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Finite Element Analysis of Temperature and Cutting Forces on Single Point Cutting Tool during Turning of AISI 1045 Steel

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Abstract:
This work will highlight the effect of the temperature and cutting forces generated on the Single Point Cutting Tool (SPCT) tip while working. Modelling of single point cutting tool will be done by PRO-Engineer Wildfire-4 software. The Finite Element Method (FEM) allows the prediction of cutting forces, stresses, wear of the tool and cutting process temperatures to still be developed for the cutting instrument. FEM has certain advantages, like solving contact issues, using bodies manufactured using various materials, approximating a curved region using finite elements or accurately describing, etc. The software will analyse the model by finite element analysis at various forces and calculate the stresses developed at the tip of the tool and the deformation of the tip of the tool. Present work investigates the effect of the spindle speed, feed rate and depth of cut on stress, deformation, temperature and cutting forces in turning of AISI 1045 steel using a coated cutting tool. Then the temperature readings and the forces will be calculated at different depths of cut are given as an input to the software.
Keywords: FEM, AISI, SPCT, 3D.

1. INTRODUCTION

Finite Element Analysis seems to be a technique of simulating the loading conditions in such a design and determining the design's response. The design is modelled with the so-called components of discrete building pieces. Every element contains specific formulae describing how such a given load reacts. The overall response from all the elements in the model is the "summary." The elements have such a finite amount of unknowns, which is why the term is Finite. The finite element model, having a limitless number of unknowns, only can approximate the physical system's reaction that contains endless unknowns.

Design Of Experiment

The overall steps active in the Taguchi method are these:

- Determine the machining parameters that are influenced by the machining process variables such as material removal rate, surface finishing and over cut etc.
- The prospective of a procedure may also be a minimum or optimum. The prospective may increase the material removal rate.
- Establish the strategy variables affecting the machining process. Variables are parameters within the strategy that influence the performance measures such as cutting speed, feed rate etc., that may be simply controlled. The number of levels that the variables should be varied at should be specified. Like, a feed rate could be varied to a low and high value.
- Build orthogonal arrays for the design of the variable, indicating how many and situations for every experiment. The decision of orthogonal arrays is based on the number of variables and the quantities of variation for every parameter and will be discussed below.
- Perform the experiments indicated in the completed array to get data on the

consequence of the performance measure.
- Comprehensive data analysis to discover the aftereffect of different variables on the performance measure.

Background

Finite Element Analysis (FEA) This has been known from 1960 to 1970 and is utilised for forming and tooling analysis. The Finite Element Method (FEM) allows the prediction of cutting forces, stresses, wear of the tool and cutting process temperatures to still be developed for the cutting instrument. The optimal cutting settings are established with this approach. FEM has certain advantages, like solving contact issues, using bodies manufactured using various materials, approximating a curved region using finite elements or accurately describing, etc. The continuous medium is described by two types of finite element formulations: Lagrangian and Eulerian. It's also commonly used during lagrangian. The mesh grid deforms only with the material in a Lagrangian analysis, although the grid remains fastened in space using Eulerian analysis [1].

The Lagrangian Analysis mimics intermittent and discontinuous stages of the chip creation, whereas the Eulerian can model intermittent & discontinuous phases of chip production. Nevertheless, the Eulerian formulation does not need chip partitioning and prevents mesh distortion [2]

Most studies, except those who prefer using the Eulerian formulation, have utilised the Lagrangian formulation. To determine the scope and quality of both the analysis, the correct choice of both the finite element software seems highly crucial. Abaqus, Deformation and Advant Edge are perhaps the most powerful software programs used for metal cutting simulation [3].

FEM models may be used in six categories: tool board design, wears, chip flow, burr development, plus surface integrity and residual stress.

Why is FEA needed?

- Computer simulation allows several "what-if" scenarios to be rapidly and efficiently examined to decrease the quantity of prototype testing.
- To mimic designs during prototype testing, including artificial knee surgery implants. Example:
- Bottom line: –Cost savings –Savings in time –Saving time on the market! –Creating more dependable designs that are higher in quality.

FEM to designers:

- Applied easy to complicated, irregular objects with various materials and complex boundary conditions.
- Eigen Value issues, applied to stable time dependant.
- For linear and non-linear issues applicable.
- Amounts of FEM packages were accessible for specific purposes.
- CAD applications for Solid modelling and mesh generators may be linked to the FEM software.
- Many FEM software packages have graphical and automatic interfaces. Automakers and advanced post processors help speed up the analyses and make the pre and after process user-friendly.

2. FINITE ELEMENT ANALYSIS OF TURNING PROCESS

Finite element analyses are a most effective and precise way for identifying field variables, made feasible by advances in computer computing and processing capacity and thus nearly utilised in recent years in all computer-aided design approaches. Applications include heat flux, fluid flow, magnetic flux, filtration, and other flux problems from deformation and stress analysis. This analytical technique discovered a complicated area that defines a continuum as primary geometric forms termed finite elements. The present study was also based on finite element use for thermal analysis of a single-point cutting tool. Once the single-point cutting tool template is established, it is also suitable for other multi-point operations, such as boiling, friction, and grinding.

3D cuts are a continuous field of research effort because of substantial cost reductions and give insights into the mechanism that is not easy to evaluate in tests, utilising finite element approaches. In addition, heat transmission and cutting process modelling need to be carefully considered in every modelling work. This article provides a model for such a process of turning steel type EN-24. A Finite Element Analysis program, Deform 3D, has been utilised in this work to examine the impacts on temperature compatibility of both the cuts, feed rate and kind of alloy steel. The workpiece has been designed to take on a thermal, elastic and plastic effect with elastic-plastic materials. For each circumstance, the workpiece is represented by a model of a liner of varying lengths.

The short length of the material was chosen to reduce computer time without affecting the model's integrity, as heat generation is restricted to tiny regions surrounding the cutting location. The workpiece from being built by the machining module DEFORMS and contains the geometry of an earlier tool pass, including the necessary cut-and-nose radius depths. The automated mesh generating mechanism of DEFORM has been used to create an unstructured tetrahedral final element mesh.

3. METHODOLOGY AND EXPERIMENTATION

The objectives of the present work have already been mentioned in the preceding chapter. According to our defined objectives, the present work has been done through the following phases. These phases are as follows:

- Modelling of the cutting tool in Deform 3D.
- A performing turning process under dry conditions on specimens according to Taguchi's experiment design in Deform 3D.
- The length of the cut was kept constant at 50 mm for both dry and wet turning.
- Measuring stress, cutting forces, deformation and temperature

Process Variables and Their Limits

The operating range of the selected parameters for the design of the experiment is based on Taguchi's L9 Orthogonal Array (OA) design, and it has been selected using MINITAB 15 software. In the present study, spindle speed, feed rate, and cut depth have been considered process variables. The process variables with their units (and notations) are listed in Table 1.

Table 1: Process variables and their limits

Parameters/Factors		level		
		1	2	3
A	Spindle speed (rpm)	160	320	620
B	Feed rate (mm/rev)	0.3	0.4	0.5
C	Depth of cut (mm)	0.7	0.8	0.9

Design of Experiment

Simulations have been conducted using Taguchi's L9 Orthogonal Array (OA) design of experiment, which consists of 9 combinations of spindle speed, feed rate and depth of cut. According to the design catalogue prepared by Taguchi, L9 Orthogonal Array has been found suitable in the present work. It considers three process parameters (without interaction) to be varied in three discrete levels. The experimental design is shown in Table 2.

Table 2: Cutting Parameters and Levels for Turning

Experiment no.	Spindle speed (rpm), N	Feed rate (mm/rev), f	Depth of cut (mm), a
1	160	0.3	0.7
2	160	0.4	0.8
3	160	0.5	0.9
4	320	0.3	0.8
5	320	0.4	0.9
6	320	0.5	0.7
7	620	0.3	0.9
8	620	0.4	0.7
9	620	0.5	0.8

Material Used

The material selected was AISI 1045 MS bars (of diameter 50 mm and length 140 mm) because it was suitable for most engineering and construction applications.

AISI 1045

AISI 1045 is a low-cost alloy, medium-carbon steel with adequate strength and toughness characteristics. AISI 1045 is valuable for induction- or flame-hardened components. The hardness of the bar is 187 HB.

Table 3: Chemical Composition of AISI 1045 steel in %

C	Si	Mn	P	S	Cu	Ni	Cr
0.45	0.20	0.72	0.015	0.018	0.10	0.09	0.07

Applications

They were used in automotive-type applications. Axle and spline shaft are two examples of automotive components produced using this material where the turning is the prominent machining process used.

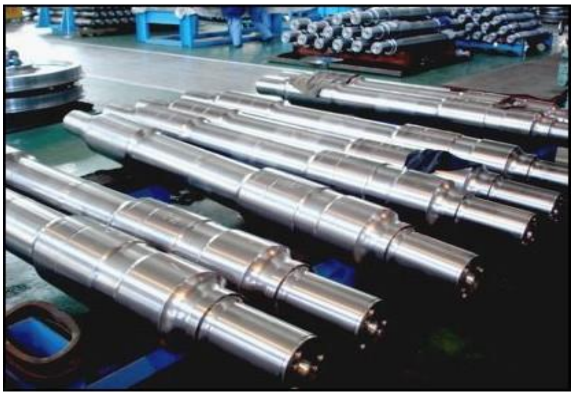

Figure 1: Axle Shaft

Figure 2: Propeller Shaft

Coated Carbide Tool Insert Description

Coated carbide tools have been known to perform better than uncoated carbide tools when turning steel. For this reason, a commercially available CVD coated carbide insert was used in this investigation. The cutting inserts used were multi-layer coated cemented carbide by (TiN-Al2O3-TiCN) from WIDIA with a standard notation of CNMG 120408 of nose radius 0.8 mm. Table 3.4.1 list the cutting tool geometry. The selected cutting tool was based on the cutting tool manufacturer's manual.

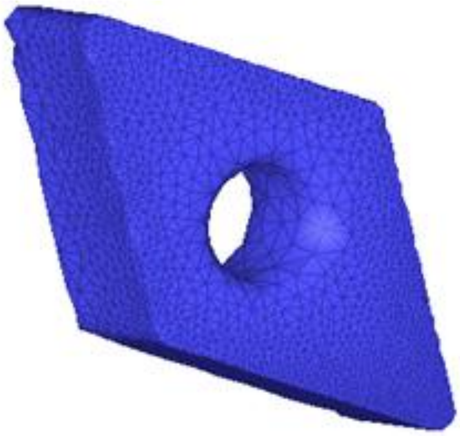

Figure 3: WIDIA CNMG 120408 in Deform 3D

Cutting Tool Designation

The codes given for tool have a special meaning as shown in table

C	N	M	G	12	04	08	TN 4000
1	2	3	4	5	6	7	8

Table 4: Designation of Insert

S. No.	Symbol	Meaning	Figure	Description
1	C	Insert shape	80°	The angle of 80° between the two edges
2	N	Insert clearance angle	0°	0° angle between the upper and lower edge
3	M	Tolerances	B, Rε, D, S	Inscribed circle radius- S= ± 0.13
4	G	Insert feature		Insert with hole
5	12	Insert size	12	12
6	04	Insert thickness	S	4.76
7	08	Corner radius	R	0.8
8	TN4000	Company grade		

Cutting Tool Holder Description

For turning operations, a WIDIATM turn tool was used. This tool is used for turning and facing applications. The tool has the following code, and it is used only for CNMG inserts.

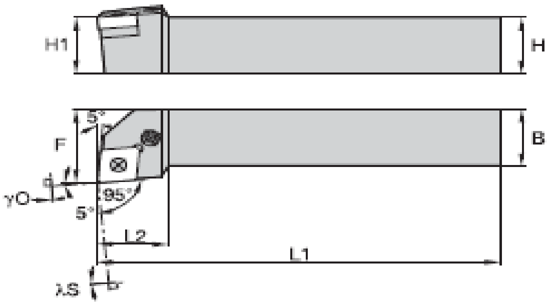

Figure 4: Tool Holder Geometry

The dimensions for the tool are

Ordering code	H	B	F	L1	L2	λS°	γO°
PCLNR 2525 M 12	25	25	32	150	26	-6	-6

Cutting Tool Holder Designation

P	C	L	N	R	25	25	M	12
1	2	3	4	5	6	7	8	9

Table 3.5: Tool Holder Designation

S.No.	SYMBOL	MEANING	FIGURE	DESCRIPTION
1	P	Clamping system		Insert clamping by toggle lever for insert with hole
2	C	Insert shape		CNMG
3	L	Tool holder style		95°
4	N	Insert clearance angle		0°
5	R	Hand of tool	R Right hand	Right-hand tool
6	25	Shank size-height		25
7	25	Shank size-width		25
8	M	Shank tool length		150
9	12	Cutting edge length		10

Data Collection

The workpiece of diameter 50 mm and length 140 mm required for experimenting have been prepared first. Nine numbers samples of the same material and exact dimensions have been made. Then, using different levels of the process parameters, nine specimens have been turned in dry conditions using Deform 3D. The results of the simulations are shown in Table 3.6. Analysis has been made based on simulation data in the following chapter. Taguchi has made the optimisation.

Table 6: Simulation Data

Experiment no.	Spindle speed (rpm), N	Feed rate (mm/rev), f	Depth of cut (mm), d	Stress (MPa)	Cutting forces (N)	Deformation (mm)	Temperatur (°C)
1	160	0.3	0.7	838	374	0.612	146
2	160	0.4	0.8	829	298	0.283	141
3	160	0.5	0.9	814	274	0.178	139
4	320	0.3	0.8	924	386	0.771	158
5	320	0.4	0.9	918	372	0.704	149
6	320	0.5	0.7	901	358	0.698	131
7	620	0.3	0.9	977	425	0.745	169
8	620	0.4	0.7	961	338	0.647	158
9	620	0.5	0.8	945	298	0.532	147

Some of the simulation results

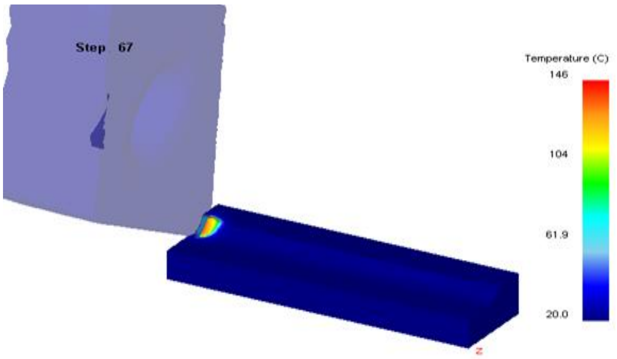

Figure 5: Temperature Simulation

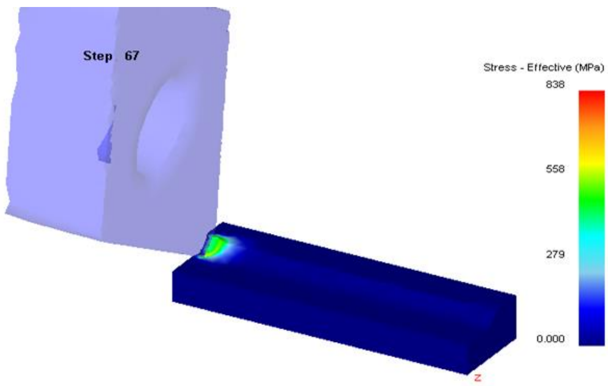

Figure 6: Stress Simulation

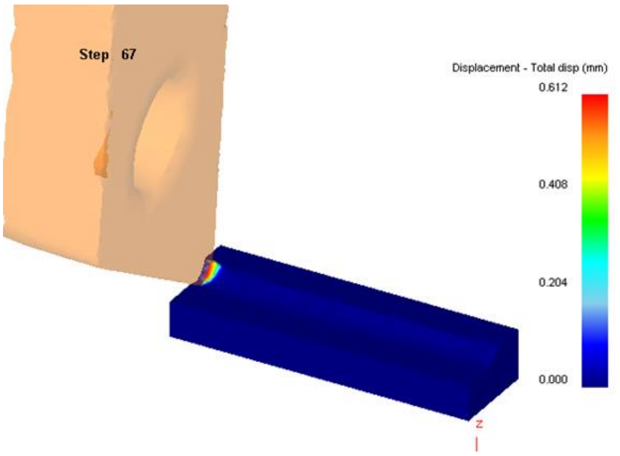

Figure 7: Displacement Simulation

Signal-to-Noise Ratio

Parameters that affect the output can be divided into controllable (or design) factors and uncontrollable (or noise) factors. The designer can adjust the value of controllable factors. Still, the value of uncontrollable factors cannot be changed because they are the sources of variation because of the operational environment. The best set of control factors as they influence the output is determined by performing experiments. Smaller-the-Better is used for surface roughness because we minimise the surface roughness.

Measurement of F-Value of Fisher's (F Ratio)

The F values determine the significance of the parameters. More significant the F value, the greater the effect on the performance characteristic due to the change in that process parameter. F value is defined as:

$$F = \frac{MS fortheterm}{MS fortheerrorterm} \quad \ldots\ldots\ldots\ldots 1$$

ANOVA

ANOVA is a statistical tool that determines the contribution of individual factors to control the final response. It calculates the parameters like the sum of squares (SSS), degree of freedom, variance, f value and P-value for each factor. The ANOVA calculations were done using the help of the MINITAB 15 software.

4. RESULTS AND DISCUSSIONS

Analysis of Variance

The results obtained from the simulation were checked with the help of ANOVA, which predicts the significance of the input parameter for any desired response function. It shows the most significant parameter which influences the results.

ANOVA for Stress

Results obtained for the stress, cutting forces, deformation and temperature in dry turning are shown in Table 3.6. The simulation results are analysed with ANOVA are shown in Table 4.1-4.4. The F value calculated through MINITAB 15 software is shown in the second last column of the ANOVA table, which suggests the significance of the factors on the desired characteristics. More significant is the F value higher is the significance (considering a confidence level of 95%). The results show that feed rate is the most significant factor in dry turning for stress, temperature and cutting forces values. In addition, spindle speed is the most significant factor in dry turning for deformation.

Table 7: Analysis of Variance for Stress

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Spindle speed (rpm),	2	27760.9	13880.4	2402.38	0.000*
Feed rate (mm/rev)	2	1056.2	528.1	91.40	0.011*
Depth of cut (mm)	2	22.9	11.4	1.98	0.335
Error	2	11.6	5.8		
Total	8	28851.6			

Table 8: Analysis of Variance for Cutting forces

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Spindle speed (rpm),	2	5017	2508.3	4.35	0.187
Feed rate (mm/rev)	2	11382	5691.0	9.87	0.012*
Depth of cut (mm)	2	1741	870.3	1.51	0.398

Error	2	1153	576.3		
Total	8	19292			

Table 9: Analysis of Variance for Deformation

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Spindle speed (rpm),	2	0.22180	0.110900	20.95	0.046*
Feed rate (mm/rev)	2	0.09039	0.045195	8.54	0.105
Depth of cut (mm)	2	0.02758	0.013790	2.60	0.277
Error	2	0.01059	0.005294		
Total	8	0.35036			

Table 10: Analysis of Variance for Temperature

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Spindle speed (rpm),	2	416.00	208.00	10.23	0.089
Feed rate (mm/rev)	2	524.67	262.33	12.90	0.002*
Depth of cut (mm)	2	80.67	40.33	1.98	0.335
Error	2	40.67	20.33		
Total	8	1062.00			

Main Effect Plots

Main effect plots for stress, cutting forces, deformation and temperature for dry turning are shown in figure 4.1 to figure 4.4. The main effect plot shows the variation of stress, cutting forces, deformation and temperature concerning Spindle speed, feed rate and depth of cut. The X-axis represents a change in the variable's level, and the y-axis represents the change in the resultant response.

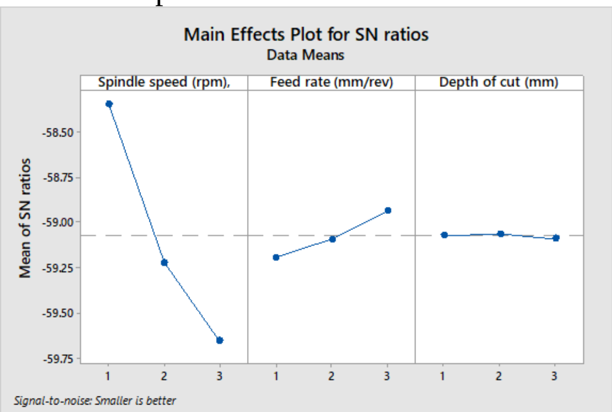

Figure 8: Main effects plot for means for stress

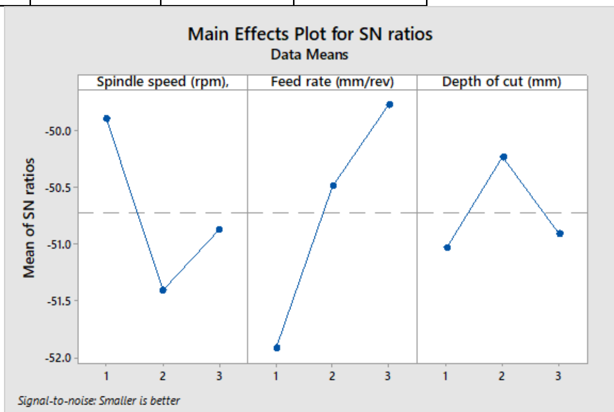

Figure 9: Main effects plot for means for cutting forces

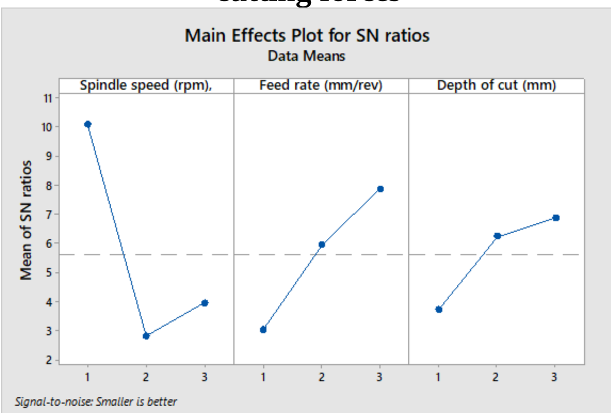

Figure 10: Main effects plot for means for deformation

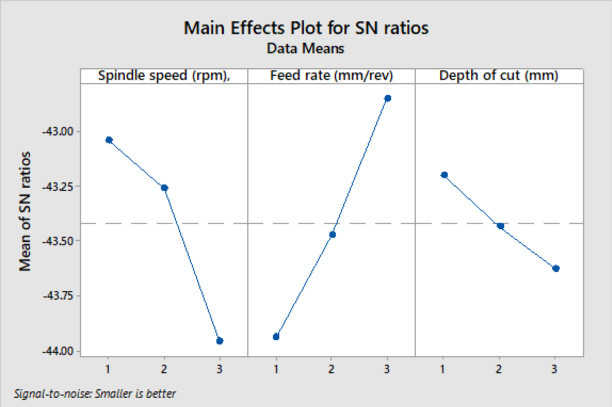

Figure 11: Main effects plot for means for temperature

Determination of Optimum Solution

The optimum condition of the turning process is concerned with minimising the stress, cutting forces, deformation and temperature, but this cannot be achieved simultaneously with a particular combination of control parameter settings. Optimal parameter setting for stress, cutting forces, deformation and temperature in dry turning has been determined from Figures 8 to 11. The optimal settings for stress, cutting forces, deformation and temperature in dry and turning are determined individually by Taguchi's approach. Table 8 to 11 shows these individual optimal values and their corresponding settings of the process parameters for the specified performance characteristics.

Table 11: Parameters and their selected levels for optimal stress

Parameter designation	Process parameters	Optimal levels
A	Spindle speed (rpm), N	A3
B	Feed rate (mm/rev), f	B1
C	Depth of cut (mm), d	C3

Table 12: Parameters and their selected levels for optimal cutting forces

Parameter designation	Process parameters	Optimal levels
A	Spindle speed (rpm), N	A2
B	Feed rate (mm/rev), f	B1
C	Depth of cut (mm), d	C1

Table 13: Parameters and their selected levels for optimal deformation

Parameter designation	Process parameters	Optimal levels
A	Spindle speed (rpm), N	A2
B	Feed rate (mm/rev), f	B1
C	Depth of cut (mm), d	C1

Table 14: Parameters and their selected levels for optimal temperature

Parameter designation	Process parameters	Optimal levels
A	Spindle speed (rpm), N	A3
B	Feed rate (mm/rev), f	B1
C	Depth of cut (mm), d	C3

5. CONCLUSIONS

In the simulation, Taguchi L9 design was used to study the effect of spindle speed, feed rate and depth of cut on stress, cutting forces, deformation and temperature in dry conditions. ANOVA was used to study the significance of various parameters. From the experiment following results were obtained.

- The results show that feed rate is the most significant factor in dry turning for stress, temperature and cutting forces values
- The stress, cutting forces, deformation and temperature is affected by feed rate, depth of cut and spindle speed.
- From ANOVA analysis, we can say that the parameters affecting stress, cutting forces, deformation and temperature are spindle speed, feed rate and depth of cut.

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