Optimization of Turning Process Parameters for AISI 4340 Steel using Taguchi Method

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Abstract -*Manufacturing technology has been a driving force behind modern economies since the Industrial Revolution. Although manufacturing techniques have become more sophisticated in the improvement of industrial products and processes. Quality is designed, not manufactured into the product. The key element for achieving high quality and low cost is parameter design. Through parameter design, levels of product and process factors are determined, product's functional characteristics are optimized and the effect of noise is minimized.*

Advances in material sciences have greatly enhanced our ability to develop predictive capability and to achieve the goal of optimization for a wide variety of applications. The objective of the present work is to apply Taguchi method to investigate the effects of turning parameters such as cutting speed, depth of cut and feed rate on surface roughness, Material removal rate and Power consumption in dry Turning of EN 24 steel using Chemical Vapour Deposition tool. The Signal–to- Noise (S/N) ratio and ANOVA are used to analyse the effect of cutting parameters on the quality characteristic of machined work piece.

A series of experiments are performed based on L27 orthogonal array. Theoretical analysis has been performed to find the critical parameters. Based on orthogonal array of L27 DOE the experiments were conducted to predict the surface roughness (Ra), Material removal rate (MRR) and Power consumption (PC) and the main objective of this experiment is to predict the better operating conditions and also the influence of each parameter is evaluated. This indicates application feasibility of the aforesaid techniques for correlated response optimization and off-line quality control in turning operation.

Keywords: *Manufacturing technology, optimization, Taguchi method, ANOVA, orthogonal array, Material removal rate (MRR), Turning operation.*

1. INTRODUCTION

Alloys steels, especially AISI 4340 are the mostly used materials for high production in industrial applications such as casting, metal forming, machining and sintering. During machining of these steels, high cutting zone temperature are generated which affects the quality characteristics and tool life. The performance of cutting tool is higher if the cutting edge of the tool is used for longer time. Due to tool wear, the tool has to be changed so that a fresh edge can be used, which leads to increase in production time and cost. The most commonly used tool materials for machining alloy steel are coated, uncoated carbides and high speed steel. The tools have to withstand high temperature and stress during turning; they have to be shock resistant during Turning, corrosion resistant and chemically inert towards the work piece material. Moreover, the machining forces play an important role in the generation stresses and temperature in the machined surface. They further affect the stresses and temperature along tool-chip and tool-work interfaces. All these effects finally led to poor surface integrity if the working conditions or cooling methods are not properly selected. Therefore, it is important to know the machining factors, which reduces the cutting forces, tool wear and surface roughness.

The turning operation is a machining operation performed on metals that is used widely in various industries working on metal cutting. The machining parameters selected for a turning operation is an important procedure in order to achieve high performance. Surface roughness is a term considered as a product quality index that is used to measure the surface finish of a product. As better as the surface finish, we can get the improved strength properties. The best parameter to judge the quality of turned product is surface roughness which is very important for a product. Surface roughness is one of the most commonly used criteria to determine quality of a turned surface. Surface roughness gives product a longer life, strength properties & affects the functional properties like friction, heat transmission, light reflection properties, etc. Production cost of an individual product is also get affected by surface roughness. As we try to minimize the surface roughness, we can accomplish towards the optimal parameters by optimizing some of the cutting parameters.

2. TAGUCHI METHOD

The Taguchi approach is a controlling tool for designing a process based on the OA- Orthogonal Array. ANOVA used to minimize the number of experiments and also efficiently improve the processes. In this investigation consider the responses of surface roughness (Ra), Material removal rate (MRR) and Power consumption (PC) and the input parameters are Speed, Feed and Depth of cut .

This study considers the design of experiments of L27 orthogonal array the step by step procedure performed in the Taguchi approach is given below;

Step 1: Parameter Selection and identification of control factors
Step 2: Identification of each factors level
Step 3: Selection of an Orthogonal Array (OA) experiment
Step 4: Execution of matrix experiment by assigning control factor to columns of OA
Step 5: Data analysis to predict the optimal value and evaluate the performance
Step 6: Verification and confirmation of analyzed data.

3. EXPERIMENTAL DETAILS

3.1 Work Piece Material

AISI 4340 is an unalloyed medium carbon steel with good tensile strength and suitable for manufacturing automobile parts, axles, shafts etc. It is normally supplied in cold drawn or as rolled. Tensile properties can vary but are usually between 500-800 N/mm2. AISI 4340 is available from stock in bar and can be cut to your requirements. The chemical composition for the chosen work material is given in the Table 3.1 with diameter Ø50 mm and length 300mm.

Table 3.1 chemical composition of AISI 4340

Element	Composition (%)
Fe	95-96
Ni	1.65-2.0
Cr	0.7-0.9
Mn	0.6-0.8
C	0.37-0.43
Mo	0.2-0.3
Si	0.15-0.3
S	0.04
P	0.035

3.2 Tool Material:

The composition of selected CVD tool is as follows (Tic + Al_2O_3 + Tin), it is having coating layer with gold colour .The grade number of the selected tool is CA 5525, for this tool Density- 14.5, Hardness(HV)-1400, Young's Modulus(Gpa)-13.7, Fracture toughness, Flexural toughness(Mpa)-2780. The model picture for CVD CA5525 tool is as shown below figure 3.1.

Fig: 3.1 CVD CA5525 Tool

3.3 Experimental set up and procedure

A Lathe machine was used for conducting the experiments. AISI 4340 was used as the work material and CVD coated cemented carbide tipped tool was used as the cutting tool. The average surface roughness on the work piece was measured using Mitutoyo surface finish measuring instrument. The experimentation for this work was based on Taguchi's design of experiments (DOE) and orthogonal array. A large number of experiments have to be carried out when the number of the process parameters increases. To solve this task, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. In this work, three cutting parameters namely, cutting speed, depth of cut and feed rate were considered for experimentation. Accordingly, there are four input parameters and for each parameter three levels were assumed. For three factors, three level experiment, Taguchi had specified L_{27} (3^3) orthogonal array for experimentation. The response obtained from the trials conducted as per L_{27} array experimentation was recorded and further analysed. The design of experiment (DOE) is an effective approach to optimize the throughput in various manufacturing-related processes. The DOE has been implemented to select manufacturing parameters that could result in a better-quality product. In this study, the minimum surface roughness of cylindrical work piece and cutting forces was investigated. The L_{27} orthogonal array was selected for this study.

Fig: 3.2: Experimental setup

Fig: 3.3: surface roughness measuring instrument

3.4 Plan of Experiments:

The cutting parameters of machining of AISI 4340 are cutting speed, feed, and depth of cut are taken as three levels as shown below Table 3.2

Level	Speed (s) (rpm)	Feed rate(f) (mm/rev)	Depth of cut(d) (mm)
1	740	0.09	0.15
2	580	0.07	0.10
3	450	0.05	0.05

Table 3.2 Process parameters and their levels

Turning was performed with three parameters: Speed, Feed, Depth of cut and varying them for three levels.

S.No.	Speed, s (rpm)	Feed, f (mm/rev)	Depth of cut, d(mm)
1	740	0.09	0.15
2	740	0.09	0.1
3	740	0.09	0.05
4	740	0.07	0.15
5	740	0.07	0.1
6	740	0.07	0.05
7	740	0.05	0.15
8	740	0.05	0.1
9	740	0.05	0.05
10	580	0.09	0.15
11	580	0.09	0.1
12	580	0.09	0.05
13	580	0.07	0.15
14	580	0.07	0.1
15	580	0.07	0.05
16	580	0.05	0.15
17	580	0.05	0.1
18	580	0.05	0.05
19	450	0.09	0.15
20	450	0.09	0.1
21	450	0.09	0.05
22	450	0.07	0.15
23	450	0.07	0.1
24	450	0.07	0.05
25	450	0.05	0.15
26	450	0.05	0.1
27	450	0.05	0.05

Table 3.3: Orthogonal array with process parameters

A set of experiments were performed based on the run order generated by the Taguchi model. The responses for the model are surface roughness (Ra), Material removal rate (MRR) and Power consumption (PC). In Orthogonal array, first column is assigned to speed (N), second column is assigned to feed (mm/rev) and third column is assigned to Depth of cut (mm) and the remaining columns are assigned to their interactions.

. The Signal to Noise (S/N) ratio, which condenses the multiple data points within a trial, depends on the type of characteristic being evaluated. In this study, "smaller the better" characteristic was chosen to analyze the surface roughness (Ra) and Power consumption (PC). The S/N ratio for the surface roughness (Ra) and Power consumption (PC) "smaller the better" characteristic given by Taguchi, is logarithmic transformation of the loss function, is given as:

$$S/N = -10 \log [1/n (\Sigma y^2)]$$

Where y is the observed data (surface roughness (Ra) and Power consumption (PC)) and n is the number of observations. The above S/N ratio transformation is suitable for minimization of surface roughness (Ra) and Power consumption (PC).The response table for signal to noise ratios shows the average of selected characteristics for each level of the factor. This table includes the ranks based on the delta statistics, which compares the relative value of the effects. S/N ratio is a response which consolidates repetitions and the effect of noise levels into one data point. Analysis of variance of the S/N ratio is performed to identify the statistically significant parameters.

In this study, "Larger the better" characteristic was chosen to analyze the Material removal rate (MRR). The S/N ratio for the Material removal rate (MRR) "Larger the better" characteristic given by Taguchi, is logarithmic transformation of the loss function, is given as:

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum\frac{1}{y^2}\right).$$

Where y is the observed data (Material removal rate (MRR)) and n is the number of observations. The above S/N ratio transformation is suitable for maximization of Material removal rate (MRR). The response table for signal to noise ratios shows the average of selected characteristics for each level of the factor. This table includes the ranks based on the delta statistics, which compares the relative value of the effects. S/N ratio is a response which consolidates repetitions and the effect of noise levels into one data point. Analysis of variance of the S/N ratio is performed to identify the statistically significant parameters.

4. RESULTS AND DISCUSSION

4.1 Experimental Observations for AISI 4340 on CVD

Based on orthogonal array of L_{27} DOE the experiments were conducted to predict the surface roughness (Ra), Material removal rate (MRR) and Power consumption (PC), and the main objective of this experiment is to predict the better operating conditions and also the influence of each parameters is evaluated. Therefore, the experiments are conducted with cutting tool CVD on AISI 4340 for L_{27} to predict Ra, MRR and PC. From the experimental data Taguchi analysis is carried out which is explained in the section.

Based on the orthogonal array L_{27} the parameters such as surface roughness (Ra), Material removal rate (MRR) and power consumed (PC) are experimentally evaluated and the responses for Surface roughness (Ra), Material Removal Rate (MRR) and power consumed (PC) are shown in the Table 4.1 below.

Table 4.1: Experimental Observations for CVD tool

S.No	Speed, s (rpm)	Feed, f (mm/rev)	Depth of cut, (mm)	Surface Roughness Ra (μm)	Material removal rate (mm^3/min)	Power Consumed (kw)
1	740	0.09	0.15	2.8422	0.75	9.3416
2	740	0.09	0.1	4.7161	0.394737	11.75489
3	740	0.09	0.05	2.8118	0.266667	10.3628
4	740	0.07	0.15	4.1796	0.4	10.5261
5	740	0.07	0.1	4.8156	0.674157	8.74391
6	740	0.07	0.05	4.6386	0.514286	7.73641
7	740	0.05	0.15	5.2697	0.580645	9.164832
8	740	0.05	0.1	4.1441	0.45283	7.66528
9	740	0.05	0.05	3.9445	0.514286	5.3281
10	580	0.09	0.15	2.73	0.761905	7.286254
11	580	0.09	0.1	5.8497	0.461538	5.01187
12	580	0.09	0.05	2.8809	0.48	6.17281
13	580	0.07	0.15	4.8045	0.643432	7.848
14	580	0.07	0.1	4.2464	0.571429	6.72485
15	580	0.07	0.05	3.733	0.45	8.766383
16	580	0.05	0.15	6.985	0.638298	5.445271
17	580	0.05	0.1	4.3915	0.633803	4.361176
18	580	0.05	0.05	3.9445	0.327273	5.12973
19	450	0.09	0.15	3.4964	0.461538	7.659078
20	450	0.09	0.1	3.7343	0.164384	4.970542
21	450	0.09	0.05	1.972	0.338028	7.3297
22	450	0.07	0.15	5.4475	0.474308	3.792101
23	450	0.07	0.1	3.9944	0.645161	4.56132
24	450	0.07	0.05	2.518	0.116732	5.37698
25	450	0.05	0.15	5.1373	1.929825	6.42373
26	450	0.05	0.1	2.6061	0.098361	5.61887
27	450	0.05	0.05	2.8618	0.106572	3.709838

4.2 Analysis of Signal-to-Noise ratio

In Taguchi's method S/N ratio indicates the order of controlling parameters according to their dominance. Response table for S/N ratios of surface roughness (Ra) displayed in below table 'Smaller-the-better' characteristic was chosen for present analysis. The difference between the peak values gives the delta value of corresponding controlling parameter as shown in below Table 4.2.

Level	Speed(S)	Feed(f)	Depth of Cut(d)
1	-10.517	-12.447	-9.981
2	-12.505	-12.424	-12.447

3	-12.181	-10.333	-12.776
Delta(max-min)	1.988	2.115	2.795
Rank	**3**	**2**	**1**

Table 4.2. Response Table for Signal to Noise Ratios for CVD tool [Ra]

For the CVD material the S/N ratios are plotted in the Figures 4.1. shows that level 2-2-3 for the parameters (speed, feed, and depth of cut) is the best level for the response surface roughness (Ra).

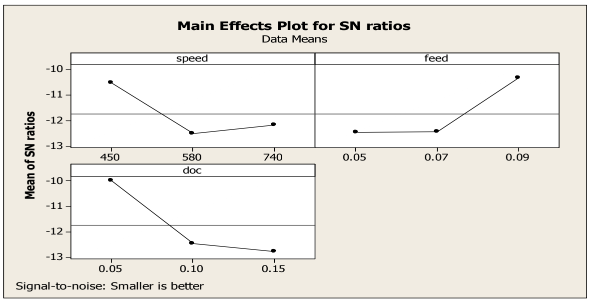

Fig 4.1: S/N ratio for Surface roughness (Ra) on CVD tool

Optimal testing conditions of those control factors could be very easily determined from the response graph.

Parameter	Level	Value
speed	2	580
feed	2	0.07
Depth of cut	3	0.15

Table 4.3. Optimal levels for Signal to Noise Ratios for CVD tool [Ra]

Response table for S/N ratios of Power consumption (PC) displayed in below table 'Smaller-the-better' characteristic was chosen for present analysis. The difference between the peak values gives the delta value of corresponding controlling parameter as shown in below Table 4.4.

Level	Speed(S)	Feed(f)	Depth of Cut(d)
1	-14.54	-15.08	-16.09
2	-15.79	-16.64	-15.93
3	-18.85	-17.46	-17.15
Delta(max-min)	4.31	2.38	1.22
Rank	**1**	**2**	**3**

Table 4.4: Response Table for Signal to Noise Ratio for CVD tool [Power Consumption]

For the CVD material the S/N ratios are plotted in the Figures 4.2. Shows that level 3-3-3 for the parameters (speed, feed, and depth of cut) is the best level for the response Power consumption (PC).

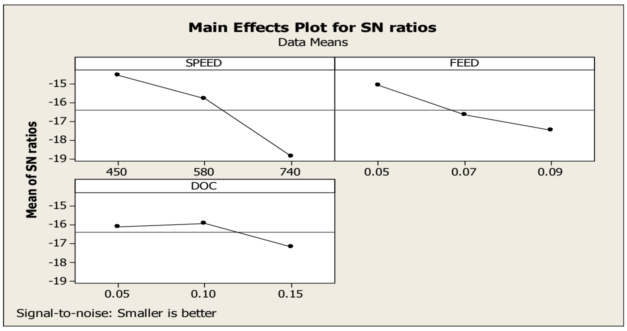

Fig4.2: S/N ratio for Power Consumed on CVD tool

Optimal testing conditions of those control factors could be very easily determined from the response graph.

Parameter	Level	Value
speed	3	740
feed	3	0.09
Depth of cut	3	0.15

Table 4.5. Optimal levels for Signal to Noise Ratios for CVD tool [power consumed]

Response table for S/N ratios of Material removal rate (MRR) in below table 'Larger-the-better' characteristic was chosen for present analysis. The difference between the peak values gives the delta value of corresponding controlling parameter as shown in below Table 4.6.

Level	Speed(S)	Feed(f)	Depth of Cut(d)
1	-10.516	-7.647	-10.397
2	-5.405	-6.859	-8.172
3	-6.288	-7.703	-3.639
Delta(max-min)	5.111	0.844	6.757
Rank	**2**	**3**	**1**

Table 4.6: *Response Table for Signal to Noise Ratio for CVD tool [MRR]*

For the CVD material the S/N ratios are plotted in the Figures 4.3. Shows that level 2-2-3 for the parameters (speed, feed, and depth of cut) is the best level for the response Material removal rate (MRR).

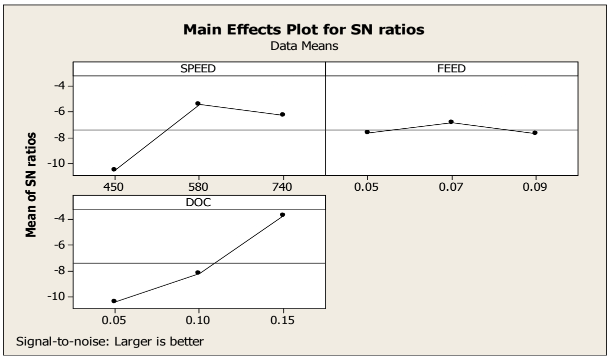

Fig 4.3: S/N ratio for Material removal rate on CVD tool

Optimal testing conditions of those control factors could be very easily determined from the response graph.

Parameter	Level	Value
speed	2	580
feed	2	0.07
Depth of cut	3	0.15

Table 4.5. Optimal levels for Signal to Noise Ratios for CVD tool [MRR]

5. ANALYSIS OF VARIANCE (ANOVA)

The experimental results were analysed with the analysis of variance (ANOVA), which is used to investigate which design parameters significantly affect the quality characteristic. This is too accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error.

The results of ANOVA for the responses surface roughness (Ra), Material removal rate (MRR) and Power Consumption (PC) are shown the following Tables 5.1, 5.2 and 5.3. surface roughness (Ra) versus Speed (s), Feed (f), and Depth of cut (d), Power Consumption(PC) versus Speed (s), Feed (f), and Depth of cut (d) and material removal rate (MRR) versus Speed (s), Feed (f), and Depth of cut (d) interactions of parameters is also allowed to determine the effect of any two cutting parameters where as other parameter is maintained constant throughout the design of experiments.

SOURCE	DOF	SUM OF SQUARES	MEAN OF SQUARES	F RATIO	% OF CONTRIBUTION
Speed(S)	2	3.59096	1.795480	1.55713	13.7285501
Feed(F)	2	4.54964	2.274822	1.97284	17.393674
DOC(D)	2	8.31500	4.157503	3.60559	31.7889771
SXF	4	0.34266	0.085665	0.07429	1.31002538
SXD	4	2.63119	0.657797	0.57047	10.0592617
FXD	4	6.72742	1.681855	1.45859	25.7195053
ERROR	8	9.22455	1.153069		
TOTAL	26	26.1568			100

Table 5.1: ANOVA for the response surface roughness (Ra) on CVD tool

From Table 5.1 the % contribution of values for speed (13.72%), feed rate (17.39%) and depth of cut (31.78%). It is observed that the speed and depth of cut have great influence on surface roughness. The interactions speed X feed rate (SXF) (1.31%), speed X depth of cut (SXD) (10.05%) has negligible effect. But the interaction for feed rate X depth of cut (FXD) (25.71%) has more influence than other two interactions. Since this analysis is a parameter-based optimization design, from the above values it is clear that depth of cut is the major factor to be selected effectively to get the good surface finish.

SOURCE	DOF	SUM OF SQUARES	MEAN OF SQUARES	F RATIO	% OF CONTRIBUTION
Speed(S)	2	59.10341	29.55171	7.220334	66.75899
Feed(F)	2	16.6795	8.339748	2.037641	18.83997
DOC(D)	2	4.548608	2.274304	0.555678	5.137782
SXF	4	1.759423	0.439856	0.107469	1.987318
SXD	4	3.999739	0.999935	0.244313	4.517819
FXD	4	2.44184	0.61046	0.149153	2.758128
ERROR	8	32.74276	4.092845		
TOTAL	26	88.53252			100

Table 5.2: ANOVA for the response Power Consumed on CVD tool

From Table 5.2 the percentage contribution of values for speed (66.75%), feed rate (18.83) and depth of cut (5.13%). It is observed that the speed and feed of cut have great influence on Power Consumption. The interactions speed X feed rate (SXF) (1.98%), speed X depth of cut (SXD) (4.51%) and feed rate X depth of cut (FXD) (2.75%) have negligible influence. Since this analysis is a parameter-based optimization design, from the above values it is clear that speed is the major factor to be selected effectively for Power Consumption.

SOURCE	DOF	SUM OF SQUARES	MEAN OF SQUARES	F RATIO	% OF CONTRIBUTION
Speed(S	2	0.02304	0.011520	0.05473	1.73986563
Feed(F)	2	0.08311	0.041555	0.19745	6.2759712
DOC(D)	2	0.73587	0.367935	1.74825	55.5679469
SXF	4	0.10960	0.027400	0.13019	8.2763776
SXD	4	0.24736	0.061840	0.29383	18.678971
FXD	4	0.12528	0.031321	0.14882	9.46087847
ERROR	8	1.68366	0.210458		
TOTAL	26	1.32427 2			100

Table 5.3: ANOVA for the response Material removal rate (MRR) on CVD tool

From Table 5.3. The percentage contribution of values for speed (1.73%), feed rate (6.27%) and depth of cut (55.56%). It is observed that the depth of cut and feed have great influence on Material Removal rate. The interactions speed X feed rate (SXF) (8.27%) have negligible influence, speed X depth of cut (SXD) (18.67%) has greater influence than other two interactions and feed rate X depth of cut (FXD) (9.46%). Since this analysis is a parameter-based optimization design, from the above values it is clear that Depth of cut is the major factor to be selected effectively to get the maximum Material Removal rate.

6. CONCLUSIONS

The results obtained in this study lead to conclusions for turning of AISI 4340 after conducting the experiments and analysing the resulting data.

1. From the results obtained by experiment, the influence of surface roughness (Ra), Material Removal Rate (MRR) and Power Consumption (PC) by the cutting parameters like speed, feed and depth of cut is

- *The feed rate has the variable effect on surface roughness, cutting speed and depth of cut an approximate decreasing trend.*
- *Cutting speed, feed rate and depth of cut for Material Removal Rate have increasing trend.*
- *Power Consumption is increase with increase in cutting speed, feed rate and depth of cut.*

2. Taguchi method is applied for optimization of cutting parameters

Responses	Input parameters		
	Speed(rpm)	Feed(mm/rev)	DOC (mm)
Surface roughness **(Ra)** (min)	580	0.05	0.15
Material Removal Rate **(MRR)** (max)	580	0.07	0.15
Power Consumption **(PC)**	740	0.09	0.15

3. Analysis of Variance (ANOVA) is done and found that it shows:

The depth of cut has great influence for the response surface roughness (31.78%), Speed has great influence for the response Material removal rate (55.56%), and Depth of cut has great influence for the response Power consumption (66.75%).

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