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OPTIMIZATION OF SURFACE ROUGHNESS AND TOOL FLANK WEAR IN TURNING OF AISI 304 AUSTENITIC STAINLESS STEEL WITH CVD COATED TOOL

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Abstract

AISI 304 austenitic stainless steel is a popularly used grade in the various fields of manufacturing because of its high ductility, high durability and excellent corrosion resistance. High work hardening, low heat conductivity and high built up edge (BUE) formation made this as difficult-to- machine material. Poor surface quality and rapid tool wear are the common problems encountered while machining it. In the present work, an attempt has been made to explore the influence of machining parameters on the performance measures, surface roughness and flank wear in turning of AISI 304 austenitic stainless steel with a two layer Chemical vapour deposition(CVD) coated tool. In order to achieve this, Taguchi approach has been employed. The results revealed that the cutting speed most significantly, influences both surface roughness and flank wear. In addition to this the optimal setting of process parameters and optimal ranges of performance measures are predicted.

Keywords: AISI 304, Surface roughness, Flank wear, Taguchi approach.

1. Introduction

AISI 304 is the most widely used of all grades of austenitic stainless steel family. It is used for aerospace components and chemical processing equipment, for food, dairy, and beverage industries, for heat exchangers, and for the containers of milder chemicals. Austenitic stainless steels are known as difficult-to-cut material by virtue of their low thermal conductivity, high built-up edge tendency and high deformation hardening [1]. Poor surface finish and a high tool wear rate are

Nomenclatures

N	Number of trials
R_a	Surface roughness
S/N	Signal to noise ratio
$\overline{T}$	Overall mean of the response characteristics
V_B	Flank wear

Abbreviations

CI	Confidence interval
dof	Degrees of freedom
OA	Orthogonal array

commonly encountered problems during machining of these materials. But a good surface finish is highly important to determine the quality of the products and is essential to improve fatigue strength, corrosion resistance, and aesthetic appeal of manufactured products. It is expressed in surface roughness value. 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 [2]. Flank wear is a severe problem in machining of materials which directly affects the surface quality of the work piece. Hence tool monitoring is an important task in the context of increasing tool life as well as to protect the surface quality. One of the most crucial functions in the area of tool monitoring is to determine the tool's wear caused by abrasion, erosion, or other influences. The result of abrasive wear of the cutting edge against the machined surface is known as flank wear [3]. Many researchers have suggested a number of ways to improve the machinability of the difficult-to-cut materials, such as using hard surface coatings on the cutting tools, optimization of cutting parameters, etc.

Selection of optimal process parameters using various optimization techniques helps to solve the problem of improper selection of process parameters. In order to select 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 [4]. Hence, there is a need for a systematic and methodological tool for optimization of parameters. The Taguchi's parametric design is one such effective tool for robust design.

In the present work, AISI 304 austenitic stainless steel was turned on CNC lathe with a two layer Duratomic^{TM} CVD coated cemented carbide tool to explore the effects of machining parameters on the two performance measures, surface roughness and flank wear. The Taguchi Design of experiments technique is a unique and powerful experimental design technique. A large number of experiments are to be conducted when the number of process parameters increases. In order to solve this task, Taguchi technique applies a special design of orthogonal arrays to study the entire parametric space and develops the best model with minimum number of experiments and thus reducing the time and cost of experiments. In the present work, Taguchi approach was employed to select cutting parameters optimally.

Austenitic stainless steel machining

The austenitic stainless steel is the most popular grade in the stainless steels family which is consumed in large volumes (72%). Many research works contributed their efforts to overcome poor machinability of austenitic stainless steels [1], [5-13]. The literature survey shows that little attention has been paid to turn the AISI 304 austenitic stainless steel under different cutting parameters with different coated tools.

2. Experimental Procedure

The turning tests are carried out according to the selected cutting conditions (Table 1) on the material in cylindrical form, 330 mm long and 50 mm diameter by a Duratomic CVD (TiCN- Al_2O_3) coated cemented carbide tool two different nose radii on a Parishudh TC-250 CN, India, CNC lathe with a variable speed of up to 3250 rpm and a power rating of 7.5kW. The work pieces 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 chemical composition of AISI 304 is given in Table 2. Two different types of cemented carbide cutting inserts of different nose radii are used. As far as possible, the machining tests were performed as per the recommendations of ISO 3685. The surface roughness of machined surfaces has been measured by a Talysurf (Taylor Hobson, Surtronic 3+, UK) surface roughness tester.

Table 1. Cutting Parameters Levels.

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

Table 2. Chemical Composition of AISI 304.

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

2.1. Cutting tool

About 70% of the industries have used coated cemented carbide tools, because coated carbide tools have shown better performance when compared to the uncoated carbide tools [14]. For this reason, available CVD of grade TP 2500 Ti (C, N) + Al_2O_3 coated cemented carbide inserts of CNMG-120404 and CNMG-120408 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 (Al_2O_3) 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. Duratomic coating is superior to traditional coatings because of its atomic structure. The DurAtomic coating has a TiCN lower layer topped by the new Al_2O_3. The cutting parameters levels are selected according to the recommendations of the cutting inserts manufacturer.

2.2. Method: 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 [15]. 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 no. 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 [15]. Numerous researchers have been used Taguchi method to materials processing for process optimization [16-21]. In the present work the first criterion selects the-smaller-the-better characteristic of the flank wear and surface roughness (R_a).

Smaller the better type S/N ratio for flank wear V_B,

$$[\eta] = -10\log_{10}\left[V_B^2\right]$$

Smaller the better type S/N ratio for R_a,

$$[\eta] = -10\log_{10}\left[R_a^2\right]$$

3. Results and Discussion

Experiments are conducted to investigate the effects cutting parameters on the flank wear a Duratomic CVD coated tool on 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.

Table 3. Experimental Results.

Trial No.	Cutting Speed (*A*) m/min	Feed (B) mm/rev	Depth of cut (C) mm	Nose radius(D) mm	Flank Wear (V_B), mm	Surface roughness (R_a), µm
1	150	0.15	0.5	0.4	0.2175	1.425
2	150	0.2	1	0.4	0.1783	2.363
3	150	0.25	1.5	0.8	0.2615	1.06
4	150	0.3	2	0.8	0.2203	0.867
5	170	0.15	1	0.8	0.3273	2.432
6	170	0.2	0.5	0.8	0.2259	1.515
7	170	0.25	2	0.4	0.4847	3.33
8	170	0.3	1.5	0.4	0.6108	4.232
9	190	0.15	1.5	0.4	0.173	1.385
10	190	0.2	2	0.4	0.3763	1.75
11	190	0.25	0.5	0.8	0.3238	2.332
12	190	0.3	1	0.8	0.2106	1.992
13	210	0.15	2	0.8	0.1989	0.962
14	210	0.2	1.5	0.8	0.3097	1.017
15	210	0.25	1	0.4	0.2932	2.932
16	210	0.3	0.5	0.4	0.1938	1.295

3.1. Analysis of variance (ANOVA)

The ANOVA used to determine the optimum combination of process parameters more accurately by investigating the relative importance of process parameters (Ross, 1996). The present work employed ANOVA. Table 4 presents the results of ANOVA for flank wear. It is observed from the ANOVA table, the cutting speed (49.53%) is the most significant parameter followed by feed (29.12%). Table 5 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 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 [15]. Larger F-values are observed for cutting speed as 2.46. It is also observed that there is negligible error contribution (0.01% for Ra and 0.002% for V_B). It indicates the absence of the interaction effects of process parameters. In other words, interaction effects are negligible for minimizing flank wear and surface roughness.

Table 4. ANOVA Results of Flank Wear.

Source	Degrees of freedom	Sum of Squares	Mean Squares	F value	Contribution (%)
Speed	3	0.045553	0.015184	2.33423	49.523
Feed	3	0.02678	0.008927	1.3722	29.114
Depth of cut	3	0.015755	0.005252	0.807302	17.128
Nose radius	1	0.003894	0.003894	0.598616	4.233
Error	5	0.032524	0.006505	--	0.002
Total	**15**	**0.091982**			

Table 5. ANOVA Results for Surface Roughness.

Source	Degrees of freedom	Sum of Squares	Mean Squares	F value	Contribution (%)
Speed	3	5.164	1.728	3.5121	46.05
Feed	3	1.909	0.636	1.2926	16.96
Depth of cut	3	1.495	0.498	1.0121	13.28
Nose radius	1	2.669	2.669	5.4247	23.70
Error	5	2.462	0.492		0.01
Total	**15**	**8.796**			

3.2. Main effect plots analysis

The analysis is made with the help of a software package MINITAB 14. The main effect plots are shown in Figs. 1 and 2. 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. The main effects plots are used to determine the optimal design conditions to obtain the optimum flank wear. Figure 1 shows the main effect plot for flank wear. According to this main effect plot, the optimal conditions for minimum flank wear 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).

Figure 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).

Interestingly both the performance responses have the same set of optimal machining parameters.

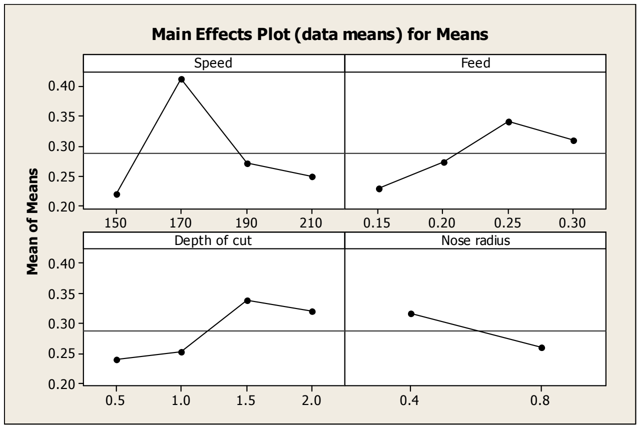

Fig. 1. Main Effect Plot for Flank Wear.

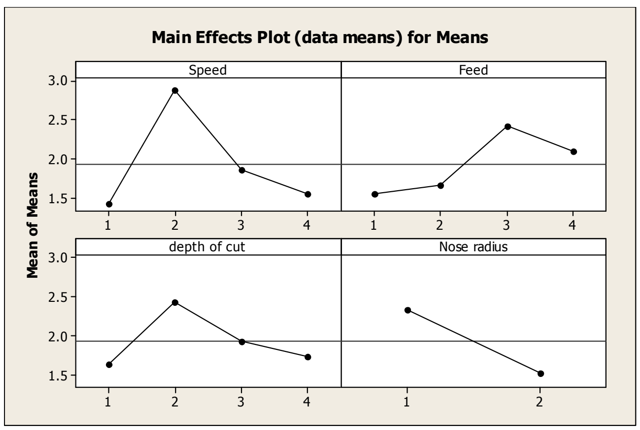

Fig. 2. Main Effect Plot for Surface Roughness.

3.3. Prediction of optimal design

Performance of *Ra* when the two most significant factors are at their better level (based on estimated average)

$\overline{\mu}_{A_1B_1} = \overline{A}_1 + \overline{B}_1 - \overline{T}$ = 1.429 +1.522 – 1.930 = 1.021 (From Table 3, $\overline{T}$ = 1.930)

$\overline{A}_1 ==$ 1.429; $\overline{B}_1 =$ 1.522 (From Table 6)

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

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

$n_{efficiency} = N/(1+dof) = 16/(1+1+3) = 3.2$

V_{error}= 0.492 (from Table 4), $F_{95\%,1,5}$ = 6.61 (From F-table)

$CI = \sqrt{6.61 \times 0.492 / 3.2}$ =1.008

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

$$1.021 - 1.008 \le \overline{\mu}_{A_1B_1} \le 1.021 + 1.008$$

$$0.013 \le \overline{\mu}_{A_1B_1} \le 2.029$$

Table 6. Mean Values of Surface Roughness (R_a).

Level	Cutting Speed m/min.	Feed Mm/rev.	Depth of Cut mm	Nose Radius mm
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 V_B when the two most significant factors are at their better level (based on estimated average)

$\overline{\mu}_{A_1C_1} = \overline{A}_1 + \overline{C}_1 - \overline{T}$ =0.2194+0.2292–0.27535=1.021 (From Table 3, $\overline{T}$=0.27535)

$\overline{A}_1$ = = 0.2194; $\overline{C}_1$ = 0.2292 (From Table 7)

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

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

$n_{efficiency} = N/(1+dof) = 16/(1+3+3) = 3.2$

V_{error}= 0.006505 (from Table 4), $F_{95\%,1,5}$ = 6.61 (From F-table)

$CI = \sqrt{6.61 \times 0.006505 \ / \ 2.2857}$ =1.3715

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

$$0.0361 \le \overline{\mu}_{A_1B_1} \le 0.3104$$

Table 7. Mean Values of Flank Wear (V_B).

Level	Cutting Speed m/min.	Feed Mm/rev.	Depth of Cut mm	Nose Radius mm
1	0.2194	0.2292	0.2403	0.2910
2	0.3622	0.2726	0.2524	0.2598
3	0.2709	0.3408	0.2888	-
4	0.2489	0.2589	0.3201	-

3.4. Mathematical modeling

A multiple linear regression model was developed for flank wear 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×Speed + 0.239×Feed- .025×depth of cut-0.817×Nose radius

The regression equation for flank wear

V_B=0.227-0.0053×Speed+0.0307×Feed+0.0326×depth of cut-0.0562×Nose radius

The diagnostic checking has been performed through residual analysis for the developed models. The residual plots are shown in Figs. 3 to 6. The residuals are generally fall on a straight line implying that errors are distributed normally. From Figs. 3 and 5 it can be concluded that all the values are within the confidence interval level of 95 %. Hence, these values yield better results in future prediction. These figures indicated that there is no obvious pattern and unusual structure. From Figs. 3 to 6, it can be conclude that the residual analysis does not indicate any model inadequacy.

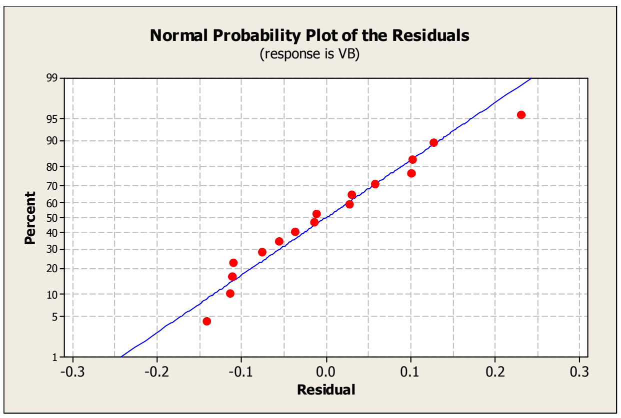

Fig. 3. Normal Probability of the Residuals.

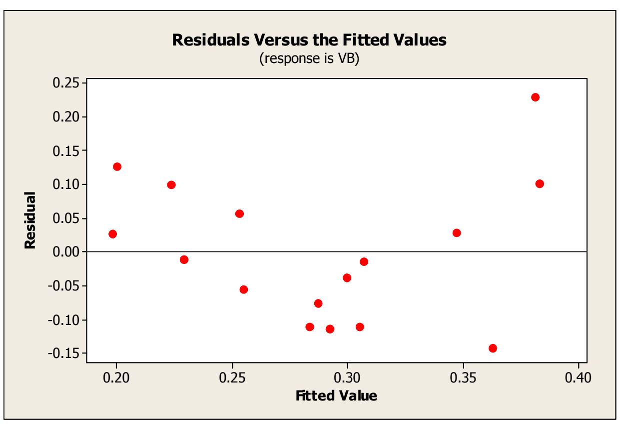

Fig. 4. Residuals versus the Fitted Values.

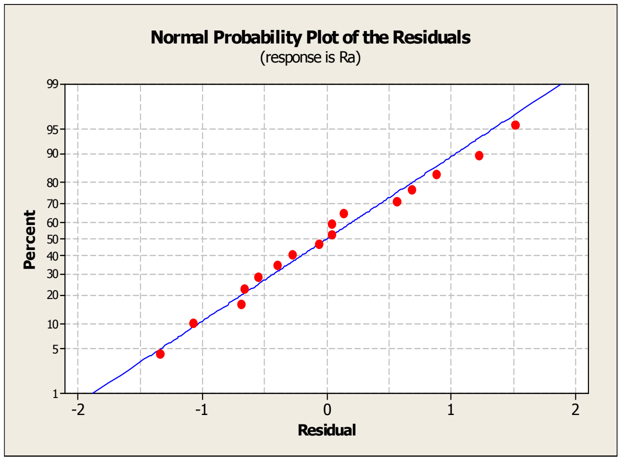

Fig. 5. Normal Probability of the Residuals for Surface Roughness.

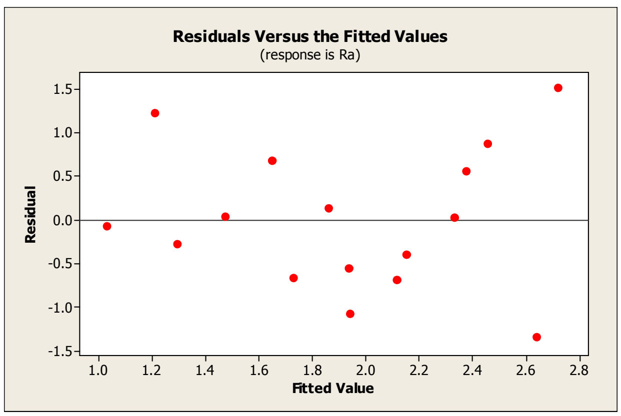

Fig. 6. Residuals versus the Fitted Values for Surface Roughness.

4. Conclusions

The experimental investigation conducted to turn AISI 304 austenitic stainless steel using CVD coated cemented carbide tool at four levels by employing Taguchi technique to determine the optimal levels of process parameters. The conclusions of the investigation can be drawn as follows:

- The ANOVA revealed that the Cutting speed is the most dominant parameter that has the highest influence on flank wear (49.52%) and surface roughness (46.05%).
- The optimal combination of process parameters for obtaining minimum flank wear values and minimum surface roughness values at 150 m/min cutting speed, 0.15 mm/rev feed, 0.5 mm depth of cut and 0.8 mm nose radius.

- Multiple linear regression models were developed for surface roughness values of work piece and flank wear values of the cutting tool. The developed models were reasonably accurate and can be used for prediction within limits. The Optimal range of flank wear and surface roughness values of the cutting tool is also predicted.
- The present work may be extended to study the influence of process parameters on other responses like tool –chip interface temperature, cutting tool vibration.

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