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Cutting Parameters Effects On Cutting Force and Surface Roughness In Hard Turning Of AISI 52100 Steel With CBN Tool

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Abstract- In the present study, an attempt has been made to investigate the effect of cutting parameters (cutting speed, feed and depth of cut) on the performance characteristics (cutting force and surface roughness) in finish hard turning of AISI 52100 bearing steel with CBN tool. The combined effects of the process parameters on two performance characteristics are investigated employing Taguchi's L_9 orthogonal array and analysis of variance (ANOVA). The results show that feed rate and cutting speed strongly influence surface roughness. However, the depth of cut is the principal factor affecting cutting force, followed by feed. The experimental data were further analyzed to predict the optimal range of cutting force and surface roughness and to correlate between cutting parameters and performance characteristics using multiple linear regression analysis.
Keywords: AISI 52100 steel, CBN tool, cutting force, surface roughness, ANOVA.

I. INTRODUCTION

In recent past, hard turning of steel parts that are often hardened above 46 HRC became very popular technique in manufacturing of gears, shafts, bearings, cams, forgings, dies and molds. In order to withstand the very high mechanical and thermal loads of the work piece and cutting materials with improved performances, such as ultrafine grain cemented carbides, cermet's, ceramics, cubic boron nitrides (CBN), polycrystalline cubic boron nitride (PCBN) and polycrystalline diamonds, have been developed and applied [1, 2]. Hard turning is a developing technology that offers many potential benefits compared to grinding, which remains the standard finishing process for critical hardened steel surfaces [2, 3]. Some decisive factors leading to this manufacturing trend are: substantial reduction of manufacturing costs, decrease of production time, achievement of comparable surface finish and reduction or elimination of environmentally harmful cooling media [4, 5].

Machined surface characteristics are important in determining the functional performance such as fatigue strength, corrosion resistance and tribological properties of machined components. The quality of surfaces of machined components is determined by the surface finish and integrity obtained after machining. High surface roughness values, hence poor surface finish, decrease the fatigue life of machined components. It is therefore clear that control of the machined surface is essential [6] and it can be achieved, among other factors, by the evaluation of the cutting forces. Indeed, the study of cutting forces is critically important in turning operations because cutting forces correlate strongly with cutting performance such as surface accuracy, tool wear, tool breakage, cutting temperature self-excited and forced vibrations, etc. Knowledge of the cutting forces is needed for estimation of power requirements and for the design of machine tool elements, tool holders and fixtures, adequately rigid and free from vibration. In turning, there are many factors affecting the cutting process behavior such as tool variables, work piece variables and cutting conditions. Tool variables consist of tool material, cutting edge geometry (clearance angle, cutting edge inclination angle, nose radius, and rake angle), tool vibration, etc., while workpiece variables comprise material, mechanical properties (hardness), chemicals and physical properties, etc. Furthermore, cutting conditions include cutting speed, feed rate and depth of cut. The selection of optimal process parameters is usually a difficult work, however, is a very important issue for the machining process control in order to achieve improved product quality, high productivity and low cost. The optimization techniques of machining parameters through experimental methods and mathematical and statistical models have grown substantially over time to achieve a common goal of improving higher machining process efficiency.

Several authors have made to optimize and investigated the effects of different parameters affecting cutting forces, surface roughness, tool wear in hard turning of various grade of steels using CBN tools. Benga and Abrao [7] investigated the effect of speed and feed rate on surface roughness and tool life using three-level factorial design (3^2) on machining of hardened 100Cr6 bearing steel (62–64 HRC) using ceramic and CBN tools. They found that feed rate is the most significant factor affecting surface

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finish and cutting speed has very little influence on surface finish for both ceramic and CBN cutting tool. Sahin and Motorcu [8] indicated that the feed rate was found out to be dominant factor on the surface roughness, but it decreased with decreasing cutting speed, feed rate, and depth of cut in turning AISI 1050 hardened steels by CBN cutting tool. The RSM predicted and experimental surface roughness values were found to be very close. Likewise, the effects of machining parameters (i.e. cutting speed, feed rate and depth of cut) on surface roughness and cutting forces during machining of AISI 52100 steel with CBN tool were investigated by Bouacha et al. [9] using three level factorial design (3^3). Results showed how much surface roughness is mainly influenced by feed rate and cutting speed and the depth of cut exhibited maximum effect on the cutting forces. Aouici et al. [10] investigated the effects of cutting speed, feed rate, workpiece hardness and depth of cut on surface roughness and cutting force components in hard turning. AISI H11 steel, hardened to 40, 45 and 50 HRC respectively, was machined using cubic boron nitride tools. Results showed that the cutting force components were influenced principally by depth of cut and workpiece hardness; however, both feed rate and workpiece hardness had statistical significance on surface roughness. Chavoshi and Tajdari [11] modelled the surface roughness in hard turning operation of AISI 4140 using regression analysis and artificial neural network. They concluded that hardness had a significant effect on the surface roughness and with the increase of hardness until 55 HRC, the surface roughness decreased; afterwards surface roughness represented the larger values increasingly. The studied range of spindle speed has a partial effect on the surface roughness. Ozel et al. [12] conducted a set of analysis of variance (ANOVA) and performed a detailed experimental investigation on the surface roughness and cutting forces in the finish hard turning of AISI H13 steel. Their results indicated that the effects of workpiece hardness, cutting edge geometry, feed rate and cutting speed on surface roughness are statistically significant. They reported that especially, small edge radius and lower workpiece hardness increased surface roughness in their experiments. Kishawy and Elbestawi [13] investigated the surface integrity of AISI D2 steel of 62 HRC machined using PCBN tools under high speed conditions. They used cutting speeds, feeds, depth of cut and tools with edge preparations, sharp, chamfered and honed. Their results showed that, surface roughness increased with increase in tool wear and this was attributed to material side flow. In addition, defects such as micro-cracks and cavities were observed on the machined surface which was found to depend on the cutting speed and feed used. Their study of machined surface structure revealed a thermally affected white layer formed due to phase transformation when machined with chamfered or worn tools but not with sharp tools. The unfavorable residual stresses were minimized at high cutting speed and high depth of cut.

In the present study, an attempt has been made to investigate the effect of cutting parameters (cutting speed, feed and depth of cut) on the performance characteristics (surface roughness and cutting force) in finish hard turning of AISI 52100 bearing steel hardened at 60HRC with CBN tool. In this research, a L_9 Taguchi standard orthogonal array is adopted as the experimental design. The combined effects of the cutting parameters on performance characteristics are investigated while employing the analysis of variance (ANOVA). The relationship between cutting parameters and performance characteristics through the multiple linear regression analysis are developed.

II. EXPERIMENTAL PROCEDURE

The working ranges of the parameters for subsequent design of experiment, based on Taguchi's L_9 (3^3) orthogonal array (OA) design have been selected. In the present experimental study, cutting speed (v), feed (f) and depth of cut (d) have been considered as cutting parameters. The identified parameters and their associated levels are given in Table 1. According to Taguchi quality design concept, for three levels and three parameters, nine experiments are to be performed and hence L_9 orthogonal array was selected as shown in Table 2.

TABLE I
CUTTING PARAMETERS AND THEIR LEVELS

Parameters	**Symbol**	**Unit**	**Levels**		
			1	2	3
Cutting speed	v	m/min	100	140	200
Feed rate	f	mm/rev	0.08	0.12	0.16
Depth of cut	d	mm	0.2	0.4	0.6

The experiments were realized in dry straight turning operation using lathe type SN 40 with 6.6 kW spindle power and AISI 52100 bearing steel as workpiece material with round bars form (41 mm diameter and 300 mm length) and with the following chemical composition: 1.05% C; 1.41% Cr; 0.38% Mn; 0.21% Si; 0.02% Mo; 0.03% Al; 0.28% Cu; 0.02% P; 0.02% Sn; 0.21% Ni and 0.01% V. After quenching treatment at 850°C followed by tempering at 250°C, an average workpiece hardness of 60 HRC was obtained. A hole was drilled on the face of the workpiece to allow is to be supported at the tailstock, shown in Figure 1 and cleaned by removing a 1.0 mm depth of cut from the outside surface of the workpiece, prior to the actual machining. The coated CBN tool employed is the CBN7020 from Sandvik Company, it's grade is a low CBN content material with a ceramic phase added (TiN). The insert ISO designation is SNGA 120408 T01020. It was clamped onto a tool holder (ISO designation PSBNR2525K12). Combination of the insert and the tool holder resulted in negative rake angle γ = -6°, clearance angle α = 6°, negative cutting edge inclination angle λ = -6° and cutting edge angle χ_r = 75°. Tool wear follow-up was achieved by using an optical Hund (WAD) microscope. A Kistler 9257B force dynamometer was used to measure cutting forces in three mutually perpendicular directions. The surface roughness criteria measurements (arithmetic average roughness Ra) for each cutting condition were obtained from a Surftest 301 Mitutoyo roughness tester.

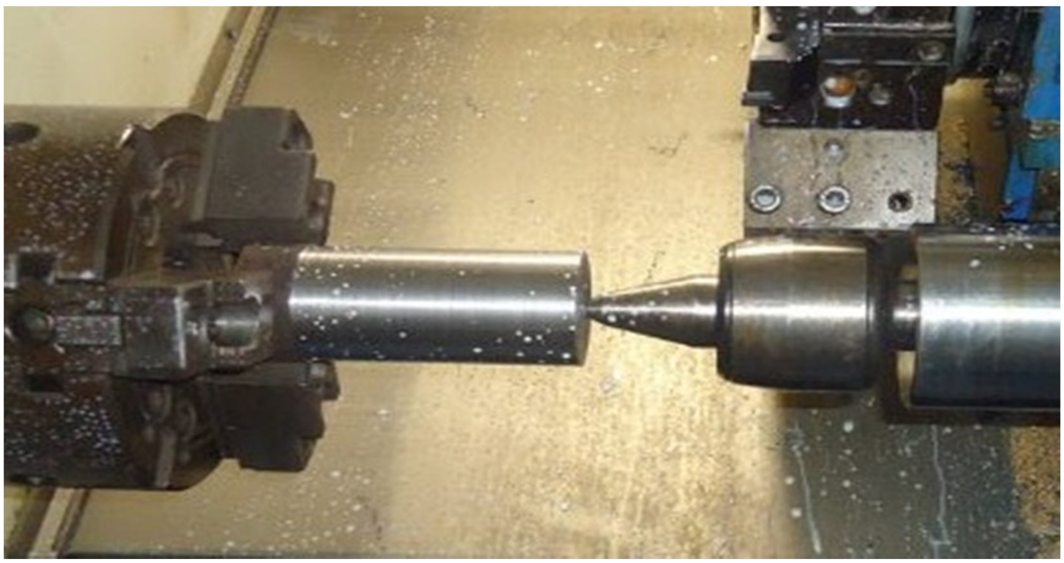

Figure 1 View of cutting zone

TABLE II
ORTHOGONAL ARRAY L_9 OF TAGUCHI EXPERIMENT DESIGN AND EXPERIMENTAL RESULTS

Run	Cutting parameters and levels			Experimental results	
	v	f	d	Fc (N)	Ra (µm)
1	100	0.08	0.2	107.535	0.60
2	100	0.12	0.4	146.475	0.89
3	100	0.16	0.4	199.566	1.00
4	140	0.08	0.4	118.908	0.56
5	140	0.12	0.4	135.487	0.67
6	140	0.16	0.2	113.417	0.88
7	200	0.08	0.6	167.314	0.53
8	200	0.12	0.2	82.62	0.65
9	200	0.16	0.4	161.842	0.75

III. RESULTS AND DISCUSSION

A. *Cutting force and surface roughness analysis*

The experimental results from Table 2 were analyzed with analysis of variance (ANOVA), which used for identifying the factors significantly affecting the performance characteristics (cutting force and surface roughness) are shown in Table 3. This analysis was carried out for significance level of α = 0.1, i.e. for a confidence level of 90%. The sources with a P-value less than 0.1 are

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Volume 3 Issue III, March 2015
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International Journal for Research in Applied Science & Engineering Technology (IJRASET)

considered to have a statistically significant contribution to the performance measures. The last column of the tables shows the percent contribution of significant source of the total variation and indicating the degree of influence on the result.

TABLE III
ANALYSIS OF VARIANCE FOR CUTTING FORCE (FC) AND SURFACE ROUGHNESS (Ra)

Source	**DOF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P-value**	**C (%)**
(a) Analysis of variance for cutting force (Fc)							
v	2	1226.2	1511.8	755.9	6.07	0.142	11.96
f	2	2175.2	2758.6	1379.3	11.07	0.083	21.22
d	2	6600.9	6600.9	3300.4	26.48	0.036	64.39
Error	2	249.3	249.3	124.6			2.43
Total	8	10251.5					100
		S= 11.1637	R-Sq= 97.57%		R-Sq(adj)= 90.27%		
(b) Analysis of variance for surface roughness (Ra)							
v	2	0.054489	0.056069	0.028035	6.04	0.142	25.11
f	2	0.147822	0.128166	0.064083	13.82	0.067	68.12
d	2	0.005435	0.005435	0.002717	0.59	0.631	2.50
Error	2	0.009276	0.009276	0.004638			4.27
Total	8	0.217022					100
		S= 0.0681036	R-Sq= 95.73%		R-Sq(adj)= 82.90%		

The most significant factor on the cutting force is depth of cut (d) which explain until a 64.39% contribution of the total variability (Table 3(a)). The next largest contribution on cutting force comes from the feed rate with the contribution 21.22%, whereas cutting speed accounts for 11.96% of the total variability. This indicates that cutting speed has little influence on cutting force. The main effect plots for cutting force in Figure 2 indicates that, cutting force (Fc) increases with the feed rate and depth of cut, on the other hand, the cutting speed has decreasing control on cutting force. This can be explained as feed and depth of cut increase, the tool-chip interface area increases which lead to increase in cutting force. However, the increase in cutting speed leads to high cutting temperature, particularly, in the shear zone and hence softening of the workpiece material (reduction of the yield strength of the work material), reducing of chip thickness and tool chip contact length and as a result, the cutting force shows a decreasing trend [14].

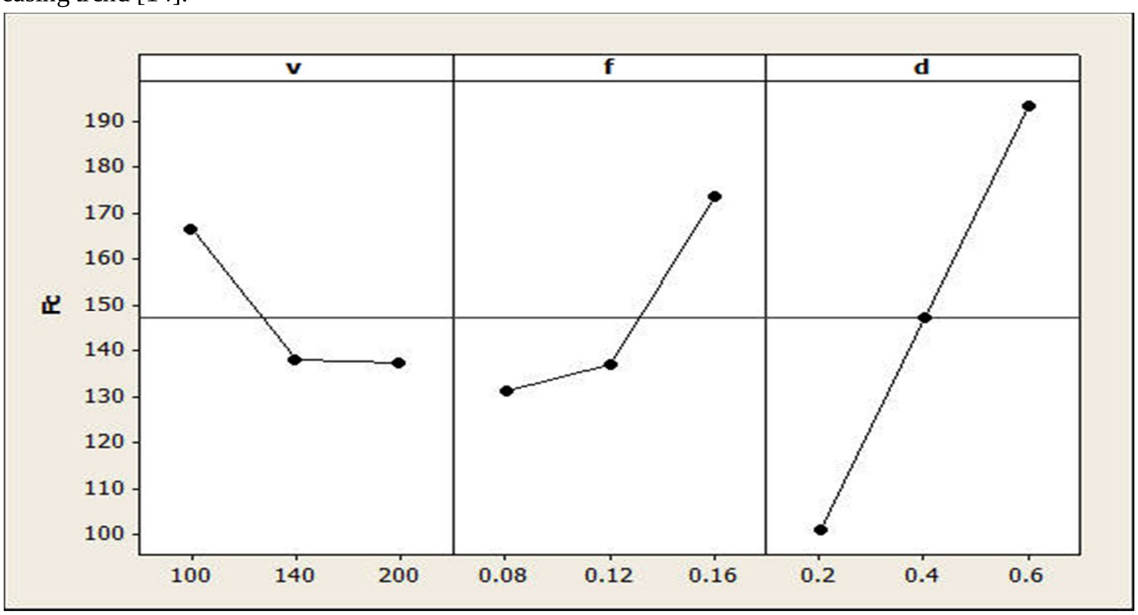

Figure 2 Main effects plot for cutting force (Fc)

Volume 3 Issue III, March 2015
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International Journal for Research in Applied Science & Engineering Technology (IJRASET)

From Table 3(b) it can be seen that the feed was found to be only significant factor on arithmetic average surface roughness (Ra) with percent contribution of 68.12%, followed by cutting speed which contributed 25.11%. In Figure 3 the main effects for average surface roughness (Ra) are plotted. Increasing of feed rate and decreasing of cutting speed lead to increase surface roughness. Specifically, the roughness increases as the feed rate increases as the theoretical geometrical surface roughness being proportional to the square of the feed rate. Moreover, the decrease in surface roughness with increasing cutting speed can be explained in terms of BUE (built-up-edge) formation observed on the tools used at low cutting speeds. At high speeds, BUE formation is eliminated and as a result, the surface finish is improved [15]. For the depth of cut (d), influence value is that smallest and it has much lower levels of contribution 2.5%. However, low depth of cut should be used in order to reduce the tendency to chatter. For all machining tests, the Ra values observed were in the range of 0.53-1.00 µm, indicating that CBN tool is able to produce parts with surfaces equivalent to those resulting from grinding and other finishing processes.

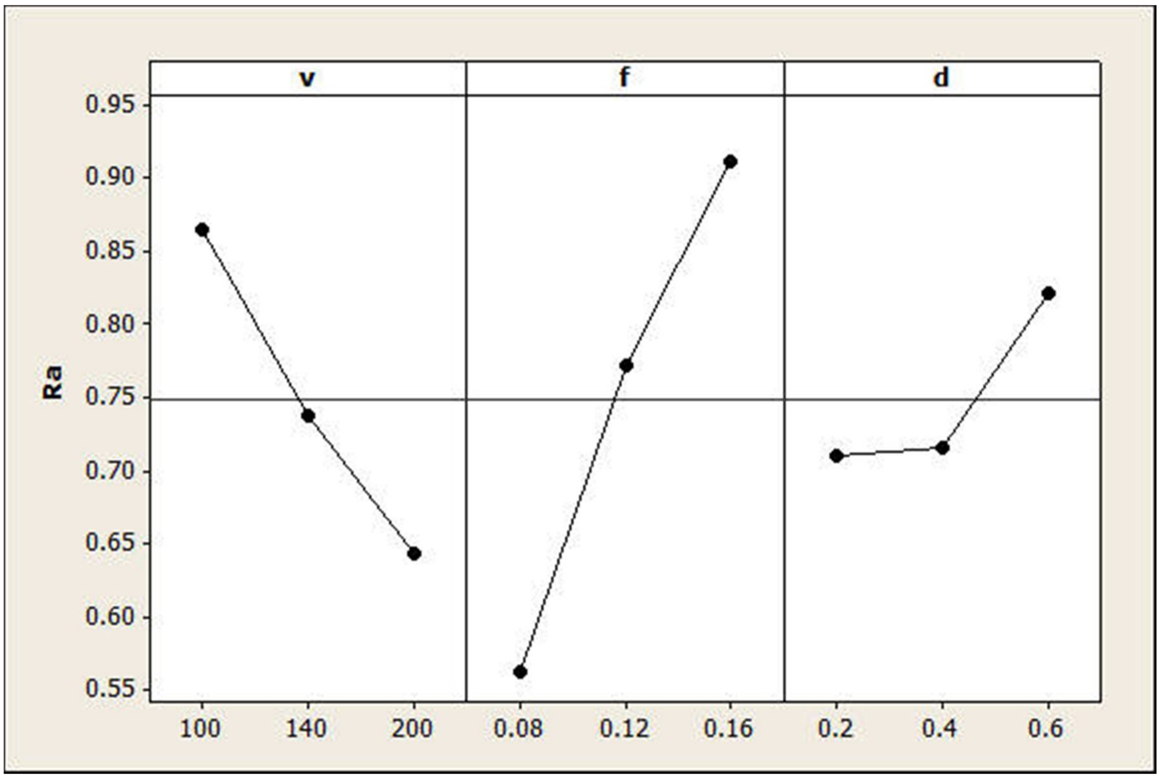

Figure 3 Main effects plot for surface roughness (Ra)

B. Prediction of optimal design

The plots of the significant parameters shown in Figyre 2 can be used to estimate the mean cutting force with optimal design conditions. Since there are two significant parameters in this experiment, plots were used to establish their most useful levels to give a smaller Fc value. Feed rate when set at 0.12 mm/rev (level-2) and depth of cut when set at 0.2 mm (level-1) gave the minimum cutting force value. The procedure of estimating the mean value depends upon the additivity of the factorial effects. If one factorial effect can be added to another to accuracy predicts the result and then good additivity exists.

When cutting force (Fc) is considered, from Table 7, an estimated average when the two most significant parameters are at their better level is

$\mu_{F_c} = \bar{f}_2 + \bar{d}_1 - \bar{T}_{F_c}$ (from Table 2, $\bar{T}_{F_c} = 137.02$)

$= (121.5 + 101.2) - 137.02 = 85.68$

The 90% confidence interval for the cutting force (Fc) can be computed using the following equation [16];

$$CI = \sqrt{\frac{F_{90\%;(1,\text{DOF error})} \times V_{\text{error}}}{\eta_{\text{eff}}}}$$

Where $\eta_{\text{eff}} = \frac{N}{1 + \text{DOF associated to that level}} = \frac{9}{1+2+2} = 1.8$

Volume 3 Issue III, March 2015
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

$F_{90\%;(1,2)} = 8.53$ and $V_{error} = 124.6$ (from Table 3(a))

Thus, CI $= \sqrt{\frac{8.53 \times 124.6}{1.8}} = 24.3$

Finally, the estimated average with the confidence interval at 90% confidence (when the two most significant factors are at their better level) is $[\mu_{F_c} - CI] \le \mu_{F_c} \le [\mu_{F_c} + CI]$ i.e.

$(85.68-24.3) \le \mu_{F_c} \le (85.68+24.3)$

$61.38 \le \mu_{F_c} \le 109.98$ N

The values of the significant factors for surface roughness (Ra) is given in the Figure 3 and Table 3(a) can be used to estimate the mean surface roughness with optimal performance conditions. Only one factor was found to be significant in ANOVA that is feed rate, which gave the smallest roughness value. When surface roughness Ra is considered, from Table 4, an estimated average when the one most significant factor is at their better level is at f_1 level. The estimated mean of the surface roughness (Ra) can be computed as [16]:

$\mu_{R_a} = \bar{f}_1 = 0.563$

$\eta_{eff} = 1.8$, $F_{90\%(1,2)} = 8.53$ and $V_{error} = 0.004638$ (from Table 3(b))

Thus, the 90% confidence interval for the surface roughness (Ra) is

CI $= \sqrt{\frac{8.53 \times 0.004638}{1.8}} = 0.148$

Finally, the estimated average with the confidence interval at 90% confidence is $[\mu_{R_a} - CI] \le \mu_{R_a} \le [\mu_{R_a} + CI]$ i.e. $(0.563-0.148) \le \mu_{R_a} \le (0.563+0.148)$

$0.415 \le \mu_{R_a} \le 0.711$ µm

TABLE IV MEAN VALUES FOR EACH PARAMETER AT EACH LEVEL FOR CUTTING FORCE AND SURFACE ROUGHNESS

Level	Cutting force (Fc)			Surface roughness Ra (µm)		
	$\bar{v}$	$\bar{f}$	$\bar{d}$	$\bar{v}$	$\bar{f}$	$\bar{d}$
1	151.2	131.3	**101.2**	0.8300	**0.5633**	0.7100
2	122.6	**121.5**	152.5	0.7033	0.7367	0.7740
3	137.3	158.3	167.3	0.6433	0.8767	0.5300
Delta	28.6	36.7	66.1	0.1867	0.3133	0.2440
Rank	3	2	1	3	1	2

Bold values indicate the levels of significant parameters for which the best result obtained and the optimal design is calculated.

C. Correlation

The correlations between the factors (cutting speed, feed and depth of cut) and the performance characteristics (cutting force and surface roughness) were obtained by multiple linear regression. The obtained models were as follows:

Fc = 26.0 – 0.281v + 542f + 245d (R^2 = 87.6%)……………….…..(1)

Ra = 0.462 – 0.00191v + 4.05f + 0.162d (R^2 = 92.1%) …………………..(2)

Inspection of some diagnostic plots of the model was done to test the statistical validity of the models. The Anderson-Darling test and normal probability plots of the residuals versus the predicted response for the cutting force (Fc) and surface roughness (Ra) are plotted in Figure 4. The data closely follows the straight line. The null hypothesis is that the data distribution law is normal and the alternative hypothesis is that it is non-normal. Using the P-value which is greater than alpha of 0.1 (level of significance), the null hypothesis cannot be rejected (i.e., the data follow a normal distribution). It implies that the models proposed are adequate. Furthermore, the effectiveness of model has been performed using coefficient of determination (R^2 value). When R^2 approaches to unity, the response model fits the actual data effectively. The model presented high determination coefficient explaining 87% and 92% of the variability in the response (Fc and Ra) which indicates that the models proposed are adequate and highly significant.

Volume 3 Issue III, March 2015
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

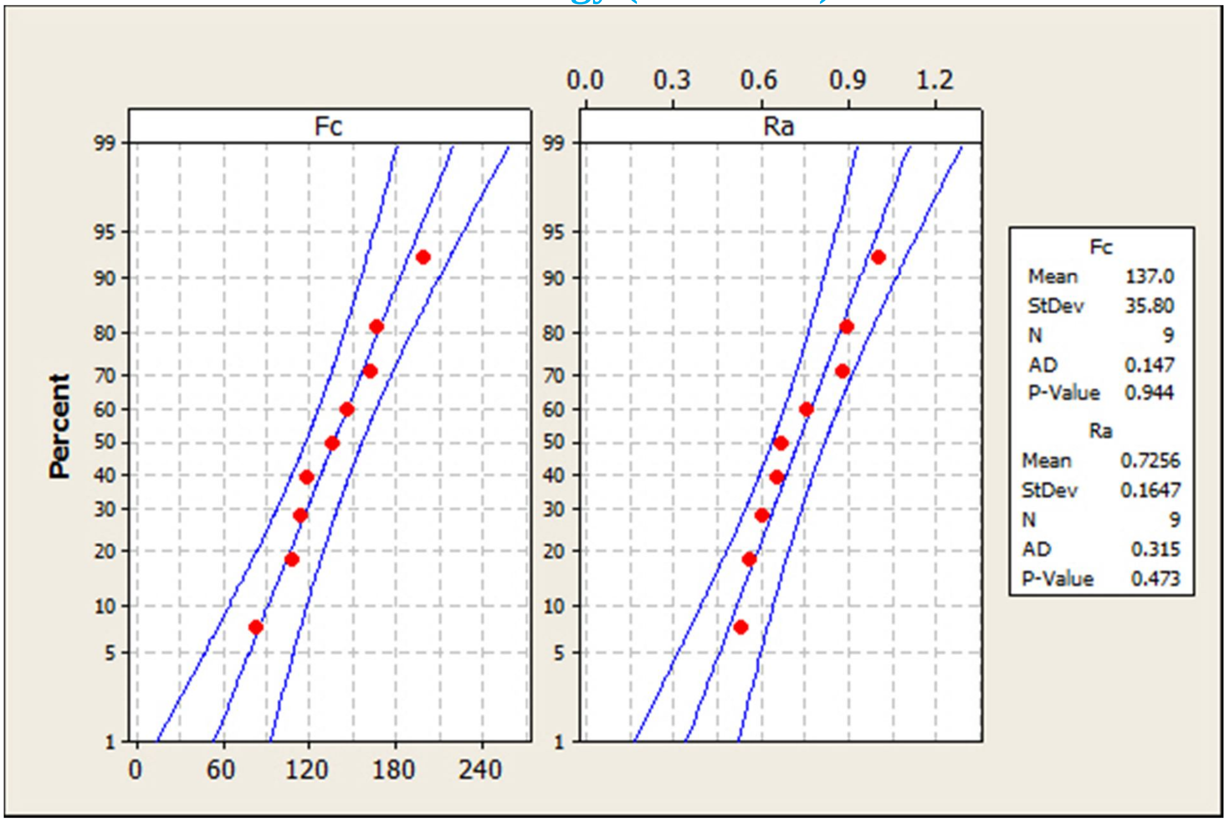

Figure 4 Normal probability plots of cutting force (Fc) and surface roughness (Ra)

IV. CONCLUSIONS

A. Cutting force shows an increasing trend with the increase in feed rate and depth of cut on the other hand they show a decreasing trend with cutting speed. The depth of cut exhibits maximum influence on cutting force (Fc) compared to the feed rate (21.22%) and cutting speed (11.96%).

B. The surface roughness is highly affected by feed rate, which explains until 68.12% of the total variation, where increasing feed rate will increase the surface roughness values. The cutting speed has a negative effect (25.11%), whereas the effect of depth of cut is negligible (2.5%).

C. This study confirms that in dry hard turning of AISI 52100 steel and for all cutting conditions tested, the found roughness criteria are close to those obtained in grinding (Ra < 1.00 µm).

D. The 90% confidence interval of the predicted optimal cutting force and surface roughness are $61.38 \leq \mu_{F_c} \leq 109.98$ N and $0.415 \leq \mu_{R_a} \leq 0.711$ µm respectively.

E. The relationship between cutting parameters (cutting speed, feed and depth of cut) and the performance measures (cutting force and surface roughness) are expressed by multiple linear regression equation which can be used to estimate the expressed values of the performance level for any parameter levels.

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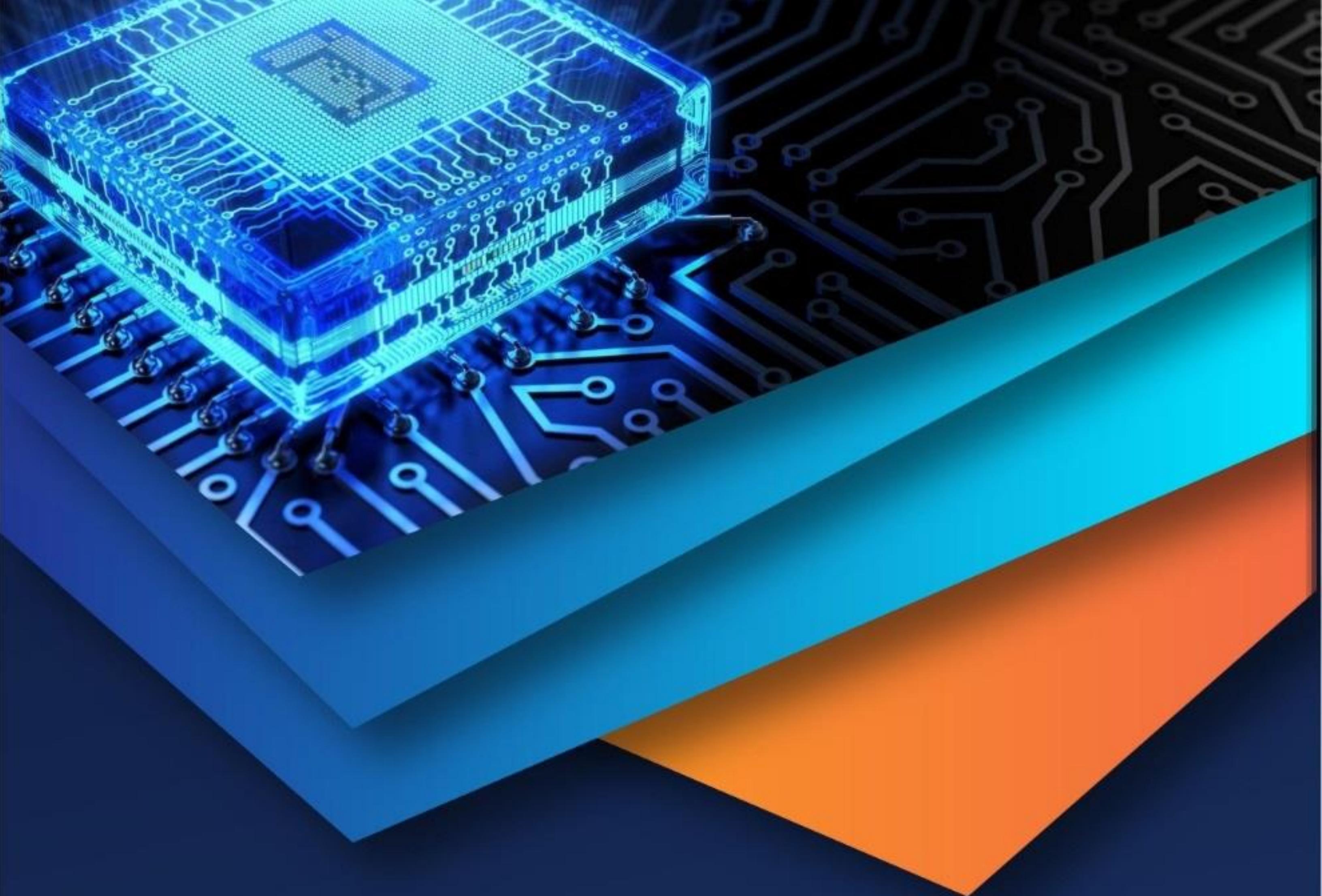

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