Study on the Turning process of high temperature Nickel-Based Superalloy Inconel 718

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Abstract: - In this work, the research is conducted cutting force and surface roughness on the high speed turning process for Nickel-based superalloy Inconel 718. The experimental investigations and statistical analysis have been carried out to study the effect of cutting parameters (speed, feed and depth of cut) on cutting force. Also has been carried out the effect of cutting speed and depth of cut to surface roughness. The orthogonal experiment is applied to coated carbide tools turning high-temperature alloy Inconel 718 and factorial design of experiments compliance to 9 run (3^k) was following for the experimental design. Analysis of variance (ANOVA) is used to study the effect of process parameters and establish correlation among the cutting speed, feed rate and depth of cut with respect to surface roughness and statistical analysis was perform on MINITAB 17.

Keywords: Superalloy; Turning; ANOVA; Cutting Force; Surface Roughness.

1 Introduction

Today Nickel-based superalloy plays an increasingly important role in mechanical engineering field. Because of its excellent performance, Inconel 718 was widely used in the casing, turbines, combustion, chamber, the space shuttle, nuclear reactors and other high temperature applications [1]. High-speed cutting is a process of great interest in modern production engineering. In order to take advantage of its potential, a knowledge of the material and structural behavior in combination with the technological conditions is essential [2]. The finish hard turning process is define as turning material with hardness higher than 40 HRC (Hardness-Rockwell C) under appropriate high feed rate and low depth of cut conditions [3].

Cutting forces and surface roughness are classified among the most important technological parameters in machining process [4]. Cutting forces play an important role to predict machining performance for any machining operation. Estimating the cutting forces helps in structural design of machine tool system, condition monitoring and studying the machinability characteristics of work materials.

A typical relationship between cutting force components acting on the cutting tool in a 3D single point cut is defined by Eq.(1):

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)\ [4\text{-}6].$$

The specific cutting forces are determined in order to understand the interference of chips that occur during the threading. With the increase in the cumulative radial feed, the corresponding specific cutting forces become higher. It is reason that the difference in the specific cutting forces results from the alteration of the interference of the flowing chips. The specific cutting forces decrease in the beginning of the threading and then increases with the cumulative radial feed. The results show that the interference of the chip flow influences the threading force components to very large extent [5]. Cutting forces has a direct influence on specific cutting pressure and power consumption, tool wear and heat generation. On the other hand, surface roughness is an important output characteristic that describes the quality of the machined surface. In order to obtain good machinability and to improve the product quality, it is necessary to obtain minimum values of cutting force and surface roughness. Cutting forces have a direct effect on specific tool wear heat generation [6]. Decades of experience and continuous product development have seen Kistler Dynamometer systems become the benchmark for machining data acquisition and analysis. They provide accurate and reliable measurements with specific units developed for all types of machining operations including turning, milling, drilling and grinding [7]. An area of research interest in turning is the analysis of cutting force, as minimum power consumption is a never ending. Among the Cutting force, Thrust force and Feed force the former prominently influences power consumption and the most common equation available for the estimation of Cutting force is given by equation 2:

$$Fc = kc \times DOC \times f \qquad (2)$$

Where, DOC = Depth of cut (mm), f = feed (mm/rev), kc = Specific cutting energy coefficient (N/ mm2)

According to equation (2), the depth of cut, feed, and specific cutting energy coefficient influences cutting force. A lot of work is in progress to study this influence and construct the models for different tool and work force material so as to optimize the power consumption [8].

The surface quality is an important factor that evaluates the productivity of machine tools as well as machined components. It is one of the most frequent customer requirements. Surface roughness affects several properties such as wear resistance, coefficient of friction, fatigue strength, heat transmission, wear rate, corrosion resistance of machined parts etc. Today, every manufacturing industry gives importance to meet the desired quality of surface finish and hence it can be said to be an important product quality characteristic [9]. Response surface methodology is popular where it can be usefully applied in many manufacturing situations. In response surface methodology, the factors that are consider as most important are used to build a polynomial model in which the independent variable is the experiment's response. In this study, Response surface methodology was using as an alternative way to estimate the surface quality in grinding [10]. RSM involves two basic concepts: (a) The choice of the approximate model and (b) The plan of experiments where the response has to be evaluate. The analysis of variance (ANOVA) is widely used to consider effects of factors on responses. In experimental investigations, ANOVA is often employed prior to other statistical analysis. Then analysis of variance is carried in order to establish a relation between independent variables and dependent variables is widely applied [11]. Studied on the optimization of process parameters in End milling process, it was observe that cutting speed was the most important factor influencing surface roughness [12]. Depth of cut, on the other hand is not directly correlate to surface roughness. Recent developments of surface roughness prediction system has shown favorable results utilizing feed rate, speed and depth of cut. Parameters such as cutting forces and vibrations were considered in predicting surface roughness in turning process. Based on this review of literature, therefore, an effective experimental design should include feed rate, spindle speed, and depth of cut. Another important consideration in developing a prediction system is the modeling technique. Regression analysis is the prominent choice for this purpose and has shown considerable results [13].

2 Experimental set up and details

The workpiece material used in the machining process was Nickel-Based Superalloy Inconel 718 and experiment was conducted by CK6140 CNC Lathe. Chemical composition of superalloy is given in Table 1.

Table 1. Chemical composition of Inconel 718 (wt %)

Element	Ni	Cr	Fe	Nb + Ta	Mo	Ti	Co	Al	Si
Content	51.55	19.62	Bal.	5.08	3.03	1.08	1.0	0.58	0.17

Table 2. Mechanical Properties of Inconel 718

Yield stress (MPa)	Tensile stress (MPa)	Strain (%)	Elastic modulus (GPa)	Thermal conductivity (W/m K)	Density (kg/m^3)
1110	1310	23.3	206	11.2	8470

The cutting forces induced during turning for various design parameters was obtained using Kistler dynamometer. Machining time were measured three forces and the resultant force was then calculated and was taken for analysis. The machined nickel alloy was examined for their surface quality with Taylor Hobson Precision Surface Roughness tester.

Table 3. Experimental Conditions

Machine tool	CNC Machine CK6140
Work material composition	Nickel Based Super Alloy GH4169, Inconel 718, Cr19-Ni52.5-Ti1-Mo3-Nb5-Si1-Mn-B
Tool material	HSS
Environment	Dry turning
Size	Diameter = 30mm and Length = 50mm

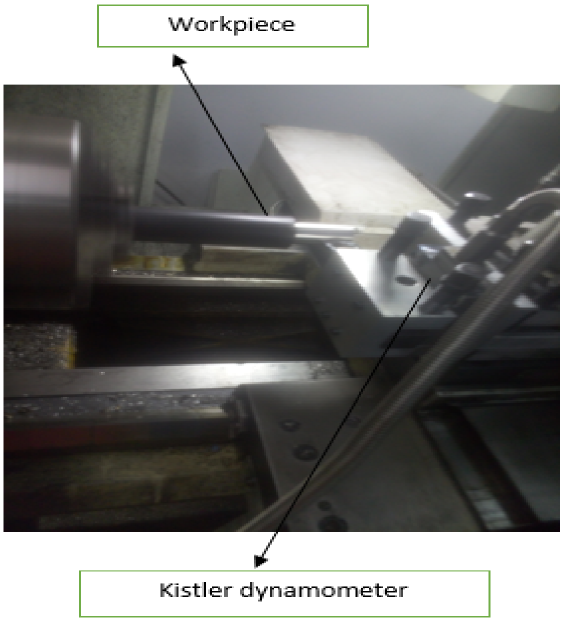

Fig.1 Experimental set up

3 Experimental Design and Results

Design of Experiments was done by Taguchi's technique. For three parameters and three level, L9 orthogonal array was selected. Through pilot study experiment, the levels of parameters were select. They are Depth, Feed and Cutting speed. Each parameter has three levels – namely low, medium and high, denoted by 1, 2 and 3 respectively. According to the Taguchi method, if three parameters and 3 levels for each parameters L9 orthogonal array should be employed for the experimentation.

Orthogonal arrays are special standard experimental design that requires only a small number of experimental trials to find the main factors effects on output. Before selecting an orthogonal array, the minimum number of experiments to be conducted is to be fixed based on the formula below

N Taguchi = 1+ NV (L – 1)

N Taguchi = Number of experiments to be conducted

NV = Number of parameters

L = Number of levels

In this work

NV = 3 and L = 3, Hence

N Taguchi = 1+ 4 (3-1) = 9

Hence at least 9 experiments are to be conducted. Based on this orthogonal array (OA) is to be selected which has at least 9 rows i.e.9 experimental runs [14].

The experiment is carried out of 9 runs, 3 level and 3 factors and after each experiment was measured cutting force and surface roughness. As it is told from testing, Kistler measurement is possible to receive only three forces F_x, F_y and F_z. With the aid of Formula 1 revealed Cutting Force Test results are listed in Table 5.

Table 4. Process parameters and their chosen levels

Process parameters	Depth of cut (mm)	Feed rate (mm/rev)	Cutting speed (m/min)
Level 1	0.1	0.1	10
Level 2	0.15	0.15	20
Level 3	0.2	0.2	30

Table 5. Experimental design and results

Factors Number	V_c/(m/min)	f /(mm/r)	ap/mm	F_x/N	F_y/N	F_z/N	F/N	R_a
1	10	0.1	0.1	40	44	16	61.58	0.86
2	10	0.15	0.15	38	36	27	58.89	0.88
3	10	0.2	0.2	37	46	36	58.72	1.50
4	20	0.1	0.15	52	51	30	78.77	1.52
5	20	0.15	0.2	45	57	38	81.96	0.96
6	20	0.2	0.1	48	40	29	68.88	1.18
7	30	0.1	0.2	100	110	45	155.32	3.34
8	30	0.15	0.1	92	80	29	125.31	3.18
9	30	0.2	0.15	98	78	41	131.79	1.98

The concerning importance amongst the cutting parameter levels is determined more accurately in ANOVA analysis. Analysis of Variance (ANOVA) is a powerful analyzing tool to identify which are the most significant factors and it's (%) percentage contribution among all control factors for each of machining response. It calculates variations about mean ANOVA results for the each response. ANOVA analysis performed using MINITAB 17 software program. [15]defines the analysis of variance (ANOVA) as being applied in a statistical study of Taguchi's method, in order to evaluate the significance of the parameters used in the process. The results of the ANOVA are presented in a table that determines the most relevant parameters for the process through the following values, as equations 3, 4, 5 and 6:

-SS: quadratic sum of factors

$$SS = \sum_{i=1}^{n}(y_i - y)^{-2} \tag{3}$$

-gl: degrees of freedom for each factor (gl)

Gl = (Number of levels for each factor – 1) (4)

-MS: quadratic average

$$MQ = \frac{SS}{gl} \tag{5}$$

-Test F: evaluates the significance of each factor

$$F = \frac{MSeffect}{MSerror} \tag{6}$$

4 Result and Discussion

4.1 Cutting Force Analysis

Exponential form empirical formula of cutting force is widely used, specific forms of expression as follows:

$$F_C = C \cdot v^{a_1} f^{a_2} a_p^{a_3} \tag{7}$$

From (3.3.1.1) formula obtained next equations:

$$F_X = C_{F_X} \cdot v^{x_{F_X}} \cdot f^{y_{F_X}} \cdot a_p^{z_{F_X}} \tag{8}$$

$$F_Y = C_{F_Y} \cdot v^{x_{F_Y}} \cdot f^{y_{F_Y}} \cdot a_p^{z_{F_Y}} \tag{9}$$

$$F_Z = C_{F_Z} \cdot v^{x_{F_Z}} \cdot f^{y_{F_Z}} \cdot a_p^{z_{F_Z}} \tag{10}$$

Where, F_X、F_Y、F_Z —feeding force, passive force, main cutting force, N;

C_{F_X} 、 C_{F_Y} 、 C_{F_Z} —coefficient, depend on workpiece material and cutting condition;

x_{F_X}、 y_{F_X}、 z_{F_X}、 x_{F_Y}、 y_{F_Y}、 z_{F_Y}、 x_{F_Z}、 y_{F_Z}、 z_{F_Z}— Index.

The purpose of the test is the analysis on the orthogonal test result using multiple linear regression analysis obtain the empirical formula index and coefficient by linear fitting. First, the exponential formula into the linear forms by getting the logarithm of the formulas. The linear formulas as following:

$$lnF_X = lnC_{F_X} + x_{F_X} lnv + y_{F_X} lnf \cdot z_{F_X} lna_p \quad (11)$$

$$lnF_Y = lnC_{F_Y} + x_{F_Y} lnv + y_{F_Y} lnf \cdot z_{F_Y} lna_p \quad (12)$$

$$lnF_Z = lnC_{F_Z} + x_{F_Z} lnv + y_{F_Z} lnf \cdot z_{F_Z} lna_p \quad (13)$$

In the formula (5), $y = lnF_X$, $a_0 = lnC_{F_X}$, $a_1 = x_{F_X}$, $a_2 = y_{F_X}$, $a_3 = z_{F_X}$, $x_1 = lnv$, $x_2 = lnf$, $x_3 = lna_p$, and the formulas (7) and (8) are the same. The simplified equation is obtained:

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 \quad (14)$$

Based on orthogonal test results, the mathematical software of MATLAB used for multiple linear regression analysis and obtain empirical formula of cutting force for turning of superalloy Inconel 718:

$$F_X = 79.17 \cdot v^{0.3716} \cdot f^{0.3191} \cdot a_p^{0.7249} \quad (15)$$

$$F_Y = 4.579 \cdot v^{0.7899} \cdot f^{-0.0907} \cdot a_p^{-0.0218} \quad (16)$$

$$F_Z = 9.854 \cdot v^{0.6344} \cdot f^{-0.2711} \cdot a_p^{0.3212} \quad (17)$$

Now suppose there are three factors A, B and C (Speed, Feed and Depth) under study and that each factor is at three levels arranged in a factorial experiment. This is a 3^3 factorial design, and the experimental layout and treatment combinations notation shown previously in Table 6. Figure 2. Shows relation between cutting force and cutting parameters (speed, feed and depth). It means influence of cutting parameters to cutting force at the time of turning process. From cutting parameters, cutting speed more influence than feed and depth of cut. Because of results analysis of variance for force introduce it in Table 6.

Table 6. Analysis of variance of Cutting Forces

Source	DF	Adj SS	Adj MS	F	P
Speed	2	25,72	12,861	252,06	0,004
Feed rate	2	0,5406	0,2703	5,30	0,159
Depth	2	0,5748	0,2874	5,63	0,151
Error	2	0,1021	0,0510	-	-
Total	8	26,940	-	-	-

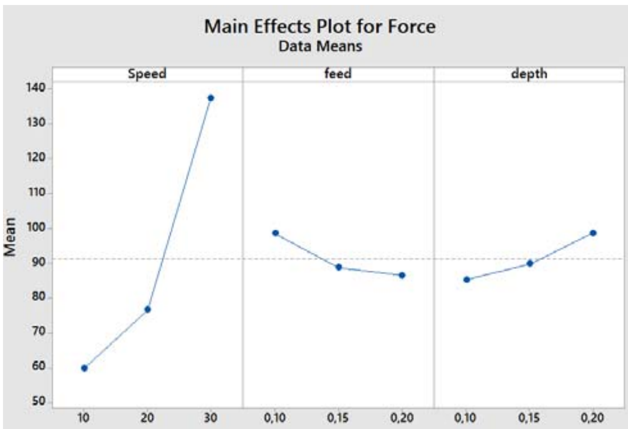

Fig.2 Main effects plot of Cutting Force

From figure 2, it is evident that while turning Nickel superalloy Inconel 718 cutting force increases as cutting speed increases; this may be due to the fact that when cutting speed increases the amount of material coming into contact with the cutting tool increases, therefore the load on the tool also increases which in turn increases the cutting force. The effect of depth of cut on cutting forces is because as the depth of cut increases the volume of the uncut chip also increases, which produces more resistance on the cutter, thus increasing the cutting force.

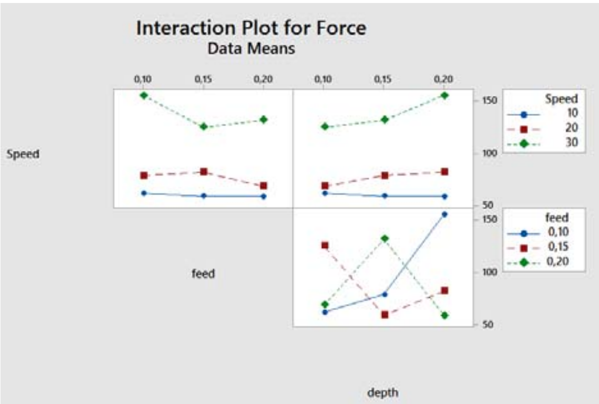

Fig.3 Interaction plot of Cutting Force

In Table 7 shown best results of cutting force and influence of cutting parameters. There are 3 levels when cutting speed 10, 20 and 30m/min, feed rate 0.1, 0.15, 0.2 mm/r and depth of cut 0.1, 0.15, 0.2 mm. For 1 level Cutting force 59.73 when cutting speed is 10m/min, 98.56 when feed rate is 0.1 mm/r and 85.26 when depth of cut is 0.1mm. From table presumably can know about influence of parameters and there shown Delta for speed 77.74, feed 12.09 and depth 13.41. The ratio of between parameters v $> a_p >$ f.

Table 7. Response Table for Means

Level	Speed	Feed	Depth
1	59,73	98,56	85,26
2	76,54	88,72	89,82
3	137,47	86,46	90,67
Delta	77,74	12,09	13.41
Rank	1	3	2

4.2 Surface Roughness Analysis

The experimental results of surface roughness values were analyzed with Analysis of variance (ANOVA), used to identify the factors significance on the response. The result of ANOVA of surface roughness was given in the Table 6. This analysis was carried out for a significance level of α = 0.5 i.e., for a confidence level of 95%. The sources with a P-value less than 0.05 are considered to have a statistically significant contribution to the performance measures [11].

Table 8. Analysis of Variance of Surface Roughness

Source	DF	Adj SS	Adj MS	F	P
Speed	2	0,7460	0,373042	5,17	0,162
Feed rate	2	0,0172	0,00862	0,1	0,89
Depth	2	0,0343	0,01718	0,2	0,80
Error	2	0,1443	0,07216	-	-
Total	8	0,9420	-	-	-

Table 8 shows the results of ANOVA for surface roughness. From the results, it is observed that the speed is the most significant parameter followed by feed rate and depth of cut has less significance in controlling the surface roughness values. From the analysis of the Table 8, p-value of speed (0.162) which is less than 0.893 and 0.808. It means that speed's influence significantly on workpiece surface roughness between three cutting parameters.

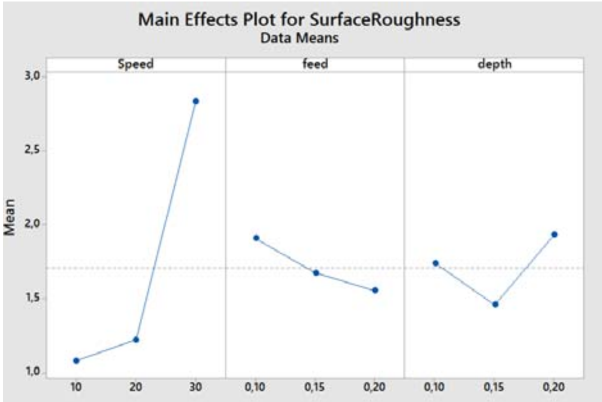

Fig.4 Main effects plot for Surface Roughness

From the Figures 4 and 5, it is observed that with the increase in cutting speed and depth of cut levels there is a less change in response. However, with the increase in the levels of feed significant change in the response can be observed. Based on the analysis the low value of surface roughness was obtained at cutting speed of 10 m/min (level 1), feed of 0.2 mm/rev (Level 3) and depth of cut of 0.15 mm (level 2).

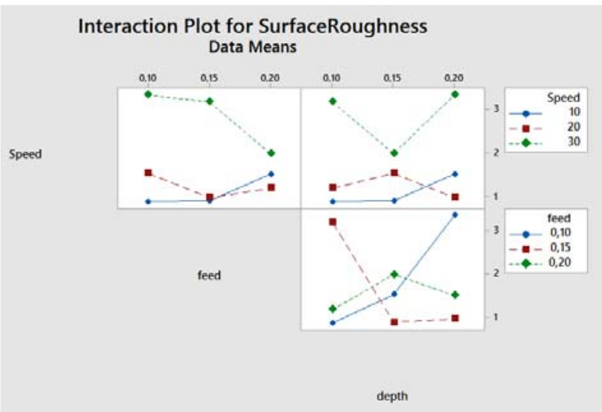

Fig.5 Interaction plot for Surface Roughness

Multiple regression analysis is a statistical technique that allows us to predict score on one variable based on their score on several other variables [16]. In this case, the dependent variable is surface roughness, while the independent variables are spindle speed, depth of cut and feed rate. In general, multiple regression equation takes the form;

$$Yi = b_0 + b_1X_{1i} + b_2X_{2i} + b_3X_{3i} \quad (18)$$

Where;

Y_i = Surface Roughness (μm)

X_{1i} = Cutting Speed (M/min.)

X_{2i} = Feed Rate (mm/min)

X_{3i} = Depth of Cut (mm)

b_0 → Error coefficient

b_1,b_2, b_3 → variable coefficient [17-18].

The analysis of the data also came out with the following coefficient value;

Table 9. Coefficients

Term	Coef	SE Coef	T	P	VIF
Constant	0.20	1.34	0.15	0.888	
Speed	0.0877	0.0281	3.12	0.026	1.00
Feed	-3.53	5.62	-0.6	0.557	1.00
Depth	1.93	5.62	0.34	0.745	1.00

Therefore, the mathematical model that produced by using multiple regression analysis was as follows;

$$R_a = 0{,}20 + 0{,}0877X_{1i} - 3{,}53X_{2i} + 1{,}93X_{3i} \quad (19)$$

Surface roughness which taken from experiment called actual surface roughness and taken using by mathematical model called estimated surface roughness. Mathematical model using multiple regression analysis was using for calculate some estimated surface roughness and compared.

Table 10. Verification of Experiments

Run	Experimental value of roughness	Predicted value of roughness	Error
1	0.86	0.91	-0.05
2	0.88	0.83	0.05
3	1.50	0.757	0.743
4	1.52	1.89	-0.37
5	0.96	1.81	-0.85
6	1.18	1.441	-0.26
7	3.34	2.864	0.476
8	3.18	2.494	0.686
9	1.98	2.198	-0.21

5 Conclusion

In this, paper the effect of cutting parameters (speed, feed rate and depth of cut) on cutting force and surface roughness in turning process. The cutting speed has significant influence on both the Cutting force and Surface roughness. Feed rate has no significant effect on the cutting force as well as the surface roughness of the chosen work piece. Depth of cut has a significant influence on cutting force and surface roughness. In turning process optimization with respect to power consumption, the focus should be on choosing an appropriate combination of feed rate and depth of cut. Optimum surface roughness can be achieved by selecting relatively Speed 10-20 m/min, feed rate 0.20 mm/r and depth of cut 0.15 mm. This study confirms that in dry hard turning of this nickel superalloy and for all cutting conditions tested, the major force is the thrust force and the roughness criteria found are close to those obtained in grinding.

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References:

[1] Yubo Liu[1,2,a] and Yongde Zhang[1,b]. 'Research on the wear mechanism of Ceramic Tool in Turning of Nickel-Based Superalloy GH4169' *International Journal of Control and Automation* Vol.7, No. 12(2014), pp. 407-414.

[2] Christian Hortig*, Bob Svendsen. 'Simulation of chip formation during high-speed cutting'. *Journal of Material Processing Technology* 186 (2007) 66-76.

[3] Li Qian*, Mohammad Robiul Hossan. 'Effect on cutting force in turning hardened tool steels with cubic boron nitride inserts'. *Journal of Materials Processing Technology,* 191 (2007) 274-278

[4] B. Fnides, H. Aouici, M. A. Yallese. 'Cutting forces and surface roughness in hard turning of hot work steel X38CrMoV5-1 using mixed ceramic'. ISSN 1392 - 1207. *MECHANIKA*. 2008. Nr2 (70).

[5] Firat Kafkas. ‘An Experimental Study on Cutting Forces in the Threading and the Side Cut Turning With Coated and Uncoated Grades’. *J. Manuf. Sci. Eng* 132(4), 041012 (Jul 23, 2010) (7 pages)doi:10.1115/1.4001867.

[6] Sita Rama Raju K, Rajesh S, Rama Murty Raju P. ‘Prediction of surface roughness in turning process using soft computing techniques’. *Int. Journal of Applied Sciences and Engineering Research*, Vol. 1, No. 2, 2012 www.ijaser.com © 2012 by the authors – Licensee IJASER- Under Creative Commons License 3.0 editorial@ijaser.com Research article.

[7] Cutting Force. Measurement Precise Measuring Systems for Machining. *www.kistler.com*

[8] Rodrigues L.L.R.1, Kantharaj A.N.1, Kantharaj B.2, Freitas W. R. C.2 and Murthy B.R.N.1. ‘Effect of Cutting Parameters on Surface Roughness and Cutting Force in Turning Mild Steel’. *Research Journal of Recent Sciences.* ISSN 2277-2502. Vol 1(10), 19-26, October (2012).

[9] Angela Dean Daniel Voss. ‘Design and Analysis of Experiments’. *Springer* – New York 1999.

[10] Uddipta Gautam1, Sanghamitra Das2*, D.K.Sarma3. ‘Prediction of Surface Roughness on dry turning using two different cutting tool nose radius’ *5th International & 26th All India Manufacturing Technology, Design and Research Conference* (AIMTDR 2014) December 12th–14th, 2014, IIT Guwahati, Assam, India.

[11] Manish Vishwakarma1*, Vishal Parashar1, V.K.Khare1. ‘Optimization and Regression Analysis of Surface Roughness for Electric Discharge Machining of EN-19 Alloy steel using Tungsten Copper Electrode’. *International Journal of Engineering Research and Applications* (IJERA) ISSN: 2248-9622 www.ijera.com Vol. 2, Issue 6, November-December 2012, pp.785-792.

[12] S.Gajanana, L .Shiva Rama Krishna, Srinivasa Rao Nandam, B.K Mohan, (2012),Optimization of process parameters of end milling process using factorial DoE, *Manufacturing Technology Today*,pp.5-13.

[13] Mohd. Suhail Ansari1 Deepak Sharma2 and Sagar Nikam3. ‘Study of Cutting Forces and Surface Roughness in Turning of Bronze Filled Polytetrafluoroethylene’. *International Journal of Advanced Mechanical Engineering.* ISSN 2250-3234 Volume 4, Number 2 (2014), pp. 151-160

[14] Dwivedi, Ankur; Das, Debasish. ‘Application of Taguchi Philosophy for Optimization of Design Parameters in a Rectangular Enclosure with Triangular Fin Array’. *NASA Astrophysics Data System* (ADS) 2015-10-01

[15] Ana Paula Barbosa Rodrigues de Freitas1, *, Leandro Valim de Freitas1, 2, Carla Cristina Almeida Loures1, Lúcio Gualiato Gonçalves1, Messias Borges Silva1, 3. ‘Response surface

method and Taguchi Orthogonal Array applied to phenolic wastewater by advanced oxidation process (AOP)'. *American Journal of Theoretical and Applied Statistics* 2014; 3(6-1): 35-41 Published online December 30, 2014 (http://www.sciencepublishinggroup.com/j/ajtas) doi: 10.11648/j.ajtas.s.2014030601.14 ISSN: 2326-8999 (Print); ISSN: 2326-9006 (Online)

[16] AUDY J. 'An appraisal of techniques and equipment for cutting force measurement*'. *Journal of Zhejiang University* SCIENCE A ISSN 1009-3095 (Print); ISSN 1862-1775.

[17] 1Rajendra Singh (Asso.Prof.), 2Rahul kr.Gupta (Asst. Prof.), 3 Jitendra Kr. Tripathi (AP). "Surface Roughness Analysis And Compare Prediction And Experimental Value For Cylindrical Stainless Steel Pipe (Ss 316l) In CNC Lathe Turning Process Using ANN Method For Optimization And Cutting Fluid". *The International Journal Of Engineering And Science* (IJES) || Volume || 3 || Issue || 7 || Pages || PP-58-71 || 2014 || ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

[18] Mohd Fadzil Faisae Ab. Rashid. 'An Improved Mathematical Model to Predict Surface Roughness Using Hybrid Method'. *International Journal of Materials, Mechanics and Manufacturing*, Vol. 3, No. 1, February 2015.

[19] M.A. Kamely, S.M. Kamil, and C.W. Chong. 'Mathematical Modeling of Surface Roughness in Surface Grinding Operation'. *World Academy of Science, Engineering and Technology International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering* Vol: 5, No: 8, 2011

[20] Jithin Babu.R1, A.Ramesh Babu2. 'Correlation among the cutting parameters, Surface Roughness and Cutting Forces in turning process by experimental studies'. *5th International & 26th All India Manufacturing Technology, Design and Research Conference* (AIMTDR 2014) December 12th–14th, 2014, IIT Guwahati, Assam, India.