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# Optimization of Surface Roughness in Hard Turning of AISI 4340 Steel using Coated Carbide Inserts

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**Abstract**

The use of multilayer coated carbide tool in hard turning has several advantages over grinding process such as; reduction of processing costs, increased productivity, short cycle time, compatible surface roughness and less enviornment problems without the use of cutting fluid. In the present study, an attempt has been made to evaluate the performance of multilayer coated carbide inserts during dry turning of hardened AISI 4340 steel (47 HRC). The effect of machining parameters (depth of cut, feed and cutting speed) on surface roughness (Ra) was investigated by applying ANOVA. The experiments were planned based on Taguchi's $L_{27}$ Orthogonal array design. Results showed that surface roughness (Ra) mainly influenced by feed and cutting speed, whereas depth of cut exhibits neglegible influence on surface roughness. The experimental data were further anlyzed to predict the optimal range of surface roughness (Ra). Finally a second order regression model was developed to find out the relationship between the machining parameters and surface roughness.

**Keywords**: AISI 4340 steel; surface roughness; ANOVA; optimization.

## 1. Introduction

The achivement of high quality, in terms of workpiece dimensional accuracy, surface finish, high production rate, less wear on the cutting tools, economy of machining in terms of cost saving and increase the performance of the product with reduced enviornmental impact are the main and effective challenges of modern metal cutting and machining industries (Das et al, 2012). Traditionally, hardened steels are machined by grinding process due to their high strength and wear resistance properties but grinding operations are time consuming and limited to the range of geometries to be produced. In recent years, machining the hardened steel in turning which uses a single point cutting tool has replaced grinding to some extent for such application. This leads to reduced the number of setup changes, product cost and ideal time without compromising on surface quality to maintain the competiveness (Hodgson et al, 1981). The improve technological process, proper tool selection, determination of optimum machining parameters (cutting speed, feed, depth of cut) or tool geometry (nose radius, rake angle, edge geometry, etc.) are necessary in order to obtain the desired surface finish comparable to grinding (Gilibrand et al, 1996).

In order to decide the surface quality the statistical design of experiments (DOE) and statistical/mathematical model are used quite extensively. Statistical design of experiment refers to the process of planning the experimental so that the appropriate data can be analyzed by statistical methods, resulting in valid and objective conclusion (Montgomery, 2001). Design and methods such as factorial design, Taguchi design and response surface methodology (RSM) are now widely used in place of one factor at a time experimental approach which is time consuming and exobitant in cost. These methods have been used by some researchers for surface roughness (Suresh et al, 2012), statistical method has been used for machinability (Davim and Figueira, 2007). Sahin and Motorcu (2008) developed the surface roughness model using response surface methodology in turning AISI 1050 hardened steels by CBN cutting tools under different conditions. Feed rate was found out to be the most significant factor on the surface roughness. Davim and Figueira (2007) to investigate the machinability of cold work tool steel D2 heat treated to a hardness of 60 HRC. They concluded that with an appropriate choice of cutting parameters it is possible to obtain a surface roughness with Ra < 0.8 µm. This implies that hard machining is an alternative competitive process, which allows eliminating cylindrical grinding operation solutions. A. Bhattacharya et al. (2009) have investigated the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA. The result showed a significant effect of cutting speed on surface roughness and power consumption, while the other parameters have not substantially affected the response. In their experimental research work, Benga and Abrão (2003) underlined that feed rate is most significant factor affecting surface finish than cutting speed for both CBN and ceramic inserts. Latter Ozel et al. (2005) conducted a set of 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.

The present study is to investigate the influence of machining parameters under the surface roughness in dry turning of hardened AISI 4340 steel with CVD ($TiN/TiCN/Al_2O_3/ZrCN$) multilayer coated carbide tool and determine the optimal levels of machining parameters for optimizing the surface roughness (Ra) by employing Taguchi's orthogonal array design and utilizing analysis of variance (ANOVA). The relationship between the machining parameters (depth of cut, feed and cutting speed) and the performance measures i.e. surface roughness (Ra) has been developed by using multiple second order regression models.

## 2. Experimental Details

AISI 4340 medium carbon low alloy high strength steel is used in the form of round bars of diameter 45 mm and 100 mm long and is hardened to 47 HRC (quenching at $920^0$C followed by oil tempering at $400^0$C). In tests, multilayer coated carbide insert ($TiN/TiCN/Al_2O_3/ZrCN$) of ISO designation CNMG 120408 ($80^0$ diamond shaped insert) mounted on a PCLNR2525M12 tool holder has been employed for experimentation. The machining parameters and their levels are shown in Table 1. The experiments were planned according to Taguchi's $L_{27}$ ($3^{13}$) Orthogonal array with 26 degree of freedom. The turning experiments were carried out in order to obtain experimental data in the dry condition on CNC lathe machine (Jobber XL, AMS India) which has a maximum spindle speed of 3500 rpm and a maximum power of 16kW. Prior to actual machining, the skin layers were removed by a new cutting edge of uncoated carbide insert of very small depth of cut. This was done in order to remove the rust layer or hardened top layer from the outside surface and to minimize any effect of in homogeneity on the experimental results. A hole was drilled on the face of the workpiece to allow it to be supported at the tailstock as shown in Fig. 1.The surface roughness of the turned surface has measured using a portable Mitutoyo surface roughness tester (Taylor Hobson, Surtronic 25) in terms of arithmetic average roughness (Ra). Typically, grinding or honing surface-finishing processes yield surfaces with a Ra in the range of 0.1–1.6µm. We used 1.6µm as the control criterion for finish hard turning (Noordin et al, 2007). The experimental results at each run are shown in Table 2.

## 3. Results and Discussions

### 3.1 Analysis of Variance (ANOVA)

The experimental results are analyzed with analysis of variance (ANOVA), which is used for identifying the factors significantly affecting the performance measures. The results of the ANOVA with surface roughness (Ra) are shown in Table 3. This analysis was carried out for significance level of $\alpha$=0.05, 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. The last column of the tables shows the percent contribution of significant source to the total variation and indicating the degree of influence on the result.

Table 3 presents ANOVA results for surface roughness, Ra. It is observed that the feed (52.55%) has highest statistical significant parameter followed by cutting speed (25.85%) and depth of cut (4.91%) on surface roughness, Ra. The interactions (D×F), (F×V) and (D×V) are not statistical significant. Respectively, their contributions are 3.24%, 7.25% and 2.10%. In other words, interaction effects are negligible for minimizing surface roughness. The error contribution is 4.1% for surface roughness (Ra). As the percent contribution due to error is very small it signifies that neither any important factor was omitted nor any high measurement error was involved.

### 3.2 Main effects Plot

The data are further analyzed to study the main effect plot with the help of a software package MINITAB15 and shown in Fig. 2. The plot shows the variation of individual response with the three parameters, i.e. cutting speed, feed and depth of cut separately. Figure 2 shows the main effect plot for surface roughness, Ra. The main effects plot used to determine the optimal design conditions to obtain the optimum value of surface finish. The results show that with the increase in feed there is a continuous increase in surface roughness value. Here also, the main effect plot shows the decrease in roughness with increased cutting speed. Similar conclusions can be found in the literature (Suresh et al, 2012). According to this main effect plot, the optimal conditions for surface roughness are: feed at level-1(0.10 mm/rev) and cutting speed at level-3 (150 m/min).

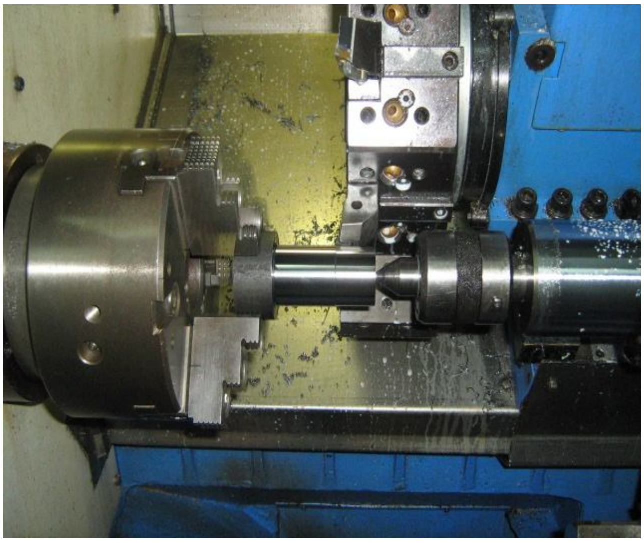

**Figure 1**: View of cutting Zone/

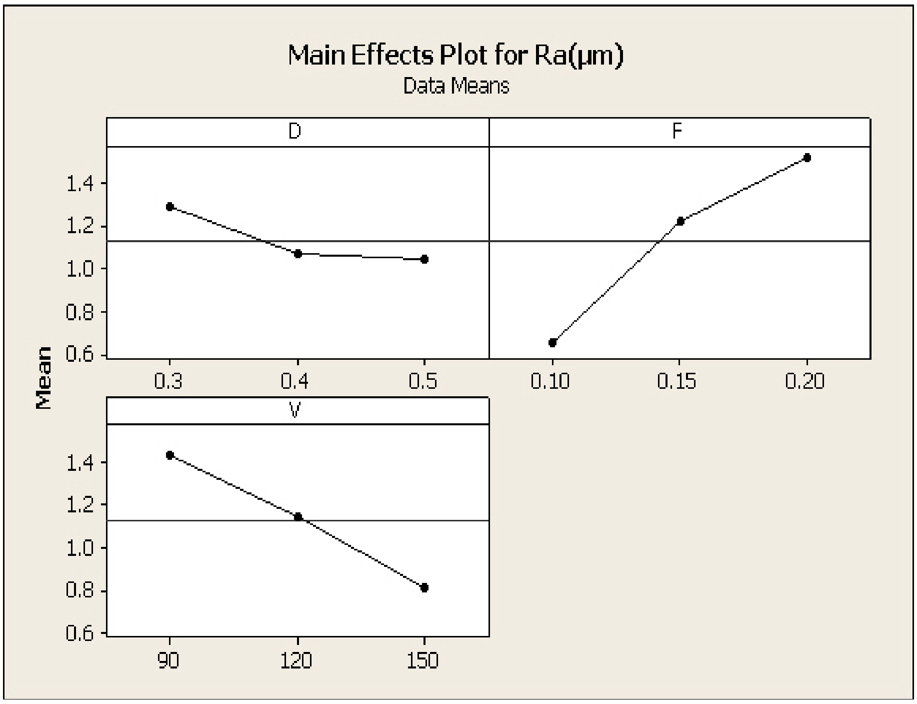


**Figure 2**: Main effects plot for surface roughness.

**Table 1**: Machining parameters and levels.

| Parameters | Unit | Levels | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Depth of Cut (D) | mm | 0.3 | 0.4 | 0.5 |
| Feed (F) | mm/rev | 0.1 | 0.15 | 0.2 |
| Cutting speed(V) | m/min | 90 | 120 | 150 |

**Table 2:** Orthogonal array $L_{27}$ of Taguchi experiment design and experimental results.

| Test No. | D | F | V | Ra (µm) | Test No | D | F | V | Ra (µm) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.3 | 0.1 | 90 | 0.88 | 15 | 0.4 | 0.15 | 150 | 0.82 |
| 2 | 0.3 | 0.1 | 120 | 0.72 | 16 | 0.4 | 0.2 | 90 | 2.36 |
| 3 | 0.3 | 0.1 | 150 | 0.55 | 17 | 0.4 | 0.2 | 120 | 1.5 |
| 4 | 0.3 | 0.15 | 90 | 1.8 | 18 | 0.4 | 0.2 | 150 | 0.795 |
| 5 | 0.3 | 0.15 | 120 | 1.467 | 19 | 0.5 | 0.1 | 90 | 0.837 |
| 6 | 0.3 | 0.15 | 150 | 1.3 | 20 | 0.5 | 0.1 | 120 | 0.615 |
| 7 | 0.3 | 0.2 | 90 | 1.91 | 21 | 0.5 | 0.1 | 150 | 0.6 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 8 | 0.3 | 0.2 | 120 | 1.55 | 22 | 0.5 | 0.15 | 90 | 1.24 |
| 9 | 0.3 | 0.2 | 150 | 1.39 | 23 | 0.5 | 0.15 | 120 | 1.175 |
| 10 | 0.4 | 0.1 | 90 | 0.65 | 24 | 0.5 | 0.15 | 150 | 0.71 |
| 11 | 0.4 | 0.1 | 120 | 0.602 | 25 | 0.5 | 0.2 | 90 | 1.81 |
| 12 | 0.4 | 0.1 | 150 | 0.42 | 26 | 0.5 | 0.2 | 120 | 1.635 |
| 13 | 0.4 | 0.15 | 90 | 1.4 | 27 | 0.5 | 0.2 | 150 | 0.742 |
| 14 | 0.4 | 0.15 | 120 | 1.04 | | | | | |

**Table 3:** Analysis of variance for surface roughness (Ra).

| Source | DOF | SS | MS | F-value | P | C (%) |
|---|---|---|---|---|---|---|
| D | 2 | 0.32679 | 0.16340 | 4.81 | 0.043 | 4.91 |
| F | 2 | 3.49684 | 1.74842 | 51.45 | 0.000 | 52.55 |
| V | 2 | 1.72030 | 0.86015 | 25.31 | 0.000 | 25.85 |
| D×F | 4 | 0.21598 | 0.05400 | 1.59 | 0.267 | 3.24 |
| F×V | 4 | 0.48252 | 0.12063 | 3.55 | 0.060 | 7.25 |
| D×V | 4 | 0.13935 | 0.03484 | 1.03 | 0.450 | 2.10 |
| Error | 8 | 0.27186 | 0.03398 | | | 4.10 |
| Total | 26 | 6.65364 | | | | 100 |
| S = 0.184343 R-Sq = 95.91% R-Sq(adj) = 86.72% | | | | | | |

**3.3 Prediction of Optimal Design**

When surface roughness (Ra) is considered from Table 4, an estimated average when the two most significant factors are at their better level is

$\mu_{R_a} = \bar{F}_1 + \bar{V}_3 - \bar{T}_{R_a}$ (from Table 2, $\bar{T}_{R_a}$ = 1.1303)

= (0.6527 + 0.8141) – 1.1303 = 0.3365

$F_{95\%.1,\,8}$ = 5.32 and $V_{error}$ = 0.03398 (from Table 3)

Where $\eta_{eff} = \frac{N}{1 + \text{DOF associated to that level}} = \frac{27}{1+2+2} = 5.4$

$$CI = \sqrt{\frac{F_{95\%.1,DOF\,error} \times V_{error}}{\eta_{eff}}} = \sqrt{\frac{5.32 \times 0.03398}{5.4}} = 0.1829$$

Finally, $(0.3365\text{-}0.1829) \le \mu_{R_a} \le (0.3365+0.1829)$

$$0.1536 \le \mu_{R_a} \le 0.5195$$

**Table 4:** Mean values of surface roughness (Ra) at different levels.

| Level | Roughness Ra (µm) | | |
|---|---|---|---|
| | $\bar{D}$ | $\bar{F}$ | $\bar{V}$ |
| 1 | 1.2852 | **0.6527** | 1.4319 |
| 2 | 1.0652 | 1.2169 | 1.1449 |

| | | | |
|---|---|---|---|
| 3 | 1.0404 | 1.5213 | **0.8141** |
| Delta | 0.2448 | 0.8687 | 0.6178 |
| Rank | 3 | 1 | 2 |

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

### 3.4 Correlation

Multiple second order regression model has been implemented at 95% confidence level to obtain the correlation between the machining parameters (depth of cut, feed and cutting speed) and the measured surface roughness (Ra). The obtained equation was as follows:

$$Ra = - 1.9366 - 6.0036D + 43.7467F + 0.0206V + 9.7611D^2 - 51.9556F^2 - 0.000V^2 - 9.4167D\times F - 0.0135D\times V - 0.1309F\times V \quad (R^2 = 90.97\%)$$

The layer value of $R^2$ is always desirable. This confirms the suitability of the multiple regression equation and correctness of the calculated constants. To test statistical significance of 2nd order model, analysis of variance table is constructed and shown in Table 5 for surface roughness (Ra). F-ratio is also the important index to check the adequacy of model, where calculated F-value should be greater than F-table value. From Table 5, second order model is found to be statistically significant as P-value (probability of significance) is less than 0.05 and F calculated value is greater than F-table value (2.49). It is revealed that terms mentioned in the model have significant effects on the responses.

**Table 5:** Analysis of variance for surface roughness (Ra) 2nd order model.

| Source | DOF | Seq SS | Adj SS | Adj MS | F | P | Remarks |
|---|---|---|---|---|---|---|---|
| Regression | 9 | 6.05270 | 6.052697 | 0.672522 | 19.02 | 0.000 | Significant |
| Linear | 3 | 5.38266 | 0.621567 | 0.207189 | 5.86 | 0.006 | |
| Square | 3 | 0.16127 | 0.161269 | 0.053756 | 1.52 | 0.245 | |
| Interaction | 3 | 0.50877 | 0.508765 | 0.169588 | 4.80 | 0.013 | |
| Residual Error | 17 | 0.60095 | 0.600946 | 0.035350 | | | |
| Total | 26 | 6.65364 | | | | | |

## 4. Conclusion

Feed was found to be most significant parameter for the workpiece surface roughness (Ra) with a percent contribution of 52.55%. Cutting speed was found to be the next significant parameter for Ra with contribution of 25.85%. Depth of cut was found a negligible influence in case of Ra. The surface roughness is within recommended range of hard turning i.e. Ra value within 1.6 µm for multilayer ZrCN coated carbide inserts. From the study, it is evident that, the multilayer coated carbide inserts have performed well at a combination of cutting speed (150 m/min), feed (0.10 mm/rev) and depth of cut (0.4 mm). The predicted optimal range of workpiece surface roughness (Ra) is $0.1536 \leq \mu_{R_a} \leq 0.5195$. The relationship between machining parameters (depth of cut, feed and cutting speed) and machined surface roughness (Ra) are expressed by multiple quadratic regression model which can be used to estimate the expressed values of the performance level for any parameter levels. The regression models of workpiece surface roughness (Ra) presented high determination of coefficient ($R^2$ = 0.9097) close to unity) explaining 90.97% of the validity in the response which indicates the goodness of fit for the model and high significance of model.

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