# Effect of Cutting Parameters on Material Removal Rate and Cutting Power During Hard Turning of AISI 52100 Steel

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## Abstract

*The turning of hardened steels has been applied in many cases in production. The purpose of this research was to analyze the effect of the cutting parameters on the material removal rate, cutting power and material removal rate per cutting power during turning of AISI 52100 steel when using polycrystalline cubic boron nitride tools. Forces measured resulted in relatively low values, being the radial component the largest of all. The analysis of the result shows that the depth of cut has the greatest influence on material removal rate while cutting speed plays a dominant role in determining the cutting power and material removal rate per cutting power.*

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*Keywords;* hard turning , cutting forces, Taguchi design

## 1. Introduction

Hard turning is an emerging technology that can potentially replace many grinding operations due to improved productivity (increasing production efficiency, high speed machining), increased flexibility (increasing the range of material that can be machined), decreased capital expenses (saving in cost), and reduced environmental waste [1].In hard turning, ferrous metal parts that are hardened usually between (45-70 HRc) are machined with the single point cutting tools. This has become possible with the availability of the new cutting tool materials (cubic boron nitride (CBN) and ceramics). Since a large number of operations is required to produce the finished product, if some of the operations can be combined, or eliminated, or can be substituted by the new process, product cycle time can be reduced and productivity can be improved. The traditional method of machining hardened materials includes rough turning, heat treatment, and then grinding process.

Hard turning eliminates the series of operations required to produce a component and thereby reduces the cycle time resulting in productivity improvement [2-4].While most hard machining research thus far has focused on chip formation mechanisms and tool wear characterization, it is of great interest to study the effect of cutting conditions on chip morphology. It has been observed that the chip dimension changes as cutting conditions change [5,6]. According to results establish during hard cutting by Federico M. Aneiro et al. the radial force showed to be the highest, because the depths of cut and the feed rates selected were significantly smaller than the insert nose radius (0.8 mm). As a result, the chip sectional area was very small, which contributes to lower cutting forces [7]. The results of hard cutting, which is different from conventional cutting, indicated that in general, the radial force is the highest followed by the tangential and axial forces[8,9,10]. In hard turning, cutting forces have been found to be influenced by a number of factors such as cutting speed, feed rate and depth of cut [11]. However, there is still no systematic study of material removal rate per unit power in hard turning.

## 2. Experimental technique

### 2.1 Experimental setup

Hardened 52100 bearing steel with a hardness of 48~50 HRc was chosen for experimental studies because of its wide use in both automobile industry and research fields. The chemical compositions of the AISI52100 Steel are shown in the Table 1. Turning operations were performed dry using a ACE design Jobber computer numerical control lathe. The uncoated CBN cutting inserts (Mitsubishi, Japan) with a negative $5^0$ rake angle and a 0.8 mm nose radius were used for turning experiments.

**Table 1 Chem. composition of the work material**

| C | Cr | Mn | Si | S | P |
|---|---|---|---|---|---|
| 0.92 | 1.06 | 0.51 | 0.22 | 0.039 | 0.040 |

The geometry and grade of insert is NP-CNMA120408G (Mitsubishi). Inserts are recommended for machining hardened steel and cast iron in finish operations. It is a highly recommended cutting tool material for hardened steel machining because is suitable for high speed finishing of heat treated steel, sintered ferrous alloy and cast iron stability at elevated temperature and low affinity to iron, thus good surface finishes is possible.

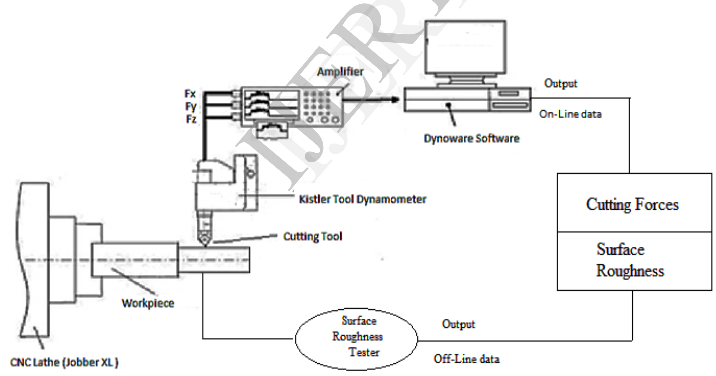


**Figure 1** Experimental set up

The tool holder used for clamping the insert is PCLNR 2525 M (Make- WIDIA). It has 95º approach angle and -6º back rake angle. The experimental set-up is shown in Figure 1.

### 2.2 Experimental Design

The experimenters were performed according to Taguchi $L_9$ orthogonal array[11,12]. Based on the experimental work, the results are presented in this paper. It consists of the assessment cutting force components in hard turning of EN 31 Steel. Table 2 presents design layout according to $L_9$ design. The statistical analysis was performed in order to determine the significant factors that have more effect on the cutting force components using MINITAB16 software. The analyzed results were presented using mean effects plots and surface plots. The results predicated by ANOVA at the 95% confidence interval. Hard turning operation involves various input variables that include cutting speed, feed rate and depth of cut. These variables have direct as well as indirect effect on the performance of hard turning process. All three levels of every factor are equally represented in 9 experiments. Since the experimental design is orthogonal, it is possible to separate out the effect of each factor at each level.

**Table 2 Design layout according to $L_9$ design**

| Expt. No. | Cutting Speed, *v* (m/min) | Feed, *f* (mm/rev) | Depth of cut, $a_p$ (mm) |
|---|---|---|---|
| 1 | 250 | 0.03 | 0.1 |
| 2 | 250 | 0.04 | 0.2 |
| 3 | 250 | 0.05 | 0.3 |
| 4 | 300 | 0.03 | 0.2 |
| 5 | 300 | 0.04 | 0.3 |
| 6 | 300 | 0.05 | 0.1 |
| 7 | 350 | 0.03 | 0.3 |
| 8 | 350 | 0.04 | 0.1 |
| 9 | 350 | 0.05 | 0.2 |

## 3. Results and Discussion

Experiments were conducted to assess the effect of cutting speed, feed rate and depth of cut on the material removal rate and material rate per unit power. All the inputs and the desired outputs were determined by using the following equations.

**Table 3 Experimental results following $L_9$ orthogonal array**

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| Expt. No. | Axial Force Fx (N) | Radial Force Fy (N) | Tangential Force Fz (N) | Resultant Force (Fr) (N) | MRR ($mm^3$/ min) | Cutting power (Kw) | MRR/ Cutting power |
|---|---|---|---|---|---|---|---|
| 1 | 6.5613 | 11.3525 | 4.9133 | 14.00 | 750 | 0.04 | 18750 |
| 2 | 11.9324 | 17.8223 | 8.5144 | 23.07 | 2000 | 0.07 | 28571 |
| 3 | 26.2451 | 51.2695 | 24.0479 | 62.65 | 3750 | 0.21 | 17857 |
| 4 | 23.4070 | 39.1846 | 20.4468 | 50.013 | 1800 | 0.19 | 9473 |
| 5 | 42.3889 | 69.1071 | 35.9802 | 85.83 | 3600 | 0.34 | 10588 |
| 6 | 58.0444 | 97.3511 | 88.1653 | 143.59 | 1500 | 0.48 | 3125 |
| 7 | 91.9495 | 97.3206 | 52.2766 | 143.72 | 3150 | 0.56 | 5625 |
| 8 | 36.2244 | 49.8657 | 45.5017 | 76.61 | 1200 | 0.29 | 4137 |
| 9 | 10.4370 | 24.4141 | 11.2610 | 28.84 | 3500 | 0.14 | 25000 |

### 3.1 Material Removal Rate (MRR)

The material removal rate (MRR) in turning operations is the volume of material that is removed per unit time in $mm^3$/min. For each revolution of the work piece, layer of material is removed. [12, 13,14]

The metal removal *Zw* rate is given by

$$Z_w = v.\,f\,.a_p \times 1000 \ (\text{mm}^3 / \text{min}) \qquad \text{--------------} \quad (1.1)$$

The maximum metal removal rate Z*w (max.)*

$$Z\,w\,(max.) = v_{max}\,.\,f_{max}\,.a_{pmax} \times 1000 \ (\text{mm}^3 / \text{min}) \qquad \text{--------------} \quad (1.2)$$

### 3.2 Cutting power $P_c$

Referring to finishing operations, the depth of cut and feed rate is small than the nose radius, the main cutting force component is the tangential force Fz, in turning process [15,16].The cutting power $P_c$ is calculated as [17],

$$P_c = Fz.\ V \qquad \text{------------} \qquad (1.3)$$

Table 3 illustrates the experimental results of material removal rate, Cutting Power ($P_c$) and MRR/ Cutting power.

### 3.3 Statistical analysis of Material Removal Rate

In table 4, the ANOVA result shows that the F value for the depth of cut (factor C) is 28.11 which is larger than that of the other two cutting parameters i.e., the largest contribution to the material removal rate is due to depth of cut.

**Table 4** ANOVA result for Material removal rate

| **Source** | **Sum of Squares** (SS) | **DOF** | **Mean Squares** SS/DOF) | **F-ratio** (MS/Error) | **P-value** | **Contri. (%)** |
|---|---|---|---|---|---|---|
| Cutting speed | 320556 | 2 | 160278 | 1.08 | 0.843 | 3.05 |
| Feed | 1590556 | 2 | 795278 | 5.38 | 0.527 | 15.12 |
| Depth of cut | 8307222 | 2 | 4153611 | 28.11 | 0.048 | 79.02 |
| Error | 295556 | 2 | 147778 | -- | -- | 2.81 |
| Total | 10513889 | 8 | -- | -- | -- | 100 |
| **R-Sq = 97.19%** | | | | | | |

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From Percentage Points of the F Distribution, for 2 degree of freedom for the numerator and 2 degrees of freedom for the denominator, Table value is $F_{2,2,0.05} = 19.00$, so the main effects of depth of cut is significant. The portion of the total variation observed in the experiment attributed to each significant factor is reflected by the percent contribution in the last column of the tables. Depth of cut contributed 79.02% for material removal rate. The percent contribution of the second most factor feed rate was found 15.12% to be only.

The cutting speed 3.05% and error contribution is 2.81 respectively. Therefore, for the material removal rate parameter depth of cut was found to be the only significant parameter with % contribution upto 79.02%. The effect of depth of cut is more significant due to the associated smallest P-values from this ANOVA table.The Figure 2 illustrates the evolution of the material removal rate according to the cutting speed, feed rate and depth of cut.

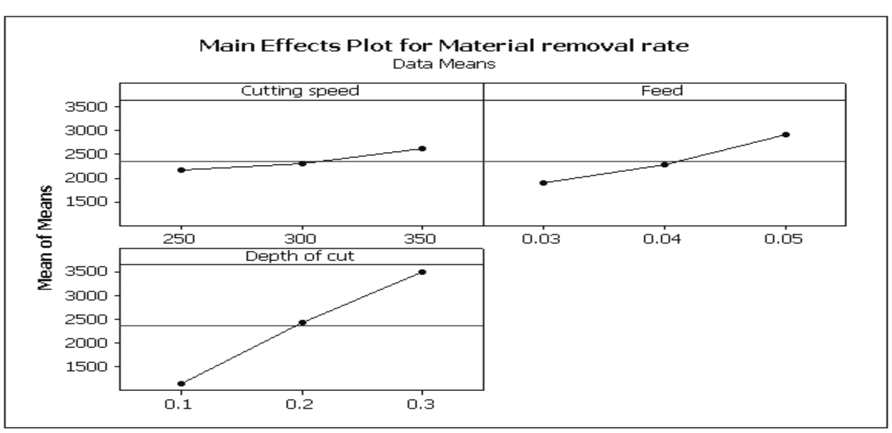


**Figure2: Main Effect plot for material removal rate**

The results show that with increase in cutting speed, feed rate and depth of cut there is continuous increase in material removal rate. Lowest material removal rate 750 $mm^3$/min was observed at 250 m/min where resultant force of 14 N.Maximum material removal rate 3750 $mm^3$/min observed at 250 m/min where resultant force of 62.65 N. It is observed that there is no considerable effect of cutting speed (in the range of 300 – 350 m/min.) on the material removal rate.

When the depth of cut increases from 0.1 to 0.3 mm, there is a tendency on the contact length to grow, this may account for the increase on the cross section of the uncut chip thickness, and also on removal rate, together with a proportional increase in cutting forces.The variations of cutting parameters leads to the increase in material removal rate, this increase almost linear. The MRR is increased by increasing any of the cutting process parameters. The effect of depth of cut and feed rate is more as compared to variation in cutting speed.This study thus concluded that the cutting speed (250m/min),feed rate (0.05mm/rev.) and depth of cut (0.03mm) lead to maximum material removal rate.

### 3.4 Statistical analysis of Cutting Power

In table 5 the ANOVA result shows that the F value of factor cutting speed (factor A) is larger than that of the other two cutting parameters i.e., the largest contribution to the cutting power is due to cutting speed. ANOVA table 5 shows that the major effect on the response is due to cutting speed and very little effect due to feed rate during power consumption.

**Table 5 Analysis of Variance for cutting power ($P_c$)**

| **Source** | **Sum of Squares** (SS) | **DOF** | **Mean Squares** (SS/DOF) | **F-ratio** (MS/Error) | **P-value** | **Contri. (%)** |
|---|---|---|---|---|---|---|
| Cutting speed | 0.10282 | 2 | 0.05141 | 1.67 | 0.374 | 40.81 |
| Feed | 0.00296 | 2 | 0.00148 | 0.05 | 0.954 | 1.17 |
| Depth of cut | 0.08469 | 2 | 0.04234 | 1.38 | 0.421 | 33.61 |
| Error | 0.06149 | 2 | 0.03074 | -- | -- | 24.41 |
| Total | 0.25196 | 8 | -- | -- | -- | 100 |
| **R-Sq = 75.60%** | | | | | | |

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The cutting speed contributed 40.81% for cutting power. The percent contribution of the second most factor depth of cut was found 33.61% to be only. The feed 1.17% and error contribution is 24.41 respectively.

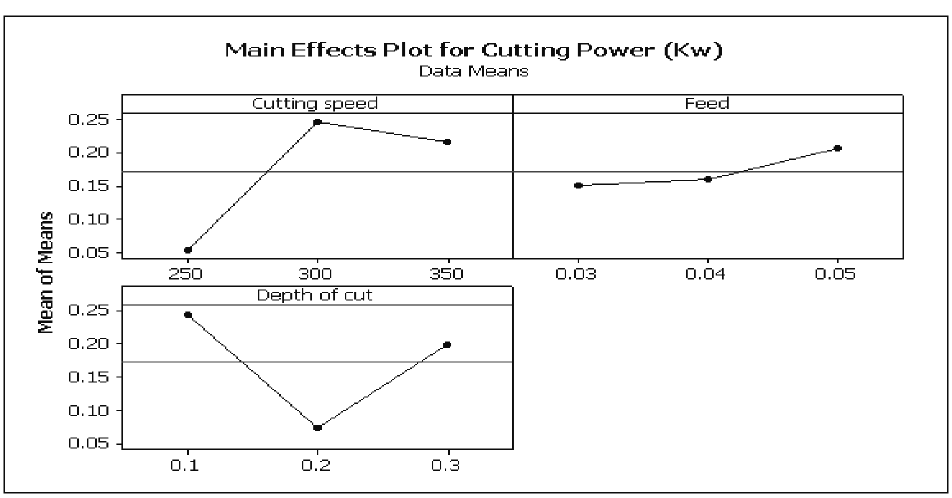


**Figure 3: Main Effects plot for cutting power ($P_c$)**

The effect of depth of cut and cutting speed is more as compared to variation in feed rate. The Figure 3 illustrates the evolution of the cutting power according to the cutting speed, feed rate and depth of cut.

### 3.5 Statistical analysis of material removal rate per cutting power

In table 6, the ANOVA result shows that the F value for the cutting speed (factor A) is larger than that of the other two cutting parameters i.e., the largest contribution to the material removal rate per cutting power is due to cutting speed.

**Table 6: Analysis of Variance for MRR/Cutting Power**

| **Source** | **Sum of Squares** (SS) | **DOF** | **Mean Squares** (SS/DOF) | **F-ratio** (MS/Error) | **P-value** | **Contri. (%)** |
|---|---|---|---|---|---|---|
| Cutting speed | 313607211 | 2 | 156803605 | 3.33 | 0.231 | 45.61 |
| Feed | 27079251 | 2 | 13539625 | 0.29 | 0.777 | 3.94 |
| Depth of cut | 252865896 | 2 | 126432948 | 2.69 | 0.271 | 36.78 |
| Error | 94103361 | 2 | 47051680 | -- | -- | 13.67 |
| Total | 687655718 | 8 | -- | -- | -- | 100 |
| **R-Sq = 86.32%** | | | | | | |

Cutting speed contributed 45.61% for material removal rate per cutting power. The percent contribution of the second most factor depth of cut was found 36.78.The feed 3.94% and error contribution is 13.67 respectively. Main effect plot for the material removal rate per cutting power has been shown in Figures 4.

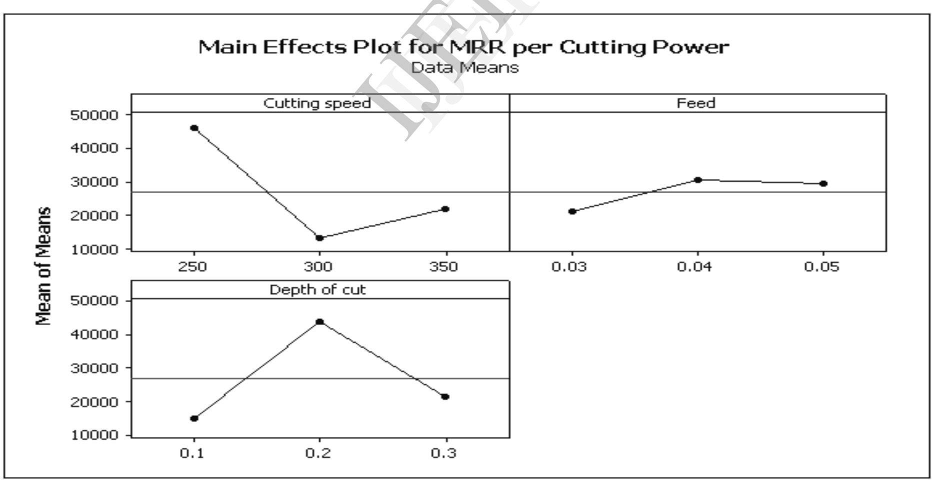


**Figure 4: Main Effects plot for MRR/Cutting Power**

The Figure 4 illustrates the evolution of the material removal rate per cutting power according to the cutting speed, feed rate and depth of cut.The effect of depth of cut and cutting speed is more as compared to variation in feed rate.As it is clear from the data curves presented in Figure 2 to Figure 4 the material removal rate, cutting power and material removal rate per power shows complex relationship with respect to machining parameters.The measured responses are similar with other documented studies of Ozel et al. [18] and Gaitonde et al. [19] in machining AISI D2 Cold work tool steel at 60 HRc, and similar phenomena were observed in turning of investigation of Bhattacharya et al. [20] during AISI 1045 steel. Although the data set presented in table 5.16 is not large, it is adequate to for Taguchi modeling this relationship.

Further experimentation can be carried by keeping the cutting speed at lowest range to study the optimistic determination of mrr/power. When the depth of cut increases from 0.1 to 0.3 mm, there is a tendency on the contact length to grow, this may account for the increase on the cross section of the uncut chip thickness, and also on removal rate, together with a proportional increase in cutting forces.

From the above discussions, it can be concluded that the machinability performance in terms of mrr/power is superior at 250 m/min. Lower values of cutting speed are essential to minimize cutting power and maximize mrr/power.

## 4. Conclusions

The present work reports a systematic experimental study on, the influence of turning parameters on mrr, cutting power and mrr/power in hard turning of EN31 Steel with uncoated PCBN (MITSUBISHI) insert. From the analysis of experimental data, the following conclusions can be drawn.The important conclusions drawn from this work are summarized as follows:

The depth of cut is found to be the most important parameter effecting on material removal rate (mrr), followed by feed rate while cutting speed has the least effect. The optimal parameters for maximum mrr, were as follow: cutting speed 350m/min., feed rate 0.05mm/rev., and depth of cut of 0.3mm. Thus, if we want much removed amount of chip, we must use the highest level of cutting speed, 350 m/min, the level of feed rate, 0.05 mm/rev and the high level of depth of cut, 0.30 mm.

The cutting speed is found to be the most important parameter effecting on cutting power ($P_C$), followed by depth of cut while feed rate has the least effect. To get good power consumption parameter, the lowest level of cutting speed, 250 m/min, the medium level of feed rate, 0.04 mm/rev and the medium level of depth of cut,0.2 mm. are recommended. In hard turning as cutting speed increases,the force and power consumption being high.

The cutting speed is found to be the most important parameter effecting on material removal rate (mrr) per cutting power ($P_C$), followed by depth of cut while feed rate has the least effect. The optimal parameters for maximum MRR/cutting power, were as follow: cutting speed 350 m/min.,feed rate 0.05mm/rev., and depth of cut of 0.3mm. Machining with lowest cutting speed has positive effect on material removal rate (mrr) per cutting power ($P_C$).

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