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Optimization of Machining Parameters in Turning AISI 304 Using Taguchi Method and Principal Component Analysis

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Abstract*—The present study focuses on the optimization of machining parameters in turning AISI 304 using taguchi method and principal component analysis. Turning operations are carried out on AISI 304 in dry condition using a coated carbide insert. L_{27} orthogonal array of taguchi method is used to design the experiment with three input parameters (Cutting velocity, feed rate and overhang length) of three different levels to measure surface roughness and vibration amplitude. In the present study, S/N ratio is calculated as the logarithmic transformation of the loss function by using smaller-the-better criterion as minimum values of surface roughness and vibration amplitude is desired. From ANOVA analysis it is found that feed rate (39.65%) is the most influential factor followed by cutting velocity (30.27%) and overhang length (29.77%). Optimum levels of parameters have been identified from main effect plot. To validate the test result, confirmation test is performed to check whether the responses are correlated or not. From PCA analysis, 50 m/min cutting speed, 0.1 mm/rev feed and 35 mm overhang length is the optimum condition where surface roughness is 1.171 µm and vibration amplitude is 72.91 dB.

***Index Terms*— AISI 304, Turning, Surface roughness, Vibration amplitude, Taguchi method, Main Effects Plot, Principal component Analysis.**

◆

1 INTRODUCTION

Turning is a type of machining, a material expulsion process, which is utilized to make rotational parts by removing undesirable material. Turning activity using a single point cutting tool has been one of the most established and well-known strategies for metal cutting. It has even replaced grinding in few applications with lessened lead time without influencing the surface quality. In turning, it is essential to identify the proper parameters to get the high cutting execution. In this connection, two vital perspectives which are generally considered in turning tasks are vibration amplitude and surface roughness of the work-piece. Both roughnes and vibration amplitude requires attention both from industry personnel as well as in Research & Development, because these two factors greatly influence machining performances.

Surface quality is an important performance characteristic to evaluate the productivity of machine tools as well as machined components. Surface roughness is the critical quality indicator for machined surfaces. A good quality turning surface can lead to improvement in strength properties such as fatigue strength, corrosion resistance, assembly tolerance, wear rate, coefficient of friction, cleanability, thermal resistance and aesthetics etc.

Optimization of cutting parameters is valuable in terms of providing high precision and efficient machining. Therefore, an attempt is made to optimize machining parameters using coated tool by analysis of surface roughness and vibration amplitude. Due to their significantly higher hardness, carbide-cutting tools are more widely used in the manufacturing industry today than high-speed steels.

2 LITERATURE REVIEW

In a turning operation, it is important to select cutting parameters so that high cutting performance can be achieved. Selection of desired cutting parameters by experience or using handbook does not ensure that the selected cutting parameters are optimal for a particular machine and environment [1]. Surface finish is also characterized by surface roughness. It is the vertical deviations of the real form from the ideal form [2]. For a defined sampling length, surface roughness is defined by arithmetic average of the deviations (Ra). Friction and wear increases with surface roughness, thus decreasing the life of machine elements such as bearings [3]. Surface quality of machined workpieces is one of the most important parameters in machining processes. It is highly influenced by machine vibrations because chatter vibrations cause poor surface qualities [4].

In turning, the presence of tool vibration is a major factor that leads to poor surface finish, cutting tool damage, increase in tool wear and unacceptable noise [5]. Workpiece vibration affects not only cutting instability but also product surface roughness and tool wear. Machine tool components are subjected to wide range of loads, due to the modification in cutter geometry, workpiece hardness, speed, feed and depth of cuts. Determination of machine tool vibration is highly critical and instrumental in increasing the quality of machining [6].Ozel et al. [7] investigated the effects of workpiece hardness, cutting edge geometry, cutting speed and feed rate on surface roughness and resultant forces in the finish hard turning of AISI H13 steel.

Ibrahim Ciftci [8] presented the results of experimental work in dry turning of austenitic stainless steels (AISI 304 and AISI 316) using CVD multilayer coated cemented carbide tools. The results showed that cutting speed significantly affected the machined surface roughness values. Lalwani et al

[9] investigated the effect of cutting parameters on cutting forces and surface roughness in turning of MDN250 steel and have found that cutting forces and surface roughness do not vary much with cutting speed in the range of 55–93 m/min. D.V.V. Krishan Prasad [10] also found feed as the most significant factor in turning mild steel with HSS cutting tool among speed, feed, depth of cut, side rake angle and back rake angle. Among turning parameters like cooling conditions, cutting speed, feed rate and depth of cut in AISI 1050, feed rate is found as the most effective parameters [11]. . In turning mild steel using HSS (High Speed Steel) cutting tool, feed is also found to be the most influencing factor among speed, feed and depth of cut [12]. Murat Kiyak [13] investigated the effects of changes in the tool overhang in the external turning process on both the surface quality of the workpiece and tool wear. He observed that the surface roughness of workpiece increases as the tool overhang increases. Using the same tool overhang, the surface roughness of the workpiece increases as the DOC increases. K. KHALILI [14] studied the relations between tool overhang and vibration signal. The result of his paper shows that vibration signal increase with increased tool overhang.

Kilickap [15] studied the optimal combination parameters for minimizing burr height and surface roughness, which were determined by using Taguchi design. Meanwhile, the response surface method was employed to predict burr height and surface roughness in drilling Al-7075. S/N noise ratio and Analysis of Variance (ANOVA) approve that parameter more significantly affect the surface roughness is feed rate follow by cutting speed and depth of cut [16]. Malvade and Nipanikar [17] mentioned that Taguchi methods more focus on developing the design for manufacturing process for creating high quality product compared to statistical process control, which tries to control the factors that affect the product quality. Moshat [18] et al. stated that Taguchi method is one of the efficient tools in designing an experiment for creating a high quality product manufactured and was developed by Genichi Taguchi. Taguchi's orthogonal array (OA) is a step where provides less number of experiment run with high balanced combination of inputs. While Taguchi signal-to-noise ratios (S/N) is statistical measurement for the performance of the experiment for desired output. S/N ratios can be divided into three categories which is Nominal-is-Best (NB), Lower-the-Better (LB) and Higher-the-better (HB) and tits depending on the quality of the product or process being optimize. Highest S/N means the optimal parameters combination [19].

Principal Component Analysis (PCA) is a way of identifying patterns in the correlated data, and expressing the data in such a way to highlight their similarities and differences. The main advantage of PCA is that once the patterns in data have been identified, the data can be compressed, i.e. by reducing the number of dimensions, without much loss of information [20]. Application of PCA can eliminate multi co-linearity (correlation) of the output responses and transform these correlated responses into uncorrelated quality indices called principal components. Absence of correlation between the responses is the basic assumption for applying Taguchi optimization technique [18].

3 EXPERIMENTAL METHOD

3.1 Material and Experimental Details

The present work deals with turning AISI 304. The properties of AISI 304 is shown in Table 1. Turning operation is done under dry condition using a coated carbide insert. A solid bar of AISI 304 with 50 mm diameter and 300 mm length was used as workpiece. Experimental setup is shown in Figure 1.

TABLE 1
AISI 304 MATERIAL COMPOSITION

C	Cr	Fe	Mn	Ni	P	S	Si
Max 0.08%	18-20%	66.35-74%	Max 2%	8-10.5%	Max .045%	Max .03%	Max 1%

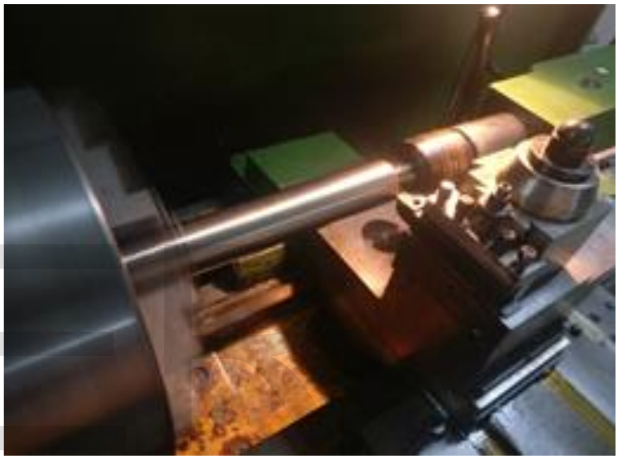


Fig. 1. Experimental Setup in turning AISI 304

The experimental instruments and cutting conditions have been summarized into the following table (Table 2).

TABLE 2
EXPERIMENTAL CONDITIONS

Machine Tool	Engine Lathe (Model: CS6266B)
Workpiece Material	AISI 304
Cutting Tool Holder	Carbon Steel
Cutting Tool Name	Single point side cutting tool
Cutting Tool Material	Coated Carbide
Cutting Environment	Dry
Surface Roughness Measuring Equipment	Surface Roughness Tester
Vibration Amplitude Measuring Equipment	Sound Level Meter

The present experimental work was done to find the optimal result for selection of cutting velocity (Vc), feed rate (f) and overhang length (OL) in order to achieve good surface roughness (Ra value) and lowest vibration amplitude. Table 3 represents selected process control parameters used during the experiments. These parameters have been segmented in three different levels which is shown in Table 3.

TABLE 3
ASSIGNMENTS OF FACTORS TO DIFFERENT LEVEL

Factor	Units	Level 1	Level 2	Level 3
Cutting Speed	m/min	50	75	100
Feed Rate	mm/rev	.1	.15	.2
Overhang length	mm	35	50	65

L_{27} orthogonal array was used to develop the combinations of machining parameters by Taguchi method. Taguchi method uses design of orthogonal arrays (OA) to study the process parameter with small number of experiments. Twenty seven experiments with combination of different cutting parameters are randomly repeated and the observed surface roughness and vibration amplitude values are shown in Table 4.

TABLE 4
EXPERIMENTAL DATA

	Input			Output	
Run No.	Cutting Speed,Vc m/min	Feed Rate,F mm/rev	Overhang Length,OL mm	Surface Roughness,Ra µm	Vibration Amplitude dB
1	50	0.1	35	1.279	73.69
2	50	0.1	35	1.171	72.91
3	50	0.1	35	1.258	73.25
4	50	0.15	50	1.282	73.32
5	50	0.15	50	1.291	73.38
6	50	0.15	50	1.273	73.4
7	50	0.2	65	1.286	73.07
8	50	0.2	65	1.281	73.1
9	50	0.2	65	1.279	73.14
10	75	0.1	50	1.267	73.45
11	75	0.1	50	1.313	73.51
12	75	0.1	50	1.285	73.39
13	75	0.15	65	1.28	73.12
14	75	0.15	65	1.275	72.98
15	75	0.15	65	1.271	73.43
16	75	0.2	35	1.233	71.26
17	75	0.2	35	1.227	72.03
18	75	0.2	35	1.239	71.17
19	100	0.1	65	1.255	73.19
20	100	0.1	65	1.278	73.21
21	100	0.1	65	1.219	73.72
22	100	0.15	35	1.217	71.31
23	100	0.15	35	1.232	71.46
24	100	0.15	35	1.296	71.39
25	100	0.2	50	1.221	71.18
26	100	0.2	50	1.253	71.14
27	100	0.2	50	1.233	72.02

3.2 Experimental Investigation

3.2.1 Taguchi Method

Taguchi's philosophy, developed by Dr. Genichi Taguchi, is an efficient tool for the design of high quality manufacturing system. Taguchi's Orthogonal Array (OA) provides a set of well-balanced experiments (with less number of experimental runs), and Taguchi's signal-to-noise ratios (S/N), which are logarithmic functions of desired output; serve as objective functions in the optimization process. Taguchi method uses a statistical measure of performance called signal-to-noise ratio. The S/N ratio takes both the mean and the variability into account. The S/N ratio is the ratio of the mean (Signal) to the standard deviation (Noise). The ratio depends on the quality characteristics of the product/process to be optimized. The standard S/N ratios generally used are as follows: Nominal-is-Best (NB), lower-the-better (LB) and Higher-the-Better (HB). The optimal setting is the parameter combination, which has the highest S/N ratio. Because, irrespective of the quality criteria may be (NB, LB, HB) S/N ratio should always be maximized [22].

Taguchi's S/N Ratio for (NB) Larger-the-best:

$$\frac{S}{N} = -10\log\left(\frac{\left(\Sigma\frac{1}{Y^2}\right)}{n}\right) \tag{1}$$

Taguchi's S/N Ratio for (NB) Smallerl-the-best:

$$\frac{S}{N} = -10\log\left(\frac{(\Sigma Y^2)}{n}\right) \tag{2}$$

Taguchi's S/N Ratio for (NB) Nominal-the-best:

$$\frac{S}{N} = -10\log\left(\frac{\mu^2}{\partial^2}\right) \tag{3}$$

Where μ^2 is the mean of the observed data, ∂^2 is the variance of observed data (Y^2), and n is the number of observed data.

3.2.2 Principal Component Analysis

Principal Component Analysis is a measurement reduction tool that can be utilized as a part of multi variable investigation issue. Principal Component Analysis goes for reducing a vast arrangement of variables to a small set that still contains the greater part of the data contained in the substantial set. It is a strategy to distinguish patterns in a data to feature their likenesses and contrasts. So the data can be compressed without losing any information. It is the most significant premise to re-express a noisy and garbled data collection. We often do not realize what estimations best mirror the elements of our system being referred to. At times we record a larger number of measurements than we truly require PCA alleviates this issue by mapping the original predictors into a set of principal components that is lesser in dimension than the number of the original variables such a transformation will usually be accompanied by a loss of information. The objective of PCA is, along these lines, to save however much information contained in the data as could reasonably be expected. The optimal number of principal components (PCs) expected to accomplish this task is not known a priori. The assignment is to locate a set of principal components with Eigen values that have a significantly larger value than the remaining components [19].

The basic equation of PCA is given by:

$$P_j = \sum_{i=1}^{r} (a_{ji} Y_i) \qquad \text{For } j = 1,2\ldots k \qquad (4)$$

Here, Y_i is the normalized value of i^{th} response (i=1,2, …r). The coefficient a_{ji} termed as Eigen vector.

Multi-response Performance Indicator can be measured as:

$$MPI = \sum_{j=1}^{k} (W_j P_j) \qquad (5)$$

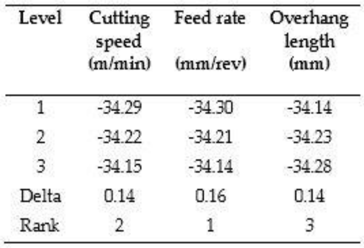
Here, W_j is regarded as weight of the corresponding principal component.

4 RESULTS AND DISCUSSIONS

4.1 Result on Taguchi analysis

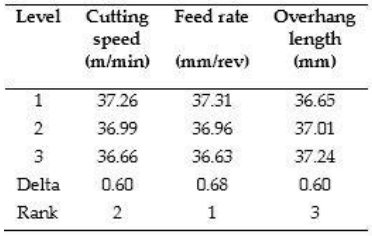
Influences of each design parameter (Cutting speed, feed rate and overhang length) on surface roughness and vibration amplitude is obtained from the response tables of S/N ratio. . Larger S/N ratio means it is close to good quality, thus, a higher value of the S/N ratio is desirable. S/N ratio is calculated based on smaller-the-better criterion for surface roughness and vibration amplitude is shown in Table 5. From Table 5 it is seen that feed rate is the most influential cutting parameter that effects surface roughness and vibration amplitude followed by cutting speed which has lesser influence on surface roughness and vibration amplitude. Overhang length has the least impact on surface roughness and vibration amplitude according to S/N ratio. The response table for mean is shown in Table 6 which also shows that feed rate has most influence on surface roughness and vibration amplitude followed by cutting speed and overhang length.

TABLE 5
RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS
(SMALLER IS BETTER)



Level	Cutting speed (m/min)	Feed rate (mm/rev)	Overhang length (mm)
1	-34.29	-34.30	-34.14
2	-34.22	-34.21	-34.23
3	-34.15	-34.14	-34.28
Delta	0.14	0.16	0.14
Rank	2	1	3

TABLE 6
RESPONSE TABLE FOR MEANS (SMALLER IS BETTER)



Level	Cutting speed (m/min)	Feed rate (mm/rev)	Overhang length (mm)
1	37.26	37.31	36.65
2	36.99	36.96	37.01
3	36.66	36.63	37.24
Delta	0.60	0.68	0.60
Rank	2	1	3

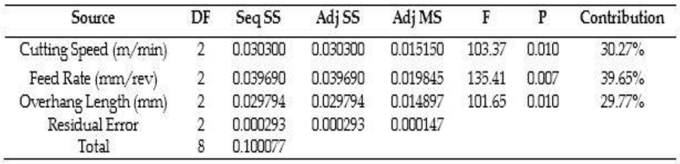
4.2 ANOVA (Analysis of Variance) for surface roughness and vibration amplitude

Analysis of variance for the response surface models were conducted in this study. Sum of squares (SS), degree of freedom (df), mean square (MS) and F-value for all the input variables along with are shown in table 5 for MQL assisted cutting environment.

Analysis of variance (ANOVA) is used to investigate which design parameter significantly affects the quality characteristics. This analysis is done for a significance level of α = 0.5 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.

Table 7 shows the results of ANOVA analysis for S/N ratios for both surface roughness and vibration amplitude. From Table 7, it is observed that the feed (39.65%) is the most significant parameter followed by cutting speed (30.27%) and overhang length (29.77%) which has less significance in controlling the surface roughness and vibration amplitude values. From the analysis of the Table 7, p-value of feed (0.007) which is less than 0.05. It means that feed's influence significantly on surface roughness and vibration amplitude between three cutting parameters.

TABLE 7
ANALYSIS OF VARIANCE FOR S/N RATIOS



Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
Cutting Speed (m/min)	2	0.030300	0.030300	0.015150	103.37	0.010	30.27%
Feed Rate (mm/rev)	2	0.039690	0.039690	0.019845	135.41	0.007	39.65%
Overhang Length (mm)	2	0.029794	0.029794	0.014897	101.65	0.010	29.77%
Residual Error	2	0.000293	0.000293	0.000147			
Total	8	0.100077					

Significant, F_{table} at 95% confidence level is $F_{0.05,\,4,8} = 19$, $F_{exp} \geq F_{table.}$

Table 8 shows the results of ANOVA analysis for means for both surface roughness and vibration amplitude and the result is almost similar to the result of S/N ratios.

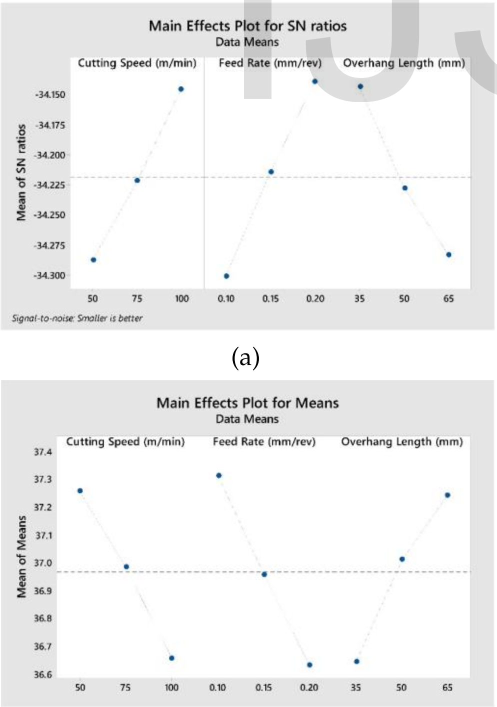
TABLE 8
ANALYSIS OF VARIANCE FOR MEANS

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
Cutting Speed (m/min)	2	0.54508	0.545076	0.272538	108.82	0.009	30.37%
Feed Rate (mm/rev)	2	0.69902	0.699025	0.349512	139.56	0.007	38.96%
Overhang Length (mm)	2	0.54517	0.545170	0.272528	108.94	0.009	30.38%
Residual Error	2	0.00501	0.005009	0.002504			
Total	8	1.79428					

Significant, Ftable at 95% confidence level is $F_{0.05,\ 4,8} = 19$, Fexp ≥ Ftable.

4.3 Main effect plot for surface roughness and vibration amplitude

From the S/N ratios given in the Tables 5 and 6 main effect plots were drawn using MINITAB-18 software and shown in the Figure 2. The plots show the variation of response with the change in cutting parameters. From the main effects plot for SN ratios and means (Figure 2(a,b), it is seen that minimum surface roughness and vibration amplitude is obtained at cutting velocity 100 m/min and feed rate 0.2 mm/rev and overhang length 35 mm. Thus, it can be concluded that higher cutting speed and higher feed rate along with minimum overhang length is required for better surface roughness and lowest vibration amplitude.



(a)

(b)

Fig. 2. Main Effects Plot for (a) SN ratios (b) Means

4.4 Result on Principal Component Analysis (PCA)

Considering 'smaller is better' criteria for both surface roughness and vibration amplitude, experimental results of Table 4 are normalized. The normalized data are shown in table 9.

TABLE 9
NORMALIZED VALUE OF SURFACE ROUGHNESS AND VIBRATION AMPLITUDE

Run	Surface Toughness (μm)	Vibration Amplitude (dB)
1	0.916	0.965
2	1.000	0.976
3	0.931	0.971
4	0.913	0.970
5	0.907	0.969
6	0.920	0.969
7	0.911	0.974
8	0.914	0.973
9	0.916	0.973
10	0.924	0.969
11	0.892	0.968
12	0.911	0.969
13	0.915	0.973
14	0.918	0.975
15	0.921	0.969
16	0.950	0.998
17	0.954	0.988
18	0.945	1.000
19	0.933	0.972
20	0.916	0.972
21	0.961	0.965
22	0.962	0.998
23	0.950	0.996
24	0.904	0.996
25	0.959	0.999
26	0.935	1.000
27	0.950	0.988

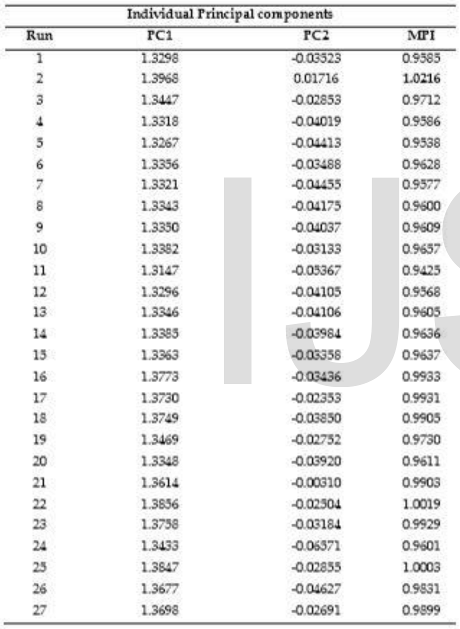
After normalization, a check has been made to verify whether the responses are correlated or not. The correlation coefficient between surface roughness and vibration amplitude becomes 0.456 (p-value= 0.017). As p-value is less than 0.05 and non-zero which indicates that the responses are correlated.

TABLE 10
PRINCIPAL COMPONENT ANALYSIS

	PC1	PC2
Eigenvalue	1.4557	0.5443
Eigenvector	0.707	0.707
	0.707	-0.707
AP	0.728	0.272
CAP	0.728	1

Principal Component Analysis (PCA) has been used to derive two principal components. Two principal components are denoted as PC1 and PC2. Table 11 represents the values of these independent principal components for 27 experimental runs. It has been found that 1st Principal Component itself can describe 72.8% variability in the data (AP=0.728). To calculate MPI (shown in table 11), accountability proportion has been utilized as individual weight of the principal components. The higher the MPI esteem the better the outcome. The combination, at which MPI is maximum, provides lowest surface roughness and vibration amplitude. From table 11 it is found that highest MPI value is 1.0216. That means 50 m/min cutting speed, 0.1 mm/rev feed and 35 mm overhang length is the optimum condition where surface roughness is 1.171 µm and vibration amplitude is 72.91 dB.

TABLE 11
PRINCIPAL COMPONENTS AND MPI



Individual Principal components			
Run	PC1	PC2	MPI
1	1.3298	-0.03523	0.9585
2	1.3968	0.01716	1.0216
3	1.3447	-0.02853	0.9712
4	1.3318	-0.04019	0.9586
5	1.3267	-0.04413	0.9538
6	1.3356	-0.03488	0.9628
7	1.3321	-0.04455	0.9577
8	1.3343	-0.04175	0.9600
9	1.3350	-0.04037	0.9609
10	1.3382	-0.03133	0.9657
11	1.3147	-0.05367	0.9425
12	1.3296	-0.04105	0.9568
13	1.3346	-0.04106	0.9605
14	1.3385	-0.03984	0.9636
15	1.3363	-0.03358	0.9637
16	1.3773	-0.03436	0.9933
17	1.3730	-0.02353	0.9931
18	1.3749	-0.03850	0.9905
19	1.3469	-0.02752	0.9730
20	1.3348	-0.03920	0.9611
21	1.3614	-0.00310	0.9903
22	1.3856	-0.02504	1.0019
23	1.3758	-0.03184	0.9929
24	1.3433	-0.06371	0.9601
25	1.3847	-0.02855	1.0003
26	1.3677	-0.04627	0.9831
27	1.3698	-0.02691	0.9899

5 CONCLUSION

In this experiment, an optimum condition of machining parameters was found to obtain minimum surface roughness and vibration amplitude. Taguchi method was used to design the experiment and to find the contribution of each parameters on surface roughness and vibration amplitude. Principal component analysis is used to optimize the machining parameters. Final outcomes of the work are as follows:

- From this analysis, it is found that feed rate is the most prominent factor followed by cutting speed and overhang length which affect the turning of AISI 304. ANOVA analysis for both S/N ratios and means shows almost same result. Feed rate has most influence (39.65%) on surface roughness and vibration amplitude where cutting speed (30.27%) and overhang length (29.77%) has less influence.
- From the main effects plot for SN ratios and means it is seen that minimum surface roughness and vibration amplitude is obtained at cutting velocity 100 m/min and feed rate 0.2 mm/rev and overhang length 35 mm. So, it can be concluded that higher cutting speed and higher feed rate along with minimum overhang length is required for better surface roughness and lowest vibration amplitude.
- Application of PCA has been recommended to eliminate response correlation by converting correlated responses into uncorrelated quality indices called principal components which have been as treated as response variables for optimization.
- 50 m/min cutting speed, 0.1 mm/rev feed and 35 mm overhang length is the optimum condition where surface roughness is 1.171 µm and vibration amplitude is 72.91 dB because of having highest MPI value.

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