

Investigation of Optimal Parametric Combination for Minimum Cutting Force in Turning: Response Surface Methodology Approach

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This paper presents results of experiments towards investigating the influence of cutting conditions on cutting force during turning of low carbon steel. In this study, the 3^k factorial design of experiment and response surface methodology, a powerful tool, is used to optimize the process parameters for effective turning. Analysis of variance (ANOVA) is employed to investigate the relative influence of cutting speed, feed and depth of cut on the cutting force & feed force respectively. The main effect plot of cutting speed, feed & depth of cut and interaction plot for feed & depth of cut on cutting force are analyzed through various graphical representations. It is observed that feed (P = 74.4%) is the most significant variable affecting cutting force followed by depth of cut (P = 15.9%) and cutting speed (P = 5%). The interaction of feed and depth of cut is the next significant factor influencing on the cutting force and other interaction of vxf and vxt are neglected being very small. The optimal parametric combination for minimum cutting force is as follows: Cutting speed at level +1 i.e 45m/min, Feed at level -1 i.e 0.05mm/rev and depth of cut at level -1 i.e 0.4mm respectively. RSM model proposed is adequate and there is no reason to suspect any violation of the independence or constant variance assumption.

Keywords: cutting force, turning, DOE, ANOVA

1. INTRODUCTION:

Progress in machining is achieved by the ingenuity, logical thought and dogged worrying of many thousands of practitioners engaged in the many-sided-arts of metal cutting. The machinist operating the machine, the tool designer, the lubrication engineer, the metallurgist are all constantly probing for solutions to the challenges presented by novel materials, high costs and the needs of faster metal removal, greater precision and smoother surface finish. However competent they may be, there can be few crafts people, engineers or scientists engaged in this field who do not feel that they would be better able to solve their problems if they had a deeper knowledge of what was happening at the cutting edge of the tool.

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It is what happens in a very small volume of metal around the cutting edge that determines the performance of tools, the machinability of metals and alloys and the final qualities of the machined surface. During cutting the interface between tool and work material is largely inaccessible to observation, but indirect evidence concerning stresses, temperatures, metal flow and other interactions has been contributed by many researchers. The forces acting on the tool are important aspect of machining [1]. For those concerned with the manufacture of machine tools, knowledge of forces is needed for estimation of

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power requirements and for the design of the machine tool elements, tool holders and fixtures adequately rigid and free from vibration. The cutting forces vary with the tool angles and process parameters that include speed, feed and depth of cut and accurate measurement of forces is helpful in optimizing tool design. The component of the force acting on the rake face of the tool, normal to the cutting edge is called cutting force. This is usually the largest of the three force components and acts in the direction of the cutting velocity. The force component acting on the tool parallel with direction of feed is referred to as the feed force. This force acts tangential to the main cutting forces. The third component tends to push the tool away from the work in a radial direction, is the smallest of the force components in semi-orthogonal cutting and for the purpose of analysis of cutting forces in simple turning, it is usually ignored. Though the forces involved are lower in magnitude as compared to other metal working methods, the small areas of contact make the stresses in metal cutting among the highest of all metal processing operations.

Optimizing cutting force with respect to the process parameters that are in control of the operator has been the principal motive behind this research. The findings are expected to lead towards ‘thumb rule’ in optimizing the machining process. What should be the approximate magnitudes of cutting speed, feed and depth of cut towards obtaining minimal power consumption thus will serve as prime goal [2]. During the process of mathematical treatment of the experimental findings also will help the author single out the variables that are expected to affect the cutting force more severely than the others. Through the data analysis it will also be possible to revalidate the characteristics of cutting.

2. RESPONSE SURFACE METHODOLOGY

Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [3]. Suppose we wish to find the levels of parameters (x_1 and x_2) that maximize the yield (y) of a process. The process yield is a function of the levels of parameters, say

$$y = f(x_1, x_2) + \varepsilon \quad (1)$$

Where ε represents the noise or error observed in the response y . If we denote the expected response

by $E(y) = f(x_1, x_2) = \eta$, then the surface represented by

$\eta = f(x_1, x_2)$ is called a response surface.

In most of the RSM problems, the form of relationship between the response and the independent variable is unknown. Thus the first step in RSM is to find a suitable approximation for the true functional relationship between y and set of independent variables employed. Usually a second order model is utilized in response surface methodology.

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i < j} \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

The β coefficients, used in the above model can be calculated by means of using least square method. The response surface analysis is then performed using the fitted surface. If the fitted surface is an adequate approximation of the true response function, then analysis of the fitted surface will be approximately equivalent to analysis of the actual system. The model parameters can be estimated most effectively if proper experimental designs are used to collect the data. Designs for fitting response surfaces are called response surface designs. The second-order model is normally used when the response function is not known or nonlinear.

3. LITERATURE REVIEW:

An on-going comparatively study of wear rates and tool lives under varying cutting parameters is presented in the paper by **G. Dawsan & Kurfess [4]**, along with results indicating the abilities and limitations of the hard turning process to produce finished surfaces with acceptable roughness and integrity. Results from this study indicated that low CBN content tools were capable of machining more material before failure due to the increased bonding strength that resulted from ceramic binder materials. Increased cutting speed diminished tool life more than increased feed rates or radial depths of cut. Thus a low CBN content tool should be selected to maximize tool life while increased radial depths of cut of feed rates should be used to maximize material removal rates instead of increased cutting speed (within recommended ranges). Further investigation of a common trend in flank wear data may enable further optimization of the process.

The study by **Y. Kevin Chou & Evans & M. Barash [5]**, investigated the performance and wear behavior of different cubic Boron Nitride (CBN) tools in finish turning of hardened AISI 52100

steel. Tool performance was evaluated based on the part surface finish and the tool flanked wear.

Results of the study by **Dawson & Kurfess [6]** indicate that cutting speed than feed a more dramatic effect on tool life than feed of depth of cut. In general, increased feed rates were found to decrease tool life in minutes, but increase the amount of material removed with the tool. The crater and flank wear behavior before tool failure was also monitored throughout the life of each tool. Significant changes in cutting geometry were recorded resulting from crater wear on the chamfered cutting edge. Flank wear behavior showed a repeating trend that is being investigated further to develop the ability to confidently predict tool life over a wide range of conditions.

Tugrul et.al [7] had performed an experiment with the objective to study the effects of cutting edge geometry, work piece hardness, feed rate and cutting speed on surface roughness and resultant forces in the finish hard turning of AISI H13 steel. Especially, honed edge geometry and lower work piece surface hardness resulted in better surface roughness. Results of the study indicate that cutting edge geometry, work piece hardness and cutting speed are found to be affecting force components. The lower work piece hardness and honed edge geometry resulted in lower tangential and radial forces.

Jacob Chen [8] did the experiment with the objective of Optimizing surface finish in a turning operation using the Taguchi parameter design method. The study found that the control factors had varying effects on the response variable, with feed rate and tool nose radius having the highest effects. The noise factors, on the other hand, were found to not have a statistically noticeable effect. The measurement of the work pieces in this confirmation run led to the conclusion that the selected parameter values from this process produced a surface roughness that was much lower than the other combinations tested in this study. The use of the Taguchi parameter design technique was considered successful as an efficient method to optimize surface roughness in a turning operation.

In the paper by **Madalina calbureanu & Alexandru stanimir [9]** considerations about using the machining of hard steels in industrial processes, the machining characteristics of hardened steel are analyzed in order to show how the cutting process can be used in process sequence optimization.

This paper presents an experimental investigation of the influence of cutting conditions on cutting force during turning of low carbon steel. The factorial design of experiment and response surface

methodology, a powerful tool, is used to perform the experiment and optimize the process parameters. 3^k factorial design and analysis of variance (ANOVA) is employed to investigate the influence of cutting speed, feed and depth of cut on the cutting force & feed force respectively.

4. EXPERIMENTATION:

Turning is a widely used machining process in which a single point cutting tool removes material from the surface of a rotating cylindrical work piece. In Orthogonal cutting, the cutting is assumed as to be uniform along the cutting edge; therefore it is a two-dimensional plane strain deformation without side spreading of the material.

Basically, cutting force is strongly correlated with cutting parameters such as cutting speed, feed, and depth of cut. Proper selection of the cutting parameters can obtain minimum cutting force in turning. In order to achieve the objective of this experimental work, low carbon steel of diameter 40mm was used for experimentation. The cutting experiments were carried out on a lathe using HSS for the machining of above steel. The cutting force was measured by two-dimensional strain gauge type turning dynamometer. Cutting tools of nomenclature of 6° orthogonal rake angle, 8° clearance angle, 90° principal cutting edge angle, 0.4mm nose radius and 0° inclination angle used for orthogonal turning operation. Each w/p was first centre –drilled on one side .This was necessary in order to support the workpiece from both sides while turning on lathe and it reduces the vibration of the w/p material and minimizes any impact force on the cutting speed .The w/p was fixed to the lathe by means of chuck .A tailstock assembly was used to support the w/p centre drilled end. The work piece and the tool were attached to the lathe machine and were made ready by adjusting speed and depth of cut. The force measuring system consists of two bridge circuits for cutting and feed force components with balancing for initial zero setting of the bridge settings. The turning tool dynamometers possessed two channel digital meters to read force in kg and ten turn helical potentiometers to balance two channels. 4 pin Amphenol sockets for connecting inputs to channels. The readings for cutting force and feed force were recorded after output stabilization and have been presented for analysis.

Table 1 Machining parameters & their levels

Coded level	Cutting speed in m/min(v)	feed in mm/rev (f)	Depth of cut in mm (t)
-1	25	0.05	0.4
0	35	0.1	0.6
1	45	0.2	0.8

Table 2 Experimental results

Run	v (m/min)	f (mm/rev)	t (mm)	Pz (Kg)	Px (Kg)
1	25	0.05	0.4	11	5
2	25	0.05	0.6	12	5
3	25	0.05	0.8	16	8
4	25	0.1	0.4	15	6
5	25	0.1	0.6	18	7
6	25	0.1	0.8	25	11
7	25	0.2	0.4	25	13
8	25	0.2	0.6	30	15
9	25	0.2	0.8	39	19
10	35	0.05	0.4	10	4
11	35	0.05	0.6	11	5
12	35	0.05	0.8	14	6
13	35	0.1	0.4	14	5
14	35	0.1	0.6	16	6
15	35	0.1	0.8	24	9
16	35	0.2	0.4	23	12
17	35	0.2	0.6	28	14
18	35	0.2	0.8	32	17
19	45	0.05	0.4	8	3
20	45	0.05	0.6	10	4
21	45	0.05	0.8	12	5
22	45	0.1	0.4	14	4
23	45	0.1	0.6	15	6
24	45	0.1	0.8	19	8
25	45	0.2	0.4	21	10
26	45	0.2	0.6	25	12
27	45	0.2	0.8	28	15

5. RESULTS & DISCUSSIONS:

The plan of tests as per 3^k factorial design of experiment was developed with the aim of relating

the influence of the cutting speed (v), feed (f) and depth of cut (t) with the cutting and feed force. The statistical treatment of the data was made in two phases. The first phase was concerned with the ANOVA and the effect of the factors and interactions. The optimal parametric combination for achieving minimum cutting force has also been investigated.

5.1 Effect of cutting speed on cutting and feed force

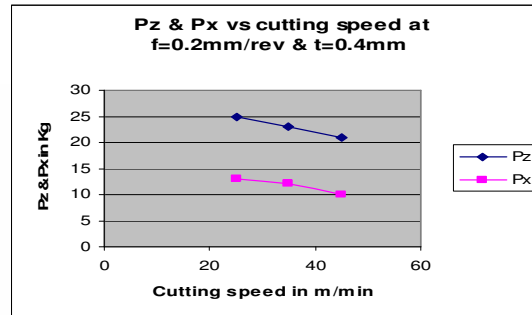


Fig. 1 Effect of cutting speed on cutting & feed force

Figure 1 shows the influence of cutting speed on the cutting and feed forces during orthogonal turning operation of mild steel workpiece. The experimental results show that the cutting force and feed force are low at high cutting speed i.e at 45m/min and comparatively high at low cutting speed i.e at 25m/min. The reason for drop of Pz with increase of cutting speed is due to the decrease in chip thickness. That means at higher speed, thinner chips are produced. It has been suggested that the drop in these forces is partly caused by decrease in contact area of flow region and partly by a drop in the shear strength in the flow zone. As cutting speed increases the chips are thinner and shear angle increases thus decreasing chip reduction coefficient and chip strains [10]. That means the plastic deformation of metal takes place with less strain because of greater shear angle, the force and power consumption being low. As cutting velocity increases, the BUE disappears and in its place a flow one is observed, deeply bonded to the tool rake face called sticking zone or seizure zone. Under sticking condition, it can no longer be assumed that relative motion takes place at the interface because the force required overcoming the interlocking and bonding is normally higher than the required to shear the adjacent layer of the metal. In this shear stress developed no more relies on the normal stress rather assumes a constant value of

shear stress at yield point. Hence coefficient of friction decreases and consequently P_z decreases.

5.2 Effect of feed and depth of cut on cutting and feed force

Figure 2&3 shows the effect of feed & depth of cut on the cutting and feed forces during orthogonal turning operation. The experimental results show that the cutting force and feed force are low at low feed i.e at 0.05mm/rev and comparatively high at high feed at 0.2mm/rev. The experimental result reveals that cutting and feed force are low at low depth of cut i.e at 0.4mm and comparatively high at high depth of cut i.e at 0.8mm. The greater the feed and depth of cut, larger the cross sectional area of the uncut chip, the volume of the deformed metal and consequently the greater is the resistance of the material to chip formation and larger is the force P_z will be in turning operation.

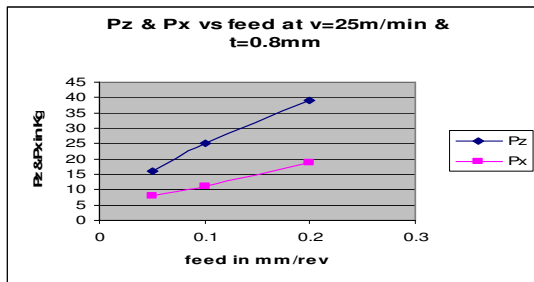


Fig. 2 Effect of feed on cutting & feed force

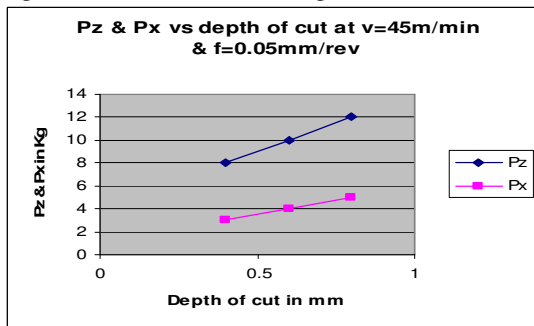


Fig. 3 Effect of depth of cut on cutting & feed force

5.3 Analysis of variance for cutting force

The purpose of the ANOVA is to investigate which of the process parameters significantly affect the performance characteristics. This analysis provides the relative contribution of machining parameters in controlling the response of machining performance criteria i.e cutting force during turning. The significance of a variable on the quality characteristic can be evaluated by using F-ratio. The F-ratio is the ratio of MS to the error. Generally, when F is greater than 3.37, it means

that the change of experimental variables has a significant effect on the quality characteristics. The ANOVA table 3 indicates that, with the exception of the v_{xf} and v_{xt} (very small value of F of 2.662 & 3.401) interaction in cutting force, all the cutting parameters and f_{xt} interaction are significant (F calculated value is more than the table value 3.37 & 2.53) at 95% confidence level. Table 3 shows that the feed ($P = 74.4\%$) is the most significant variable affecting cutting force followed by depth of cut ($P = 15.9\%$) and cutting speed ($P = 5\%$). The interaction of feed and depth of cut is the next influencing factor on the cutting force and other interaction of v_{xf} and v_{xt} are neglected being very small value of percentage of contribution which depicts the least significant effect on cutting force. Since the error refers to unknown or uncontrolled factors, the percent contribution due to error provides an estimate of the adequacy of the experiment. If the percent contribution due to error is 15% or less, then it can be assumed that no important factors have been omitted from the experiment. Percent contribution due to error in ANOVA table is less than 15%, it can be said that no important variables have been omitted from the experiment.

Table 2 Results of ANOVA

SV	SS	DF	MS	F	F (95%)	P (%)
v	84.518	2	42.259	35.128	3.15	5
f	1223.19	2	611.592	508.389	3.15	74.4
t	264.296	2	132.148	109.848	3.15	15.9
v_f	12.615	4	3.203	2.662	2.53	0.4
v_t	16.371	4	4.092	3.401	2.53	0.7
f_t	29.037	4	7.259	6.034	2.53	1.4
Error	9.629	8	1.203			2.2
Total	1639.85	26				100

5.4 Investigation of optimal parametric combination for achieving minimum cutting force in machining

To assist in the practical interpretation of this experiment, fig 4-7 presents plots of the three main effects and the feed-depth of cut interaction.

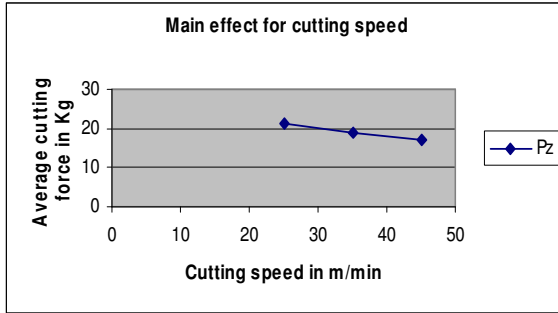


Fig-4 Main effect plot for cutting speed

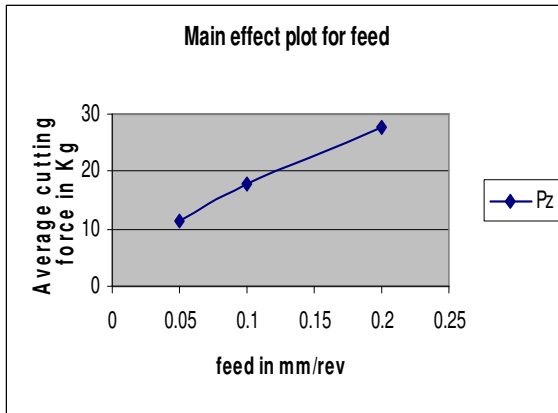


Fig-5 Main effect plot for feed

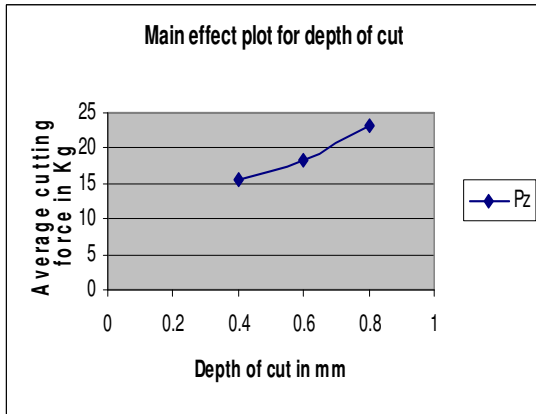


Fig-6 Main effect plot for depth of cut

The main effect plots are just graphs of the marginal response averages at the levels of the three factors. It is noticed that all the three variables have positive main effects i.e increasing the variable feed and depth of cut moves average cutting force upwards and downward for increasing cutting speed. It is evident that at low feed (level -1) and low depth of cut (level -1), the average cutting force value is small. But from main effect fig 4, it is clear that the average cutting force value decreases as

cutting speed increases i.e level +1 of cutting speed, cutting force value is small. The interaction between feed-depth of cut is fairly small, as shown by the similar shape of the curves in fig 5, 6 & 7.

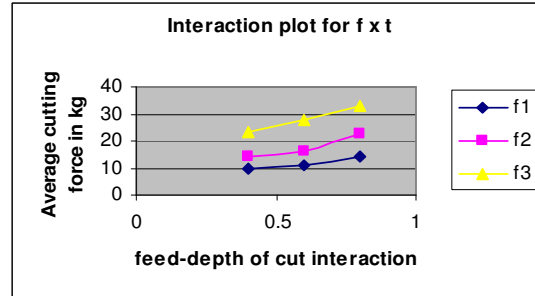


Fig-7 Interaction plot for f x t

It is observed that the combination of lowest feed i.e level -1 and the lowest depth of cut at level -1 seem most effective for minimum cutting force. As minimum cutting force is required for low power consumption in machining operation, it can be concluded from main effects and interaction plot that cutting speed at level +1, feed at level -1 and depth of cut at level -1 gives minimum cutting force in orthogonal turning of low carbon steel workpiece. Thus the optimal parametric combination for minimum cutting force is as follows:

1. Cutting speed at level +1 i.e 45m/min
2. Feed at level -1 i.e 0.05mm/rev
3. Depth of cut at level -1 i.e 0.4mm

5.5 Response surface analysis

The second order response surface representing the cutting force (Pz, Kg) can be expressed as a function of cutting parameters such as v, f and t. The relationship between the cutting force (Pz) and machining parameters has been expressed as follows:

$$Ra = \beta_0 + \beta_1 (v) + \beta_2 (f) + \beta_3 (t) + \beta_4 (v^2) + \beta_5 (f^2) + \beta_6 (t^2) + \beta_7 (vf) + \beta_8 (vt) + \beta_9 (ft) \quad (3)$$

From the observed data for cutting force, the response function has been determined in uncoded units as:

$$Pz = -1.120 + 0.297v + 140.635f - 5.625t - 0.001v^2 - 155.556 f^2 + 27.778t^2 - 1.286vf - 0.542vt + 86.905 ft$$

With R-sq = 0.98

Result of ANOVA for the response function cutting force is presented in Table 3. This analysis is

carried out for a level of significance of 5%, i.e., for a level of confidence of 95%. From the analysis of Table 3, it is apparent that, the F calculated value is greater than the F table value ($F_{0.05} = 2.49$) and hence the second order response function developed is quite adequate. The normal probability plots of residuals for cutting force is shown in fig.8. A check on the plots in fig. 8 revealed that the residuals generally fall on a straight line implying that the errors are distributed normally. Also figure shows that they have no obvious pattern and unusual structure. This implies that the RSM model proposed is adequate and there is no reason to suspect any violation of the independence or constant variance assumption.

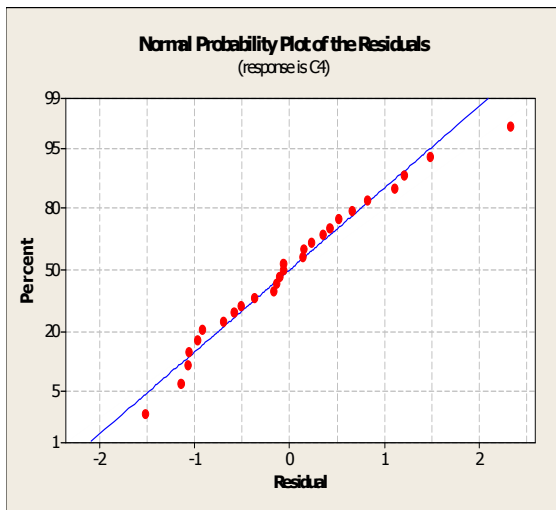


Fig. 8 Normal probability plot of residuals for cutting force data

Table 3 ANOVA table for response function of the cutting force

Source	DF	SS	MS	F-value
Regression	9	1618.8	179.8668	145.26
Residual error	17	21.05	1.2383	
Total	26	1639.85		

6. CONCLUSIONS:

Based on the performance of test results of various sets of experiments performed for analyzing the influence of different machining parameters on the cutting force in the machining of low carbon steel using HSS cutting tool, Factorial 3^k design of experiment (DOE), Analysis of variance (ANOVA), F-test values, and the following conclusions can be drawn for effective machining during turning:

1. The experimental results show that the cutting force and feed force are low at high cutting speed i.e at 45m/min and comparatively high at low cutting speed i.e at 25m/min. As cutting speed increases the chips are thinner and shear angle increases thus decreasing chip reduction coefficient and chip strains. That means the plastic deformation of metal takes place with less strain because of greater shear angle, the force and power consumption being low. At higher cutting speeds, BUE formation disappears and chip-tool contact length decreases resulting in the reduction of cutting force and improves the better surface finish of the work piece.

2. The experimental results show that the cutting force and feed force are low at low feed and depth of cut and comparatively high at high feed and high depth of cut. The greater the feed and depth of cut, larger the cross sectional area of the uncut chip, the volume of the deformed metal and consequently the greater is the resistance of the material to chip formation and larger is the force P_z will be in turning operation.

3. It can therefore concluded that higher cutting speeds produce larger shear angle and a larger cutting ratio or smaller chip reduction coefficient for which the cutting and feed forces are also low.

4. It is found that the factorial design of experiment provides a simple, systematic and efficient methodology for the ANOVA and optimization of the cutting parameters.

5. Feed ($P = 74.4\%$) is the most significant variable affecting cutting force followed by depth of cut ($P = 15.9\%$) and cutting speed ($P = 5\%$). The interaction of feed and depth of cut is the next influencing factor on the cutting force and other interaction of v_{xf} and v_{xt} are neglected being very small value of percentage of contribution which depicts the least significant effect on cutting force.

6. Thus the optimal parametric combination for minimum cutting force is as follows: Cutting speed at level +1 i.e 45m/min, Feed at level -1 i.e 0.05mm/rev and depth of cut at level -1 i.e 0.4mm respectively.

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