Parametric optimization during machining of AISI 304 Austenitic Stainless Steel using CVD coated DURATOMIC™ cutting insert

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1. Introduction

Surface roughness is concerned to the quality of the products. A good surface finish is essential to improve fatigue strength, corrosion resistance, and aesthetical appeal. It is expressed in surface roughness value. Nowadays, manufacturing industries greatly concerned with dimensional accuracy and surface finish. The surface roughness is influenced by various factors such as the cutting tool geometry, cutting parameters, microstructure of work piece and the rigidity of the lathe, chip interface, Built-up Edge (BUE) formation, tool and work piece vibration, the way of interaction of tool with work piece etc. so that ideal surface finish is difficult to obtain because of the stated reasons (Sullivan & Cotterell, 2002). The surface roughness is also influenced by improper selection of process parameters which further causes tool damage.

The consequences of tool damage leads to economical losses like work piece spoiling or poor surface quality. Selection of optimal process parameters using various optimization techniques will help to solve the problem of improper selection of process parameters. In order to select optimal cutting
parameters, manufacturing to obtain optimal cutting parameters, manufacturing industries have
depended on the use of handbook based information which leads to decrease in productivity due to sub-
optimal use of machining capability. This causes high manufacturing cost and low product quality
(Aggerwal & Singh, 2005). Hence, there is a need of a systematic methodological tool for optimization
of parameters. The Taguchi’s parametric design is such an effective tool for robust design. Numerous
experimental investigations have been carried out over the years to study the effect of cutting
parameters, tool geometries on the work pieces surface integrity using several types of work piece
materials. Tool geometry plays an important role in machining. It is found that the nose radius will
affect the performance of the machining process (Wang & Lan, 2008). Nose radius is a major factor
that affects the surface finish of work piece. It is proved that high values of nose radius causes rough
surface with high value of run out (Saad Kariem, 2009).

However, very few researchers have studied the interaction effect of nose radius (Saad kariem, 2009;
Ravindra, 2008; Kishawy et al., 1997; Chou & Song, 2004; Sundaram & Lambert, 1981; Lambert,
1983; Bhattacharya et al., 1970; Aggarwal et al., 2008; Gokaya et al., 2007). The aim of the present
experimental investigation is to evaluate the effects and optimization of process parameters on surface
roughness and material removal rate (MRR) of AISI 304 austenitic stainless steel work piece during
turning operation. The experimentation is carried out by using a chemical vapour deposition (CVD)
coated Duratomic tool on CNC lathe under dry environment. The AISI 304 is the most widely used
grades of austenitic stainless steel. It is used for aerospace components and chemical processing
equipment, for food, dairy, and beverage industries, for heat exchangers, and for the milder chemicals.

2. Literature review

The austenitic stainless steel grade used in large volumes (72%), compared with all other grades of
stainless steels. It was reported that austenitic stainless steels belong to difficult to machine materials
category because of their low thermal conductivity and high mechanical and micro structural sensitivity
to strain and stress rate (M’Saoubi et al., 2008). Many of research works contributed their efforts to
overcome poor machinability of austenitic stainless steels. Lin (2008) investigated surface roughness
variations of different grades of austenitic stainless steel under different cutting conditions in high
speed fine turning. Surface roughness and tool wear were predicted by regression analysis and
ANOVA. Xavior & Adithan (2009) determined the influence of different cutting fluids on wear and
surface roughness in turning of AISI 304 austenitic stainless steel. Ciftci (2006) conducted the
experiments to Machine AISI 304 and AISI 316 austenitic stainless steels using CVD multi-layer
coated cemented carbide tools.

The results showed that cutting speed significantly affected the machined surface roughness values.
Özek et al. (2006) investigated to determine surface roughness, tool wear and tool-chip interface
temperature in turning of AISI 304. Empirical models for tool life, surface roughness and cutting force
were developed for turning of AISI 302 developed by Al-Ahmari (2007). Multiple regression analysis
techniques, response surface methodology and computational neural networks were used to predict
models of process functions.

Caydas and Ekici (2010) used support vector machines (SVM) tools namely least square-SVM,
spider SVM and an artificial neural networks (ANN) models to develop to assess the surface roughness
values of AISI 304 austenitic stainless steel. Jahan et al. (2010) made an attempt to machine deep micro
holes in two difficult to machine materials: WC-CO & austenitic stainless steel SUS 304 with micro-
EDM drilling. Sullivan & Cotterell (2002) used an on-line Acoustic Emission (AE) analysis technique
to detect the work hardening of AISI 303 austenitic stainless steel. Korkut et al. (2004) determined the
optimum cutting conditions during machining of AISI 304 austenitic stainless steel. Probably this was
the first attempt to determine the optimum cutting conditions during machining of AISI 304 austenitic
stainless steel. Akasawa et al. (2003) conducted experiments to determine the effect of variations of the
contents of additives S, Ca, Cu and Bi on the machinability of various grades of 300 series of austenitic stainless steel. Jukka Paro et. al. (2001) selected to turn X5 CrMnN 18/8 stainless steels material to turn, to investigate its machinability with TiN and Al₂O₃ coated carbide inserts. The literature survey revealed that little attention has been focused to turn the AISI 304 austenitic stainless steel under different cutting parameters.

3. Material and Methods

3.1 Methodologies: Taguchi approach

Taguchi’s parametric design is an effective tool for robust design. It offers a simple and systematic qualitative optimal design at a relatively low cost. It has been widely used for the last two decades. The greatest advantage of this approach is to save the experimental time as well as the cost by finding out the significant factors by analysis. One of the important steps involved in Taguchi’s technique is selection of an orthogonal array (OA). An OA is a small set from all possibilities which helps to determine least number of experiments, which will further help to conduct experiments to determine the optimum level for each process parameters and establish the relative importance of individual process parameters. To obtain optimum process parameters setting, Taguchi proposed a statistical measure of performance called signal to noise ratio (S/N ratio). This ratio considers both the mean and the variability. In addition to S/N ratio, ANOVA is used to indicate the influence of process parameters on performance measures. Taguchi proposed three categories of performance characteristics in the analysis of the S/N ratio, that is, the smaller the better, the higher the better, and the nominal the better (Ross, 1996). Numerous researchers have used Taguchi method to materials processing for process optimization (Singh, 2008; Singh & Kumar, 2003; Anrin et al., 2009; Barua et al., 1997; Mahapatra et al., 2006; Thamizhmanii et al., 2007; Lan, 2009). In the present work, the first criterion selects the smaller-the-better characteristic of the surface roughness and larger the better type for MRR. Smaller the better type S/N ratio for Ra,

\[
\frac{1}{10\log_{10} R_a^2} \]

the larger the better type S/N ratio for MRR,

\[
\frac{1}{MRR^2} \]

3.2 Experimental

Turning is a popularly used machining process in which a single point cutting tool removes unwanted material from the surface of a rotating cylindrical work piece. The computer numerical controlled (CNC) machines play a major role in modern machining industry to enhance product quality as well as productivity (Tian-Syung, 2009). The machining tests are carried out on the material in cylindrical form, 330 mm long and 50 mm diameter by two layer CVD of grade TP 2500 Ti (C, N) + Al₂O₃ coated cemented carbide inserts of two different nose radii on Parishudh TC-250 CN, India, CNC lathe with a variable speed of up to 3250 rpm and a power rating of 7.5 kW. A center hole was drilled on the face of the work piece to allow supporting at the tailstock (Fig. 1).
These work pieces were cleaned prior to the experiments by removing 0.3 mm thickness of the top surface from each work piece in order to eliminate any surface defects and wobbling. The surface roughness of machined surfaces has been measured by a Talysurf (Taylor Hobson, Surtronic 3+, UK) surface roughness tester. The chemical composition of AISI 304 is given in Table 1. The present experimental investigation is carried out according to the Taguchi’s L16 mixed level design as shown in the Table 3.

Table 1
Chemical composition of AISI 304

| Elements | C     | Si    | Mn    | Cr    | Ni    | Mo    | Cu    | Ti    | V     | W     | Co    | Nb    | Fe    |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Composition(%wt) | 0.051 | 0.412 | 1.351 | 18.275 | 8.473 | 0.301 | 0.318 | 0.005 | 0.049 | 0.003 | 0.019 | 0.020 | Balance |

Table 2
Process parameters levels

| Symbol | parameters                  | Levels |
|--------|-----------------------------|--------|
|        | Cutting speed (m/min)       | 1      | 2      | 3      | 4      |
| A      | 150                         | 170    | 190    | 210    |
| B      | 0.15                        | 0.20   | 0.25   | 0.30   |
| C      | 0.5                         | 1.0    | 1.5    | 2.0    |
| D      | 0.4                         | 0.8    |

Table 3
L16 mixed level design

| Trail no. | Cutting Speed A | Feed B | Depth of Cut C | Nose radius D | Surface roughness Ra(µm) | Material removal rate (mm³/min) |
|-----------|-----------------|--------|----------------|---------------|--------------------------|-------------------------------|
| 1         | 1               | 1      | 1              | 1             | 1.425                    | 12291.67                      |
| 2         | 1               | 2      | 2              | 1             | 2.363                    | 24452.55                      |
| 3         | 1               | 3      | 3              | 2             | 1.06                     | 33141.45                      |
| 4         | 1               | 4      | 4              | 2             | 0.867                    | 33645.37                      |
| 5         | 2               | 1      | 2              | 2             | 2.432                    | 11369.05                      |
| 6         | 2               | 2      | 1              | 2             | 1.515                    | 9537.037                      |
| 7         | 2               | 3      | 4              | 1             | 3.33                     | 40492.96                      |
| 8         | 2               | 4      | 3              | 1             | 4.232                    | 37328.38                      |
| 9         | 3               | 1      | 3              | 1             | 1.385                    | 48112.86                      |
| 10        | 3               | 2      | 4              | 1             | 1.75                     | 83250.25                      |
| 11        | 3               | 3      | 1              | 2             | 2.332                    | 12592.59                      |
| 12        | 3               | 4      | 2              | 2             | 1.992                    | 26890.76                      |
| 13        | 4               | 1      | 4              | 2             | 0.962                    | 30434.78                      |
| 14        | 4               | 2      | 3              | 2             | 1.017                    | 26715.69                      |
| 15        | 4               | 3      | 2              | 1             | 2.932                    | 27085.75                      |
| 16        | 4               | 4      | 4              | 1             | 1.295                    | 10641.89                      |

3.3. Cutting tool and cutting conditions

About 70% of the industries use coated cemented carbide tools. Because coated carbide tools have shown better performance when compared with the uncoated carbide tools (Noordin et al., 2004). For this reason, available CVD of grade TP 2500 Ti (C, N) + Al₂O₃ coated cemented carbide inserts of 0.8 and 0.4mm as nose radius are used in the present experimental investigation. TP-2500 is the first grade created with the DurAtomic technology by SECO tool manufacturers. The DurAtomic technology produces chemically alter crystal structure of the aluminum-oxide (Al₂O₃) layer to create the coating that offers a high surface finish, less tool wear, greater tool life and speed capability. These advantages are particularly important in stainless steel machining (Seco tools). Duratomic coating is superior to traditional coatings because of its atomic structure. The DurAtomic coating has a TiCN lower layer topped by the new Al₂O₃. The Process parameters and levels used in the experiment are given in the
Tables 2. The cutting parameters levels are selected according to the recommendations of the cutting inserts manufacturer (Seco tools).

3.4. Calculation of Material Removal Rate

Material removal rate (MRR) has been calculated from the difference of weight of work piece before and after experiment by using the following formula. Where, \( W_i \) is the initial weight of work piece in grams; \( W_f \) is the final weight of work piece in grams; \( t \) is the machining time in minutes; \( \rho \) is the density of AISI 304 austenitic stainless steel \((8 \times 10^{-3} \text{ g/mm}^3)\).

\[
\text{MRR} = \frac{W_i - W_f}{\rho t} \text{ mm}^3 / \text{min}
\]

4. Results and discussion

Experiments are conducted to investigate the effects of cutting parameters on the surface roughness and MRR of the AISI 304 austenitic stainless steel work pieces. Table 3 gives experimental results. While estimating the mean and confidence interval, interaction effects are not taken in to account.

4.1. Analysis of variance (ANOVA)

The present work used ANOVA to determine the optimum combination of process parameters more accurately by investigating the relative importance of process parameters. Table 4 presents the results of ANOVA for surface roughness (Ra). It is observed from the ANOVA table, the cutting speed (46.05%) is the most significant parameter followed by nose radius (23.7%). However, the depth of cut has the least effect (13.28%) in controlling the surface roughness. Statistically, F-test decides whether the parameters are significantly different. A larger F value shows the greater impact on the machining performance characteristics (Ross, 1996). Larger F-values are observed for speed as 3.512 and nose radius as 5.424. As seen from the ANOVA Table 5, the influence of the depth of cut (61.31%) in affecting material removal rate (MRR) is significantly large. The cutting speed (20.40%) is the next significant factor. However, the feed has least effect (5.38%) in producing MRR.

Table 4
ANOVA results for surface roughness

| Source         | SS       | DOF | MS       | F         | C (%)     |
|----------------|----------|-----|----------|-----------|-----------|
| Cutting speed  | 5.184    | 3   | 1.728    | 3.51295   | 46.05     |
| Feed           | 1.909    | 3   | 0.636    | 1.29283   | 16.96     |
| Depth of Cut   | 1.495    | 3   | 0.498    | 1.012195  | 13.28     |
| Nose radius    | 2.669    | 1   | 2.669    | 5.424979  | 23.70     |
| Error          | 2.462    | 5   | 0.492    |           |           |
| Total          | 8.796    | 15  |          |           |           |

Table 5
ANOVA results for MRR

| Source          | SS       | DOF | MS       | F         | C (%)     |
|-----------------|----------|-----|----------|-----------|-----------|
| Cutting speed   | 976029752| 3   | 325343251| 4.333984  | 20.4069   |
| Feed           | 257782508| 3   | 85927503 | 1.144663  | 5.389153  |
| Depth of cut    | 2932898611| 3   | 977632870| 13.0231   | 61.3146   |
| Nose radius     | 616647879| 1   | 616647879| 8.214531  | 12.89152  |
| Error          | 375339678| 5   | 75067935.57| 8.214531  | 12.89152  |
| Total          | 4408019072| 15  |          |           |           |

SS= Sum of squares; DOF= Degree of freedom; MS= Mean squares C=contribution

4.2. Main effect plots analysis
The analysis is made with the help of a software package MINITAB 14. The main effect plots are shown in Fig.2 and Fig.3. These show the variation of individual response with the four parameters i.e. cutting speed, feed, depth of cut and nose radius separately. In the plots, the x-axis indicates the value of each process parameter at two level and y-axis the response value. Horizontal line indicates the mean value of the response.

**Fig. 2.** Main effect plot for Surface roughness

The main effects plots are used to determine the optimal design conditions to obtain the optimum surface finish. Fig.2 shows the main effect plot for surface roughness. According to this main effect plot, the optimal conditions for minimum surface roughness are:

- Cutting speed at level 1 (150 m/ min),
- Feed rate at level 1 (0.15 mm/ rev),
- Depth of cut at level 1 (0.5 mm),
- Nose radius level 2 (0.8 mm)

According to main effect plot Fig. 3, the optimal conditions for maximum MRR are:

- Cutting speed at level 3 (190 m/ min),
- Feed rate at level 2 (0.20 mm/ rev),
- Depth of cut at level 4 (2.0 mm),
- Nose radius level 1 (0.4 mm)

4.3. Prediction of optimal design

Performance of $R_a$ when the two most significant factors are at their best level (based on estimated average)

$$\tilde{\mu}_{A_1B_1} = \tilde{A}_1 + \tilde{B}_1 - \tilde{T} = 1.429 + 1.551 - 1.930 = 1.05$$

(From Table 3, $\tilde{T} = 1.930$).

$$CI = \sqrt{\frac{F_{95\%,1,\text{doferror}} \times V_{\text{error}}}{n_{\text{efficiency}}}}$$

where $n_{\text{efficiency}} = N/(1+dof)$ of all parameters associated to that level,

$$n_{\text{efficiency}} = 16/(1+3+3) = 2.2857, \quad V_{\text{error}} = 2.462$$

(from Table 4), $F_{95\%,1,5} = 6.61$ (From F-table)
\[ CI = \sqrt{6.61 \times 2.462 / 3.2} = 2.255 \]

The predicted optimal range of Ra at 95% confidence level is obtained as,
\[ 1.05 - 2.255 \leq \mu_{A_i B_j} \leq 1.05 + 2.255 \]
\[ -1.205 \leq \mu_{A_i B_j} \leq 3.305 \]

Table 6
Mean Values of surface roughness (Ra)

| level | speed  | feed  | depth of cut | nose radius |
|-------|--------|-------|--------------|-------------|
| 1     | 1.429  | 1.551 | 1.642        | 2.339       |
| 2     | 2.877  | 1.661 | 2.430        | 1.522       |
| 3     | 1.865  | 2.414 | 1.924        |             |
| 4     | 1.552  | 2.097 | 1.727        |             |

Performance of MRR when the two most significant factors are at their best level (based on estimated average)
\[ \mu_{A_i D_{k}} = \tilde{A} + \tilde{D}_{k} - \tilde{T} = 42712 + 46956 - 29248.94 = 60419.06 \] (From Table 3, \( \tilde{T} = 29248.94 \)).

\[ CI = \sqrt{F_{95\%,1,9} \times \text{error} \times \text{efficiency}} \]

where \( n_{\text{efficiency}} = N / (1 + \text{dof}) \) of all parameters associated to that level, \( n_{\text{efficiency}} = 16/(1+1+3) = 3.2 \),
\( V_{\text{error}} = 375339678 \) (from Table 4), \( F_{95\%,1,5} = 6.61 \) (From F-table) \( CI = \sqrt{6.61 \times 375339678 / 3.2} = 27844.47 \).

The predicted optimal range of MRR at 95% confidence level is obtained as, \( 32574.65 \leq \mu_{A_i D_{k}} \leq 88263.46 \).

Table 7
Mean Values of MRR

| level | speed  | feed  | depth of cut | nose radius |
|-------|--------|-------|--------------|-------------|
| 1     | 25883  | 25552 | 11266        | 35457       |
| 2     | 24682  | 35989 | 22450        | 23041       |
| 3     | 42712  | 28328 | 36325        |             |
| 4     | 23720  | 27127 | 46956        |             |

4.4. Mathematical modeling

A multiple linear regression model was developed for surface roughness and MRR using Minitab-14 software. The predictors are cutting speed, feed, depth of cut and nose radius. The regression equation is \( Ra = 2.78 - 0.064 \times \text{Speed} + 0.239 \times \text{Feed} - 0.025 \times \text{depth of cut} - 0.817 \times \text{Nose radius} \). The regression equation is \( MRR = 15486 + 1154 \times \text{Speed} - 294 \times \text{Feed} + 12095 \times \text{depth of cut} - 12416 \times \text{Nose radius} \).

The diagnostic checking has been performed through residual analysis for the developed models. The residual plots for surface roughness and MRR are shown in Fig. 4-7. These are generally fall on a straight line implying that errors are distributed normally. From Fig. 4-7 it can be concluded that all the values are within the CI level of 95%. Hence, these values yield better results in future prediction. Fig. 5 & 7 indicated that there is no obvious pattern and unusual structure. From the Fig. 4-7, it can be concluded that the residual analysis does not indicate any model inadequacy.
5. Conclusions

The experimental investigation was conducted to turn AISI 304 austenitic stainless steel using CVD coated cemented carbide Duratomic cutting insert at four levels of cutting parameters by employing Taguchi technique to determine the optimal levels of process parameters. The ANOVA and F-test revealed that the cutting speed is the dominant parameter followed by nose radius for surface roughness. In case of MRR response, the depth of cut is the dominant one followed by the feed. The optimal combination of process parameters for minimum surface roughness is obtained at 150 m/min cutting speed, 0.15 mm/rev feed, 0.5 mm depth of cut and 0.8 mm nose radius. The optimal combination of process parameters for maximum MRR is obtained at 190 m/min cutting speed, 0.20 mm/rev feed, 2.00 mm depth of cut and 0.4 mm nose radius. A number of multiple linear regression models were developed for surface roughness and MRR. The developed models are reasonably accurate and can be used for prediction within limits. The Optimal range of surface roughness and MRR of the work piece is also predicted.

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