

## Optimization of machining parameters in turning using Design of Experiments (DOE) and Analysis of Variance (ANOVA)

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### ABSTRACT

Metal cutting process is one of the complex process which has numerous factors contributing towards the quality of the finished product. CNC turning is one among the metal cutting process in which quality of the finished product depends mainly upon the machining parameters such as feed, speed, depth of cut, type of coolant used, types of inserts used etc. Similarly the work piece material plays an important role in metal cutting process. While machining, optimized machining parameters results in good surface finish, low tool wear, etc. This study involves in identifying the optimized parameters in CNC turning. 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 mild steel using HSS cutting tool, Factorial  $3^k$  design of experiment (DOE), Analysis of variance (ANOVA), F-test values. 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.

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### Introduction:

Turning is one of the fundamental machining processes, especially for the finishing of machined parts. Usually, the selection of appropriate machining parameters is difficult and relies heavily on the operators' experience and the machining parameters tables provided by the machine-tool builder for the target material. Hence, the optimization of operating parameters is of great importance where the economy and quality of a machined part play a key role [1]. Proper selection of cutting tools, parameters, and conditions for optimal surface quality (as well as tool life) requires a more methodical approach by using experimental methods and mathematical and statistical models. Not only does this require considerable knowledge and experience to design experiments and analyze data, but traditional design-of-experiment (DOE) techniques require a large number of samples to be produced [2]. Davim [3] conducted such a study using a steel workpiece, with control parameters of spindle speed, depth of cut, and feed rate, and the response parameter being the surface roughness. Davim [4] also conducted a more elaborate study using a composite work piece;

spindle speed, feed rate, and cutting time control variables; and tool wear, spindle power, and surface roughness response variables. Among the cutting parameters affecting machining variables for steel, speed has maximum effect & depth of cut has minimum effect. Tool tip temperature increases with increase in cutting speed. At high speeds, surface finish is least affected. Surface finish deteriorates at high feed rates; hence to obtain good surface finish, feed rate may be kept low. At low speeds cutting force are high & tendency of work material to form a built up edge is also stronger. At lower speeds, surface roughness increases with increasing feed but at higher speeds surface roughness is less dependent on feed [5]. Cakir et al. [6] studied the effects of cutting parameters on the surface roughness through mathematical models developed using a series of turning experiments. Fifty-four experiments were conducted using chemical vapor deposition (CVD) and physical vapor deposition (PVD) coated tools, and the surface roughness parameter  $R_a$  on each workpiece was measured. Regression analysis using least squares method was used to develop linear, second-order, and exponential models. Choudhury and El-Baradie [7] used RSM to develop first- and second-order surface roughness

prediction equations. Each experiment was started with a new cutting tool and the surface roughness was measured using the tactile roughness tester. Arbizu and Pérez [8] used factorial design with regression techniques to develop firstorder linear and second-order polynomial models to predict surface roughness. Arola and Ramulu [9] presented a finite element model with a predefined fracture plane to predict cutting and thrust forces in the orthogonal cutting of composites. They also used a homogeneous material model, and the results of their work agreed very well with the experimental values; however, the thrust-force predictions did not comply with the experimental trend. Mkaddem et al. [10] established another finite element model to investigate the effect of fiber orientation, depth of cut, and tool rake angle on the cutting and thrust forces; and this study was only for fiber orientations less than 90°.

**Experimental set up description:**

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, mild 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 specification of cutting tool and photographs of experimental set up are shown below. The cutting force was measured by two-dimensional strain gauge type turning dynamometer. Cutting tests were carried on a 3-jaw chuck lathe machine under dry cutting environment. H.S.S cutting tools of shank size (1/2''X1/2'') procured from dealer MIRINDA. Cutting tools have been used for Orthogonal cutting on Mild steel work piece. 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 mild steel work piece and the tool was attached to the lathe machine and was made ready by adjusting speed and depth of cut. The force readings were obtained from tool dynamometer. 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 temperature cutting force and feed force were recorded after output stabilization and have been presented for analysis.

The chips were collected each time after machining for different cutting speeds, feeds and depth of cut. The chips are first cleaned and polished before measurement. The average values of thickness of these chips were measured by means of digital caliper.

**Machining parameters and their levels**

**Table: 1**

**Results and discussion:** The plan of tests as per 3<sup>k</sup> factorial design

Parameters	Level-1 (-1)	Level-2 (0)	Level-3 (+1)
Cutting speed(v) in m/min	25	35	45
Feed(f) in mm/rev	0.05	0.1	0.2
Depth of cut(t) in mm	0.4	0.6	0.8

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 and chip reduction coefficient. 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.

**Effect of cutting speed on cutting and feed force**

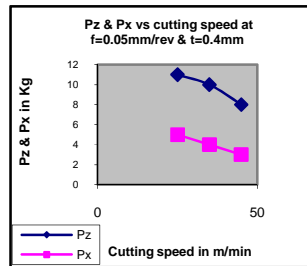


Fig: 1

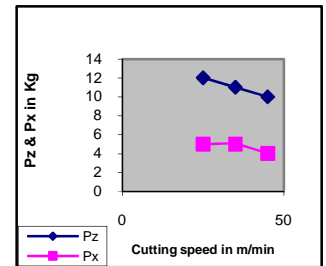


Fig: 2

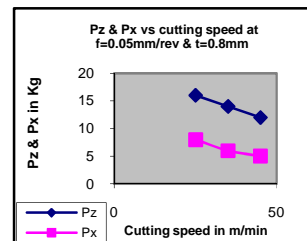


Fig: 3

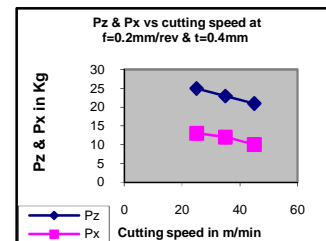


Fig: 4

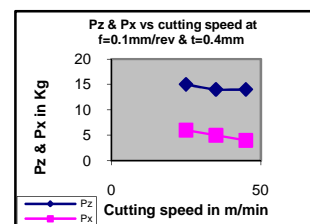


Fig: 5

Figure 1-5 shows the influence of cutting speed on the cutting and feed forces during orthogonal turning operation of mild steel work piece. 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  $P_z$  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. 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.

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

Figure6-10 shows the effect of feed on the cutting and feed forces during orthogonal turning operation of mild steel work piece. 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 effect of depth of cut on the cutting and feed force during machining is shown in fig 11-15.

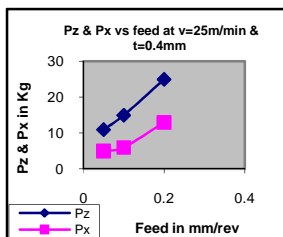


Fig: 6

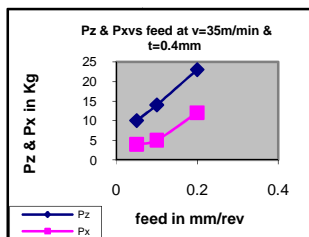


Fig: 7

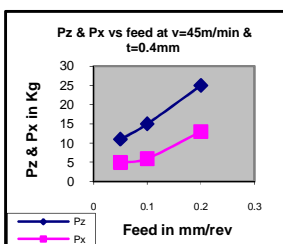


Fig: 8

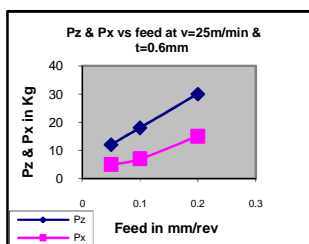


Fig: 9

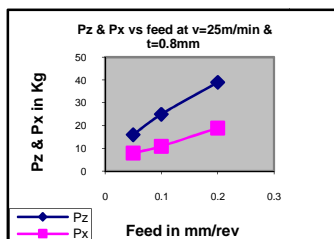


Fig: 10

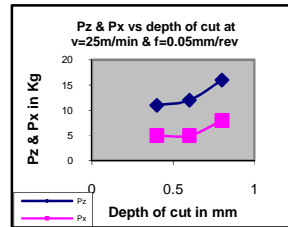


Fig: 11

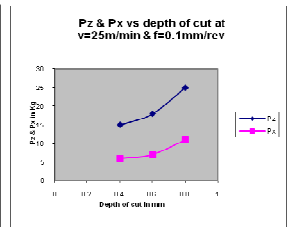


Fig: 12

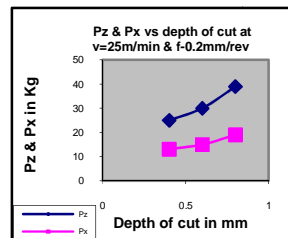


Fig: 13

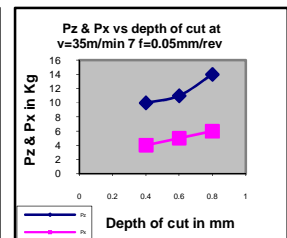


Fig: 14

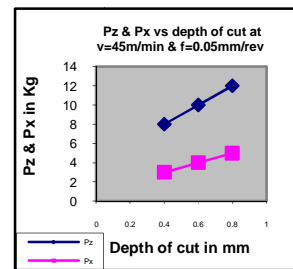


Fig: 15

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.

**Effect of cutting speed on chip reduction coefficient**

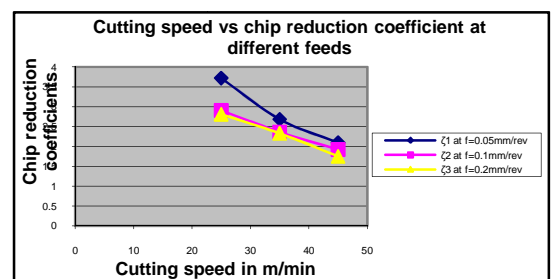


Fig: 16

The chips obtained in the tests had a uniform thickness at high cutting speeds. For low cutting speeds, the chips had a non-uniform cross-sectional area. Chips of this category were sectioned and polished and the variation in their thickness was measured by digital caliper. The average value of chip thickness was noted. The chip reduction coefficient was plotted against cutting speed for different feed as shown in fig16. The chip reduction coefficient was found to decrease with increase in cutting speed as shown in fig16. Experiment results indicate that thinner chips are produced at all higher cutting speeds. Thinner chips indicate that the deformation during the process of chip formation with greater shear angle, the energy consumption being low and decreases the kinetic coefficient of friction. 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.

**Analysis of variance for cutting force:**

**Table: 2.** Results of ANOVA for Cutting Force

SV	SS	DF	MS	F	F(95%)	P(%)
v	84.518	2	42.259	35.128	3.15	5
f	1223.2	2	611.59	508.39	3.15	74.4
t	264.3	2	132.15	109.85	3.15	15.9
vf	12.815	4	3.203	2.662	2.53	0.4
vt	16.371	4	4.092	3.401	2.53	0.7
ft	29.037	4	7.259	6.034	2.53	1.4
Error	9.629	8	1.203			2.2
Total	1639.9	26				100

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 indicates that, with the exception of the vxf and vxt (very small value of F of 2.662 & 3.401) interaction in cutting force, all the cutting parameters and fxt interaction are significant (F calculated value is more than the table value 3.37 & 2.53) at 95% confidence level. Table 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 vxf and vxt 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.

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

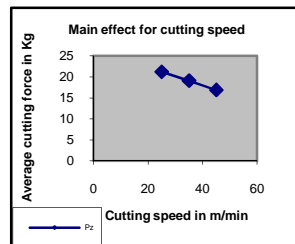


Fig-17

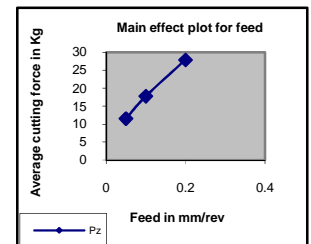


Fig-18

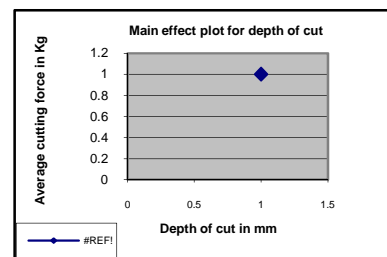


Fig-19

To assist in the practical interpretation of this experiment, fig: 17-19 presents plots of the three main effects and the feed-depth of cut interaction. 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 from main effect table 3 & that at low feed (level -1) and low depth of cut (level -1), the average cutting force value is small. But from main effect table 3, 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 two curves in fig 18-19.

It is observed from table 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 mild steel workpiece. Thus the optimal parametric combination for minimum cutting force is as follows:

Table: 3 Main effect for cutting speed	
v	Pz
25	21.22
35	19.11
45	16.88

Table: 4 Main effect for feed	
f	Pz
0.05	11.55
0.1	17.77
0.2	27.88

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

**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 mild steel using HSS cutting tool, Factorial 3<sup>k</sup> design of experiment (DOE), Analysis of variance (ANOVA), F-test values, 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 Pz 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 vxf and vxt 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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