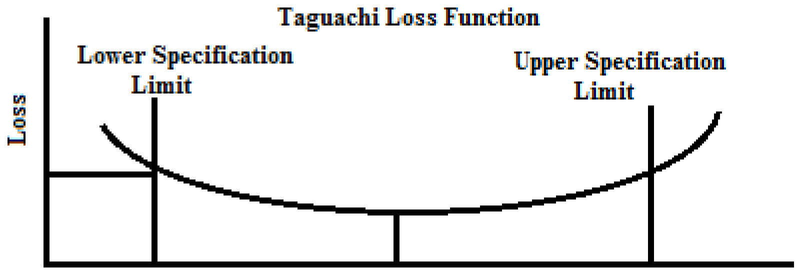

Fig. 1 Quality Loss Function used by Taguchi method

DESIGN OF EXPERIMENT (TAGUCHI METHOD)

In this study design of experiment methodology is adopted for cases generation. Taguchi method was developed by the Dr. Genichi Taguchi. It is a statistical method which is used to predict performance of response generated by various input factors and levels. This method applies the conceptual quality loss function known as Signal to Noise (S/N Ratio) ratio which is the measure of performance. Quality Loss Function shown by Fig. 1.

Signal to Noise (S/N Ratio) is the ratio of the mean (signal) and the standard deviation (noise) of the response and depends on the input factors apply for research or study. S/N ratio uses mean data and variability into its calculation three processes having used in study by S/N ratio are following:

- Nominal is best
- Large is Best
- Small is Best

Optimal combination of input factors are always highest values of S/N ratio based data obtained data. Applicable formulas used by S/N ratio are shown below. All notations are carrying their usual meaning.

Nominal is Best: $$\eta = 10\log_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{\mu^2}{\sigma^2} \quad (1)$$

Smaller is best: $$\eta = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n}{y_i}^2 \quad (2)$$

Larger is best: $$\eta = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2} \quad (3)$$

In this study small is better S/ N ratio method is used. Taguchi method is dependent on data which is coming out from designed experiments using taguchi made orthogonal arrays which uses fixed specific combinations of factors and their levels so all input factor and their levels are discussed in detail shown in below.

Factor and Levels

Design of Taguchi orthogonal array is only possible by proper selection of factors and their levels. In this study four factors are used for orthogonal array, every factor has four levels. Available DOE table is L16. Factor and their level are presented in table 3 for SS 4340. These materials are used in this study for cutting operation. Relief angle and nose radius is constant for this study. Tool wear is not studied in this study.

Table -3 Factor and Their

Factor/ Level	Cutting Speed (m/min)	Depth of cut (mm)	Rake Angle
1	100	0.25	0.0
2	125	0.50	2.0
3	150	0.75	4.0
4	200	1.00	6.0

Table 4 Experiments According Tguchi Method

Sr. No.	Cutting Speed (m/min)	Depth of cut (mm)	Rake Angle
1	100	0.25	0
2	100	0.50	2
3	100	0.75	4
4	100	1.00	6
5	125	0.25	2
6	125	0.50	0
7	125	0.75	6
8	125	1.00	4
9	150	0.25	4
10	150	0.50	6
11	150	0.75	0
12	150	1.00	2
13	200	0.25	6
14	200	0.50	4
15	200	0.75	2
16	200	1.00	0

Table -5 Response Result from FEM Simulation for SS 4304

Sr. No.	cutting speed	Depth of cut (mm)	Rake Angle	Stress
1	250	0.6	0	1188.2
2	250	0.8	2.5	1150.5
3	250	1	5	1119.5
4	250	1.2	7.5	1178.7
5	500	0.6	2.5	1111.2
6	500	0.8	0	1130.8
7	500	1	7.5	1197.6
8	500	1.2	5	1202.9
9	750	0.6	5	1162.4
10	750	0.8	7.5	1187.2
11	750	1	0	1230.9
12	750	1.2	2.5	1213.9
13	1000	0.6	7.5	1079.1
14	1000	0.8	5	1212.8
15	1000	1	2.5	1217.9
16	1000	1.2	0	1216.3

NUMERICAL SIMULATION

The finite element method (FEM), or finite element analysis (FEA), is a computational technique used to obtain approximate perfect solutions of boundary value problems in engineering fields. Boundary value problems are also called field problems. The field is the domain of interest and most often represents a physical structure. The field variables are the dependent variables of interest governed by the differential equation. The boundary conditions are the specified values of the field variables (or related variables such as derivatives) on the boundaries of the field.

The primary characteristics of a finite element are embodied in the element stiffness matrix. For a structural finite element, the stiffness matrix contains the geometric and material behaviour information that indicates the resistance of the element to deformation when subjected to loading. Such deformation may include axial, bending, shear, and torsional effects. For finite elements used in non-structural analyses, such as fluid flow and heat transfer, the term stiffness matrix is also used, since the matrix represents the resistance of the element to change when subjected to external influences.

$$Q^m = K^m q^m + Q^{om}$$

Where m=member number m, Q^m= vector of member's characteristic forces, which are unknown internal forces, K^m= member stiffness matrix which characterises the member's resistance against deformations, q^m= vector of member's characteristic displacements or deformations, Q^{om}= vector of member's characteristic forces caused by external effects (such as known forces and temperature changes) applied to the member while q^m= 0).

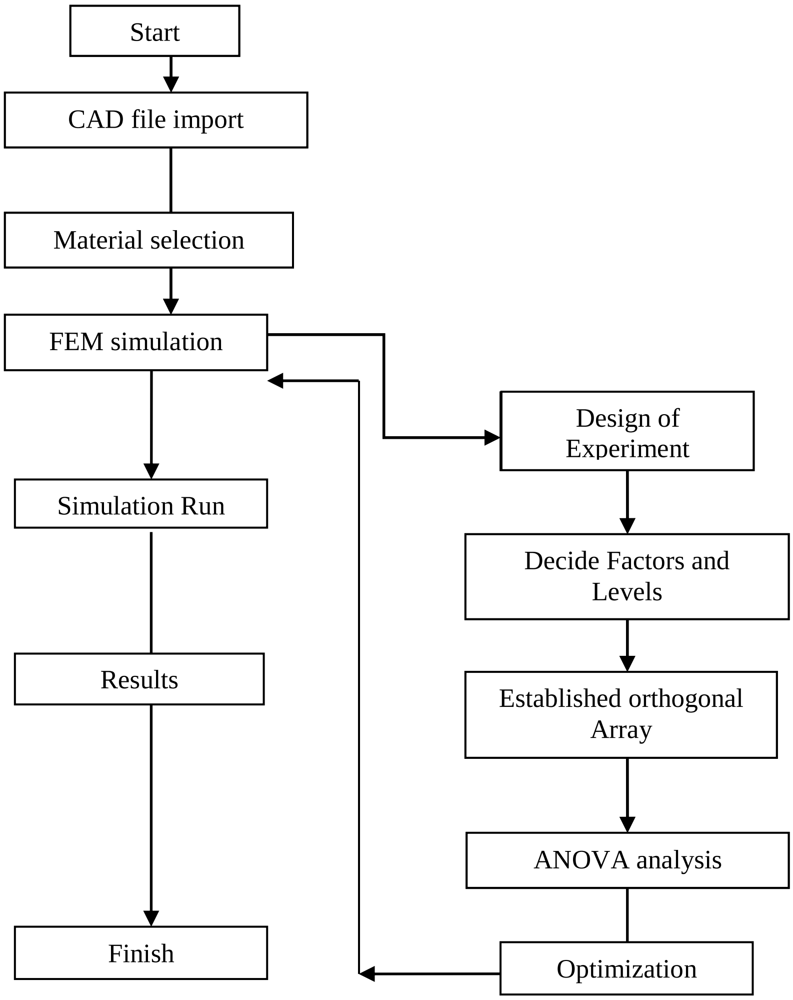

Fig. 2 Simulation flow chart

RESULT AND DISCUSSION

Single point Turning process is simulated with ANSYS Explicit Dynamics FEM package in this study. All experiments were designed according to DOE technique (Taguchi orthogonal array table), which were presented in table 3 and table 4. .Main outcomes focused in this study are following: [ANOVA Analysis, Signal to noise ratios analysis, Model equations generation].

Signal to Noise Ratio

The response tables for single point cutting tool for SS 4304 are shown in table 6 (a) smaller is better and table 6 (b) mean respectively for S/N ratio and means of stress. S/N ratio gives best combination of input parameters for SPC process.

Response table for turning process is show that input Parameter DOC is most critical responsible parameter for stress outcomes for both S/N ratio and mean analysis. Rank was also given (based on response table) to locate importance of factors of this study. Less critical parameter is rake angle because it has very low levels for better cutting. Responses Fig.s for both S/N ratio and means are shown below respectively (see Fig. 3 (a) and Fig. 3 (b)).

Although S/N ratio was good approach to find relation of input parameters with output results but for verification means based study was also done in this study and response Figure. From Fig. 3(a), 3(b) and table 7shows that most important parameter is depth of cut and cutting speed. That's why we cannot final conclude that which parameter was most responsible for response change of this study. The best set of combination parameters should be determined by selecting the levels with high mean values from Best 250, 0.6, 7.5 and Worse 750, 1.2, 7.5.

After Taguchi analysis it was clear that plate thickness and feed rate were both responsible for Eq. stress change during simulation runs of this study and this was verified by ANOVA analysis which was discussed in next section.

Table -6(a) Response Table for S/N Ratio (Smaller is Better) for Turning Process for SS 4304

Level	Cutting speed	Depth of cut	Rake angle
1	-61.28	-61.10	-61.52
2	-61.29	-61.36	-61.38
3	-61.57	-61.52	-61.39
4	-61.44	-61.60	-61.29
Delta	0.29	0.51	0.23
Rank	**2**	**1**	**3**

Table -6 (b) Response Table for Mean for Turning Process for SS 4304

Level	Cutting speed	Depth of cut	Rake angle
1	1159	1135	1192
2	1161	1170	1173
3	1199	1191	1174
4	1182	1203	1161
Delta	39	68	31
Rank	**2**	**1**	**3**

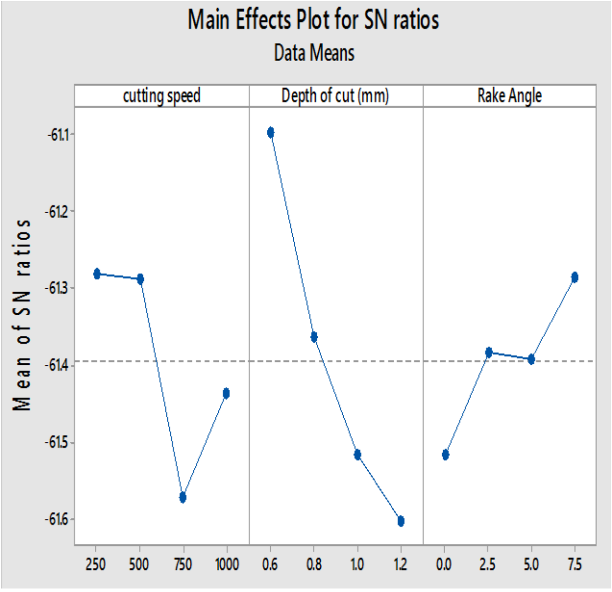

Fig. 3 (a) S/N ratio (smaller is better) for single point cutting

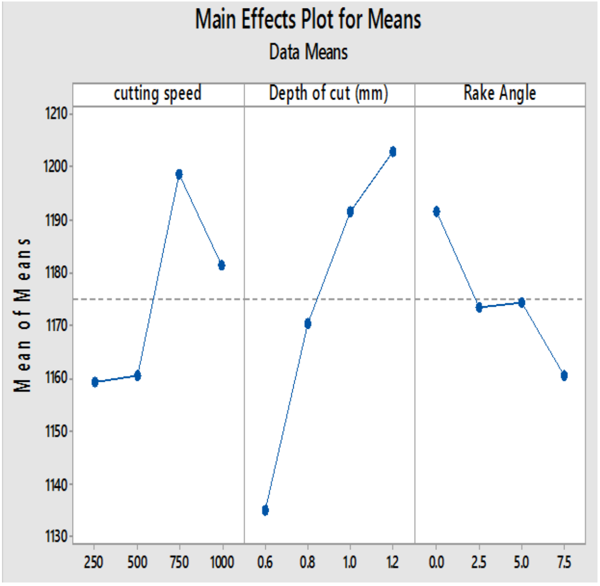

Fig. 3 (b) mean for single point cutting

ANOVA Analysis

The analysis of variance is calculated for single point cutting process and results are shown in table 7 respectively for SS 4304. In ANOVA analysis F-Test is conduct to compare a model variance with a residual variance. F value was calculated from a model mean square divided by residual mean square value. If F value was approaching to one means both variances were same, according F value highest was best to find critical input parameter. In this study Linear, square and 2-way ANOVA analysis is performed using surface response methodology.

Model F and P value for factor cutting speed and depth of cut were 4.74, 2.98 and 0.042, 0.035 respectively for single point cutting process case for response Eq. stress and it indicate that p value was very less than 0.05 and have most significant effect for Eq. stress for single point cutting process case. Other factors were not show good agreement with Eq. stress because their P values were not so improvise.

Table -7 ANOVA Results for Eq. Stress for SS 4304

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	9	22016.0	2446.22	11.77	0.025
linear	3	10990.1	3663.36	2.65	0.143
Cutting speed	1	6543.3	6543.35	4.74	0.042
Depth of cut	1	4120.4	4120.39	2.98	0.035
Rake angle	1	326.3	326.35	0.24	0.644
Square	3	919.0	306.35	0.22	0.878
Cutting speed*Cutting speed	1	341.3	341.33	0.25	0.637
Depth of cut * Depth of cut	1	558.1	558.14	0.40	0.548
Rake Angle* Rake Angle	1	19.6	19.58	0.01	0.909
2-way Interaction	3	7152.0	2384.00	1.73	0.260
Cutting speed* Depth of cut	1	2772.9	2772.91	2.01	0.206
Cutting speed*Rake Angle	1	33.7	33.66	0.02	0.881
Depth of cut *Rake Angle	1	4345.4	4345.43	3.15	0.126
Error	6	8283.1	1380.51		
Total	15	30299.0			

Regression Equations

In this study regression equations were also developed for single point cutting process case for Eq. stress output parameter based on taguchi and FEM results.

Regression Equation for Eq. stress for single point cutting process case

Stress (Mpa) = 1203 - 0.117 cutting speed - 2 Depth of cut - 40.6 Rake Angle - 0.000074 cutting speed*cutting speed - 148 Depth of cut *Depth of cut + 0.18 Rake Angle*Rake Angle + 0.355 cutting speed*Depth of cut + 0.0031 cutting speed*Rake Angle + 44.4 Depth of cut *Rake Angle

Predication Table for Regression Equations

ANOVA analysis based on linear regression analysis predict good but there was another approach which show product combinations of input variables more accurate that linear ANOVA analysis and known as surface response based ANOVA analysis and it was also carried out in this study to predict more .

Table -8 Predication Table of Model Equation SS4340

Ex No	cutting speed	Depth of cut	Rake Angle	Predict value	Difference
1	250	0.6	0	1167.68	34.5291
2	250	0.8	2.5	1134.28	27.4409
3	250	1	5	1135.72	27.4409
4	250	1.2	7.5	1172.00	34.5291
5	500	0.6	2.5	1148.13	27.4409
6	500	0.8	0	1171.64	27.4409
7	500	1	7.5	1204.45	27.4409
8	500	1.2	5	1199.91	27.4409
9	750	0.6	5	1125.47	27.4409
10	750	0.8	7.5	1180.35	27.4409
11	750	1	0	1190.06	27.4409
12	750	1.2	2.5	1216.89	27.4409
13	1000	0.6	7.5	1099.69	34.5291
14	1000	0.8	5	1194.81	27.4409
15	1000	1	2.5	1235.89	27.4409
16	1000	1.2	0	1222.92	34.5291

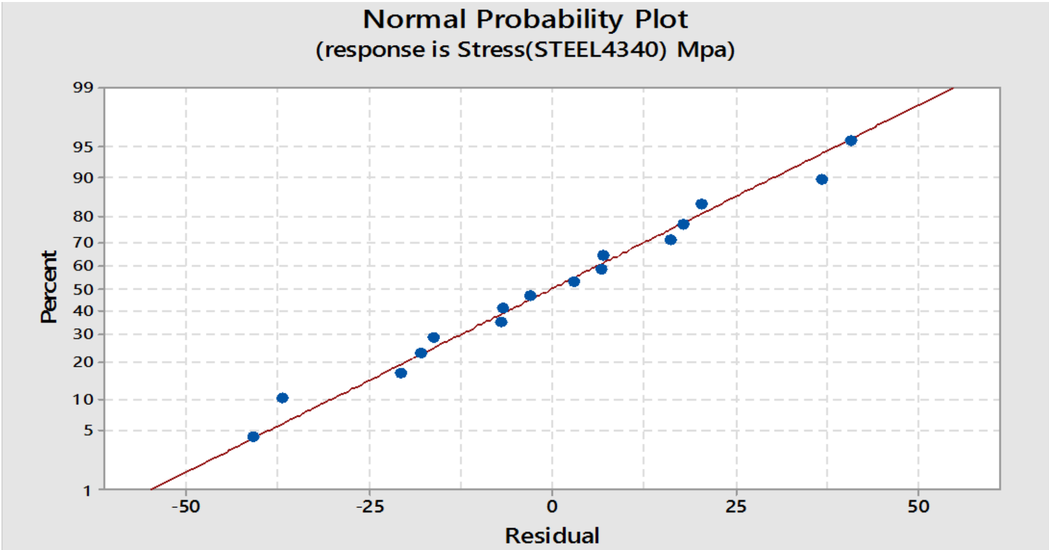

Fig. 4 Normal probability for Eq. stress for single point cutting process SS4340

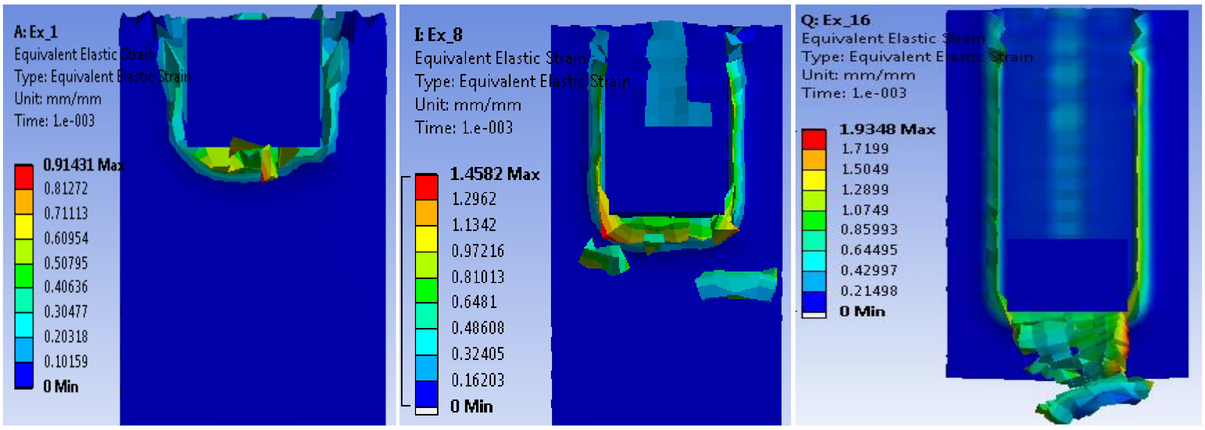

Fig. 5 Strain Contours for Steel 4340 Material for Exp 1, 8 and 16

Strain for Single Point Cutting Process Product

In this section strain generated were discussed for various cases created in this study using DOE techniques, although results were discussed using ANOVA analysis so only limited cases were show in this paper. Von misses strain were show here because it is combination of all type of strains and most accurate for results.

Although all 16 cases for product 1 show good agreement with product formability but case 16 has very high strain comparing all other cases and it means that in case 16 deformation was very high and product facture occur here because of high Eq. stress and it was because of low tool diameter than other cases for plate thickness 1mm. Here only some case were discussed for comparing purpose with single point cutting process product.

CONCLUSION

In this study metal cutting analysis is performed using single point cutting tool. Numerical simulation is performed on ANSYS explicit software. All experiments are designed according to taguchi methods. Signal to noise ratio analysis is performed in this study and the final conclusion from this test is that depth of cut and cutting speed more significant factor. Main outcome form this study is following.

- Best and worst cases for SS 4340 material are following:

Material		Cutting Speed	Depth of cut	Rake Angle
SS 4340	Best	250	0.6	7.5
	Worse	750	1.2	7.5

ANOVA analysis is performed in this study and with the help of regression modelling general modelling equation is generated for future application in turning process.

- Model equation generated in this study is following

Stress (Mpa) = 1203 - 0.117 cutting speed - 2 Depth of cut - 40.6 Rake Angle - 0.000074 cutting speed*cutting speed - 148 Depth of cut *Depth of cut + 0.18 Rake Angle*Rake Angle + 0.355 cutting speed*Depth of cut + 0.0031 cutting speed*Rake Angle + 44.4 Depth of cut *Rake Angle

- Model equations for stress response was predict accurately with Minitab software and show 90% good prediction for responses and can be used by any cutting based machining process manufacturer.

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