

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

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ABSTRACT

In this work, Taguchi method is applied to determine the optimum process parameters for turning of AISI 304 austenitic stainless steel on CNC lathe. A Chemical vapour deposition (CVD) coated cemented carbide cutting insert is used which is produced by Duratomic™ technology of 0.4 and 0.8 mm nose radii. The tests are conducted at four levels of Cutting speed, feed and depth of cut. The influence of these parameters are investigated on the surface roughness and material removal rate (MRR). The Analysis Of Variance (ANOVA) is also used to analyze the influence of cutting parameters during machining. The results revealed that cutting speed significantly (46.05%) affected the machined surface roughness values followed by nose radius (23.7%). 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. Optimal range and optimal level of parameters are also predicted for responses.

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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

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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 (Aggarwal & 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 R_a, $[\eta_1] = -10 \log_{10} [R_a^2]$, the larger the better type S/N ratio for MRR,

$$[\eta_2] = -10 \log_{10} \left[\frac{1}{MRR^2} \right].$$

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).



Fig. 1 Experimental set-up

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			
		1	2	3	4
A	Cutting speed (m/min)	150	170	190	210
B	Feed (mm/rev)	0.15	0.20	0.25	0.30
C	Depth of cut mm)	0.5	1.0	1.5	2.0
D	Nose radius(mm)	0.4	0.8		

Table 3
L₁₆ mixed level design

Trail no.	Cutting Speed	Feed	Depth of Cut	Nose radius	Surface roughness	Material removal rate
	A	B	C	D	R _a (μm)	(mm ³ /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	1	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; ρ_s is the density of AISI 304 austenitic stainless steel ($8 \times 10^{-3} \text{ g/mm}^3$).

$$MRR = \frac{W_i - W_f}{\rho_s t} \text{ mm}^3 / \text{min}$$

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	3.512195	46.05
Feed	1.909	3	0.636	1.292683	16.96
Depth of Cut	1.495	3	0.498	1.012195	13.28
Nose radius	2.669	1	2.669	5.424797	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	20.40469
Feed	257782508	3	85927503	1.144663	5.389153
Depth of cut	2932898611	3	977632870	13.02331	61.31463
Nose radius	616647879	1	616647879	8.214531	12.89152
Error	375339678	5	75067935.57		
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.

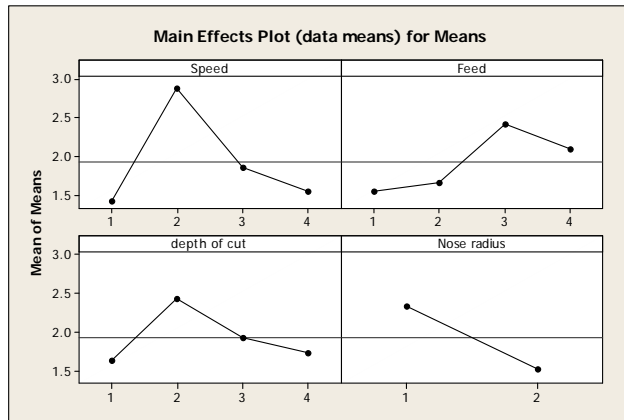


Fig. 2. Main effect plot for Surface roughness

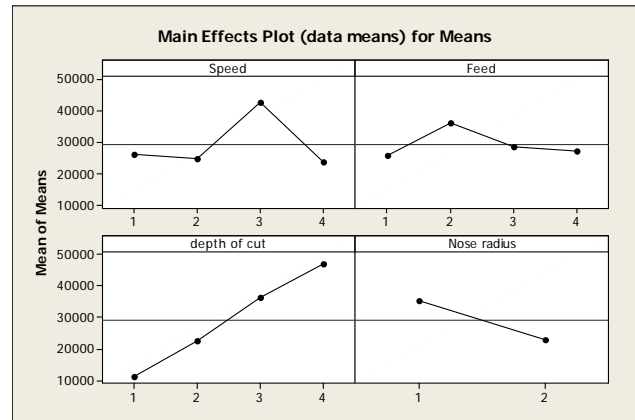


Fig.3 Main effect plot for MRR

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)

$$\bar{\mu}_{A_1B_1} = \bar{A}_1 + \bar{B}_1 - \bar{T} = 1.429 + 1.551 - 1.930 = 1.05 \text{ (From Table 3, } \bar{T} = 1.930\text{).}$$

$$CI = \sqrt{\frac{F_{95\%,1,dof_{error}} * V_{error}}{n_{efficiency}}}$$

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

$$n_{efficiency} = 16 / (1+3+3) = 2.2857, V_{error} = 2.462 \text{ (from Table 4), } F_{95\%,1,5} = 6.61 \text{ (From F-table)}$$

$$CI = \sqrt{6.61 \times 2.462 / 3.2} = 2.255$$

The predicted optimal range of R_a at 95% confidence level is obtained as,

$$1.05 - 2.255 \leq \bar{\mu}_{A_1 B_1} \leq 1.05 + 2.255$$

$$-1.205 \leq \bar{\mu}_{A_1 B_1} \leq 3.305$$

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)

$$\bar{\mu}_{A_3 D_4} = \bar{A}_3 + \bar{D}_4 - \bar{T} = 42712 + 46956 - 29248.94 = 60419.06 \text{ (From Table 3, } \bar{T} = 29248.94 \text{)} .$$

$$CI = \sqrt{\frac{F_{95\%, 1, dof_{error}} * V_{error}}{n_{efficiency}}}$$

where $n_{efficiency} = N / (1 + dof)$ of all parameters associated to that level, $n_{efficiency} = 16 / (1 + 1 + 3) = 3.2$,

$$V_{error} = 375339678 \text{ (from Table 4), } F_{95\%, 1, 5} = 6.61 \text{ (From F-table) } CI = \sqrt{6.61 \times 375339678 / 3.2} = 27844.47 .$$

The predicted optimal range of MRR at 95% confidence level is obtained as, $32574.65 \leq \bar{\mu}_{A_i D_i} \leq 88263.46$.

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 $R_a = 2.78 - 0.064 * \text{Speed} + 0.239 * \text{Feed} - 0.025 * \text{depth of cut} - 0.817 * \text{Nose radius}$.The regression equation is $MRR = 15486 + 1154 * \text{Speed} - 294 * \text{Feed} + 12095 * \text{depth of cut} - 12416 * \text{Nose radius}$.

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.

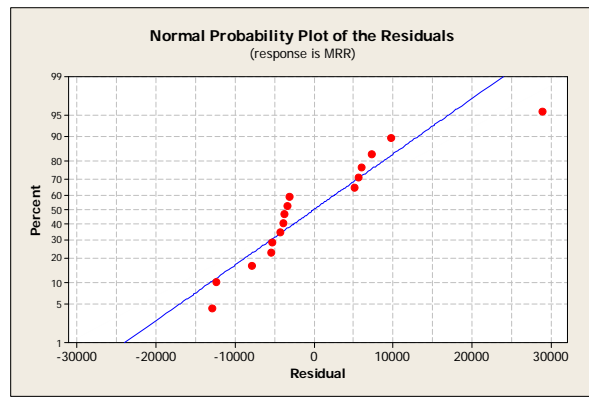


Fig. 4. Normal Probability of the residuals for MRR

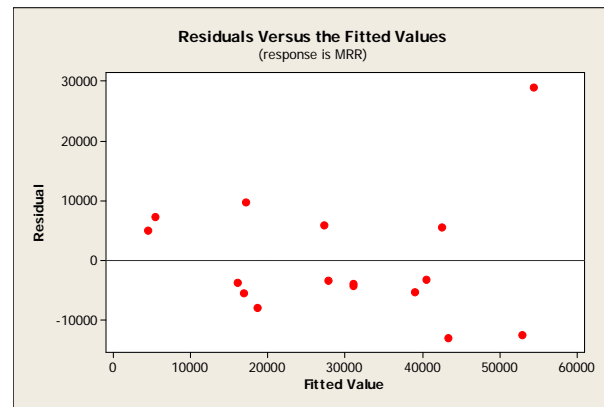


Fig. 5. Residuals versus the fitted values for MRR

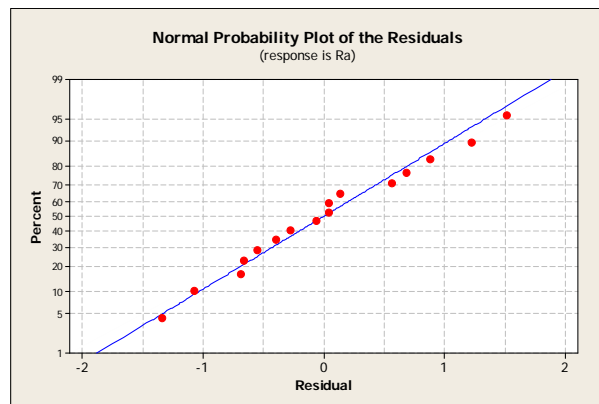


Fig. 6. Normal Probability of the residuals for Surface roughness

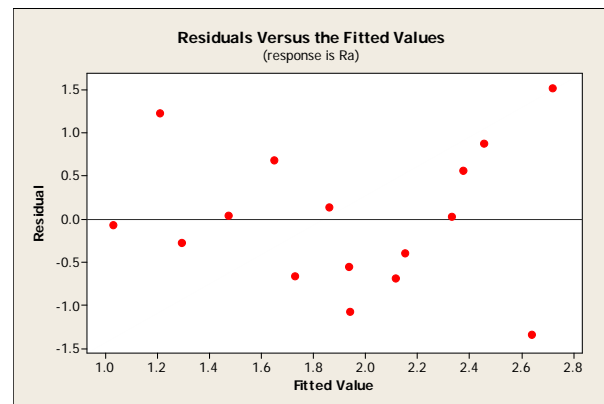


Fig. 7. Residuals versus the fitted values for Surface roughness

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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