PARAMETRIC OPTIMIZATION DURING TURNING OF AISI D3 STEEL USING TAGUCHI METHOD INTEGRATED WITH PRINCIPAL COMPONENT ANALYSIS

R.K.SURESH[1], B.LOHIT[2], DR. B.JAYACHANDRAIAH[3], P.DILEEP[4]
[1]Asst. Professor (Sr.), Dept. of M.E; **E-mail:** rayakuntapalli@gmail.com
[2]B. Tech Student, Dept. of M.E; **E-mail:** lohitb412@gmail.com
[3]Prof of M.E & Vice-Principal; **E-mail:** bjcskit2011@gmail.com
[4]Lecturer, Dept. of M.E; **E-mail:** dileepbrave@gmail.com
[1, 2, 3, 4]SriKalahasteeswara Institute of Technology (S.K.I.T), Sri Kalahasti, Chittoor Dt. A.P., India.

ABSTRACT:
To deal with the challenges that any modern machining industries face in achieving a high quality product, the proposed work aims to explore the effects of turning parameters on the performance characteristics of AISI D3 steel during turning operation. Factors like feed rate, cutting speed and depth of cut affect the performance characteristics such as surface roughness and Material Removal Rate (MRR). To get better surface finish and maximum MRR, the best optimal level of parameters has to be chosen carefully. This paper envisages the multi-objective optimization technique used in conjunction with Taguchi method and Principal Component Analysis (PCA).The experiments were performed based on Taguchi L9 Orthogonal Array (OA) by taking feed rate, cutting speed and depth of cut at three levels. The experiments were carried-out on conventional lathe with CVD coated cemented carbide as tool insert under Minimum Quantity Lubrication (MQL) condition. It was inferred that the cutting performance in turning operation could be enhanced effectively by applying this technique.

Keywords: *Material Removal Rate (MRR), Orthogonal Array (OA), turning operation, Principal Component Analysis (PCA)*

I. INTRODUCTION

The focus of any machining industry is to manufacture a product with low cost, high quality in short span of time. Productivity and quality are two conflicting objectives in any machining operations. Productivity can be increased with reduction in machining time that may hamper quality. On the other side, any improvement in quality comes at the expense of reduction in productivity as the machining time increases. Therefore, it is imperative to find the machining variables in such a manner that the desired quality is maintained without sacrificing the profit. Turning parameters such as feed, cutting speed, depth of cut has a very Considerable role on considered responses MRR and Surface Roughness.

Research study showed that the optimization in most cases was based on single objective function which leads positively in some aspects but it may affect adversely in other aspects. The problem can yield better results if multiple objectives are optimized simultaneously. Hence it is required to maximize material removal rate and minimize surface roughness concurrently by selecting an optimal process environment.

II. LITERATURE REVIEW

2.1 Introduction: Literature survey highlights immense efforts contributed by researchers in past related to turning operation to optimize various responses attribute. Moreover th article reviews the literature in detail to have a better insight of the problem discussed in this area.

S. Thamizhmanii *et al* [1], applied Taguchi Optimization Methodology to optimize cutting parameters for minimizing surface roughness using a robust design. The results showed that out of considered process parameters depth of cut played a notable role in minimizing surface roughness followed by feed, cutting speed has lower role on surface roughness from the tests. **H.S Lu *et al* [2],** had proposed PCA technique for the optimization of multi-performance characteristics in milling of steel wherein milling type, spindle speed and feed has contributed 79% in total; axial depth of cut and radial has showed comparatively less contribution among considered process parameters. **Raviraj Shettyet *al* [3],** focused the research on optimization of turning parameters for minimum surface roughness by

Surface Response Methodology (SRM). The results confirmed that optimum value of surface roughness found is 1.7Ra. They coupled their analysis with Taguchi method under pressured steam jet. **Sanjit Moshat *et al* [4]**, presented their research by eliminating correlations of individual response statistically by using PCA technique. **Yadav and Narang [5],** depicted a systematic procedure of using ANOVA analysis and Taguchi method for medium carbon steel. They inferred that process parameters – feed rate and cutting speed are making significant effect on surface roughness. It was observed that with the increase in feed rate, surface roughness also increases and as the cutting speed decreases the surface roughness increases. **Tao FU *et al* [6],** had focused on the development in optimization of milling variables in high speed milling of NAK 80 mold steel. Combination of Grey Relational Analysis and Taguchi analysis techniques were used to study the effects of process parameters were feed, cutting speed and depth of cut during machining operation. The experimental results proved that Grey Relational Analysis (GRA) combined with principal component analysis can be effectively implemented to derive an optimal setting of cutting parameters and the proposed approach can be considered as an effective methodology to reduce the cutting force. **Moshat *et al*** [**7],** attempted to adopt Principal Component Analysis (PCA) based Taguchi methodology to optimize the CNC end milling process parameters to obtain high surface finish and Material Removal Rate (MRR). This test incorporating PCA method proved to be beneficial for determining optimal setting (environment) for multi-objective problem.

2.2 OBJECTIVE OF THE PAPER:

An attempt is made in this proposed research to evaluate the optimal setting of turning parameters for minimization of surface roughness and maximization of material removal rate using the application of the Taguchi DOE concept and perform statistical analysis using PCA technique turning operation of AISI D3 steel using CVD coated carbide tool.

III. TAGUCHI METHOD AND PCA

Taguchi method is systematic and scientific tool for evaluating and implementing developments in products, processes, materials equipment, and facilities. Taguchi method focuses on robust design through use of Signal to noise ratio and Orthogonal array (OA). In this work Taguchi's DOE methodology is used in analyzing the effects of process parameters like feed, cutting speed and depth of cut on MRR and Surface Roughness of AISI-D3 work material while machining with CBN tool and to obtain an optimal setting of these parameters that may yield in effective productivity and surface finish.

The main aim of the analysis is to find the optimum turning parameters for obtaining minimum surface roughness and maximum material removal rate. Hence the concept of smaller-the-best for surface Roughness and larger the best for material removal rate were selected. The S/N ratio is the ratio of the mean (Signal) to the standard deviation (Noise). The standard S/N ratios generally used are as follows: Lower the Better (LB), Higher the Better (HB) and Nominal is Best (NB).

a. The smaller - the - better:

$$S/N = -10\log_{10}\left(\frac{\sum y2}{n}\right)$$

b. The larger- the - better:

$$S/N = 10\log_{10}\left(\frac{1}{n}\sum\frac{1}{y2}\right)$$

c. Nominal - the - best:

$$S/N = 10\log_{10}\left(\frac{y2}{s2}\right)$$

Principal Component Analysis is a dimension reduction tool that can be used in multi variable analysis problem. The objective of using PCA is to reduce a large set of variables to a small set that still contains most of the information contained in the large set. It is a method to identify patterns in a data in such a way as to highlight their similarities and differences. So the data can be compressed without losing any information.

Procedure Adopted for Optimization:

Step 1: Normalization of the responses (quality characteristics)

There are three different types of data normalization according to whether we require the LB (lower-the-better), the HB (higher-the-better) and NB (nominal-the-best). The normalization is taken by the following equations:

a) LB (lower-the-better)

$$X^*(i) = \frac{\max(X) - X(i)}{\max(X) - \min(X)}$$

b) HB (higher-the-better)

$$X^*(i) = \frac{X(i) - \min(X)}{\max(X) - \min(X)}$$

$X_i^*(k)$ is the normalized data of the *k th* element in the *ith* sequence. After data normalization, the value of $X_i^*(k)$ will be between 0 and 1. The series X_i^*, i=1, 2, 3,........, *m*. can be viewed as the comparative sequence used in the principal component analysis.

Step 2: Checking for correlation between two quality characteristics

It is the normalized series of the *ith* quality characteristic. The correlation coefficient between two quality characteristics is calculated as following:

$$R_{jk} = \frac{Cov(Qj, Qk)}{\sigma Q(i) * \sigma Q(k)}$$

Here,

j=1, 2, …. n , k=1, 2, …. n. j ≠ k

Where,

Cov(Qj , Qk) is the covariance of normalized quality characteristics Qj and Qk.

$\boldsymbol{\sigma}$Q(i) and $\boldsymbol{\sigma}$Q(k)is the standard deviation of normalized quality characteristics Qj and Qk.

Step 3: Calculation of the principal component score

Calculate the Eigen value λ_k and the corresponding Eigen vector β_k (k =1, 2,......, n) from the correlation matrix formed by all quality characteristics.

Calculate the principal component of the normalized reference sequence and comparative sequences using the equation shown below:

$$\boldsymbol{Y_i\ (k) = \sum_{j=1}^{n} Xi^*(j)\beta kj\ ,\ i = 0, 1, 2, \ldots, m;}$$
k=1,2,…, n.

where,

Y_i (k) is the principal component score of the *k th* element in the *ith* series. X_i *(j) is the normalized value of the j th element in the i th sequence, and β_{kj} is j th element of Eigen vector β_k.

The quality loss $\Delta_{0,i}$ (k) (compared to ideal situation) can be calculated as follows:

$$\boldsymbol{\Delta_{0,i}(k) = X_0(k) - X_i(k)}$$

Step 4: Evaluation of optimal setting

Optimal setting is then evaluated by minimizing this $\Delta_{0,i}$ (k) quality loss estimated by using Taguchi method

IV. EXPERIMENTAL DETAILS

The experimental tests were conducted for a work piece bar of 40mm diameter and 70mm length in a Kirloskar model centre lathe using three input cutting parameters feed, cutting speed, and depth of cut. For three factors, three level experiments, Taguchi's specified L9 design orthogonal array experimentation was considered and analyzed. The entire was conducted under Minimum Quantity Lubrication (MQL) condition with castor oil as lubricating fluid. Table 1 shows the parameters and their levels considered for experiment.

Work piece material and cutting tool insert:

AISI D3 steel was used as the work material and CVD coated cemented carbide was used as the cutting, its chemical composition is given in Table 2. The mechanical properties of the work piece are given in Table 3. Work piece bar of 40mm diameter and 70mm length was chosen for the experiment and surface roughness on the work piece was measured using SJ-201P surface roughness measuring instrument.

Material Removal Rate was calculated using the formula:

$$\text{MRR} = \frac{\pi(D^2-d^2)}{4} * \frac{l}{t}$$

Where,
D=Initial diameter of the work piece (before machining) (mm)
d=Final diameter of the workpiece (after machining) (mm)

l = Length of workpiece (mm)
t = Time taken for machining (sec)

Fig.1: SJ-201P Ra measuring instrument

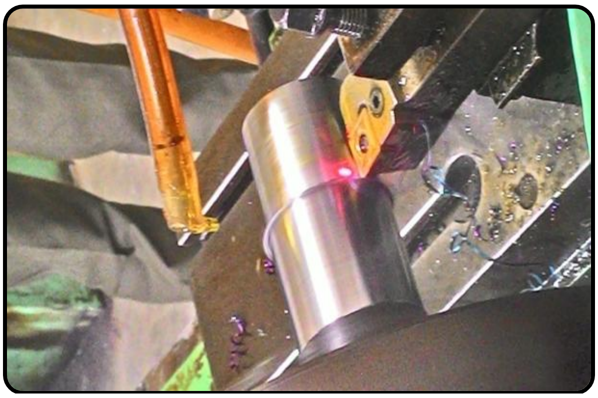

Fig.2: Turning process under MQL with castor oil

Table 1: The process parameters and their levels

Cutting Parameters	Level 1	Level 2	Level 3
Cutting Speed(m/min)	100	150	200
Feed(mm/rev)	0.05	0.07	0.09
Depth of cut(mm)	1.0	1.5	2.0

Table 2: Chemical composition of AISI D3 cold work Steel

Elements	C	Si	Mn	Cr	P	S	Ni	Mo	Al	B
%	2.179	0.511	0.511	12.634	0.027	0.021	0.050	0.178	0.042	0.065

Table 3: Mechanical Properties of Steel

Properties	Metric	Imperial
Izod Impact Unnotched	28.0 J	20.7 ft-lb
Poisson's ratio	0.27-0.30	0.27-0.30
Elastic modulus	190-210 GPa	27557-30457 ksi

V. EXPERIMENTAL DATA ANALYSIS AND EVALUATION OF OPTIMAL SETTING

The Table 4 below shows standard L9 OA designed by Taguchi with experimental results. The different units used here are: speed – rpm, feed – mm/rev, depth of cut – mm, surface roughness – Ra – µ-mm and MRR – mm^3/sec. After calculating the all data of responses for different combination, normalizing S/N ratios of MRR and Ra to be calculated is tabulated in table 5. The next step is to find out Eigen value and Eigen vectors for responses characteristics is given in Table 6.

Table 4: Experimental Observations of AISI D3 with CVD tool

S.No.	Cutting speed	Feed rate	Doc	Surface Roughness	Material Removal Rate
1	100	0.05	1.0	0.268	55.19
2	100	0.07	1.5	0.738	80.909
3	100	0.09	2.0	1.113	116.664
4	150	0.05	1.5	0.336	73.896
5	150	0.07	2.0	0.680	138.459
6	150	0.09	1.0	0.854	177.686
7	200	0.05	2.0	0.184	206.897
8	200	0.07	1.0	0.452	263.404
9	200	0.09	1.5	0.596	349.252

Table 5: Normalized SN Ratio

S.No	Cutting speed	Feed	Doc	Surface Roughness	Material Removal Rate	Normalized SNRA1	Normalized SNRA2
1	100	0.05	1.0	0.268	55.19	0.208931	0.00005
2	100	0.07	1.5	0.738	80.909	0.771723	0.207339
3	100	0.09	2.0	1.113	116.664	1.0000	0.405697
4	150	0.05	1.5	0.336	73.896	0.334564	0.158198
5	150	0.07	2.0	0.680	138.459	0.726247	0.498529
6	150	0.09	1.0	0.854	177.686	0.852832	0.633728
7	200	0.05	2.0	0.184	206.897	0.000005	0.716223
8	200	0.07	1.0	0.452	263.404	0.499337	0.847099
9	200	0.09	1.5	0.596	349.252	0.652991	1.00000

The effect of each response characteristic (Ra and MRR) using S/N data and means for each level of factor is shown in figure 3,4,5 and 6 respectively.

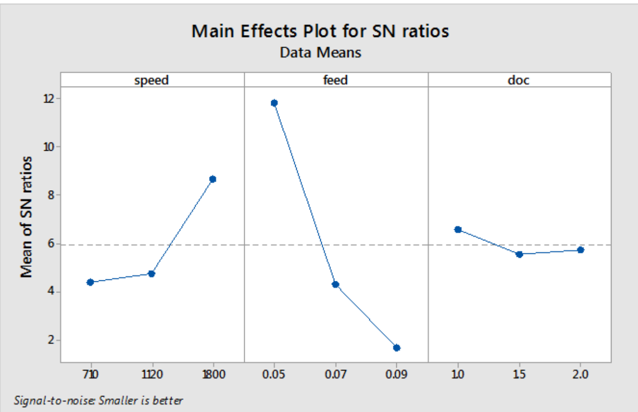

Fig.3: Main Effects Plot for SN ratios (Ra)

Fig.4: Main Effects Plot for Means (Ra)

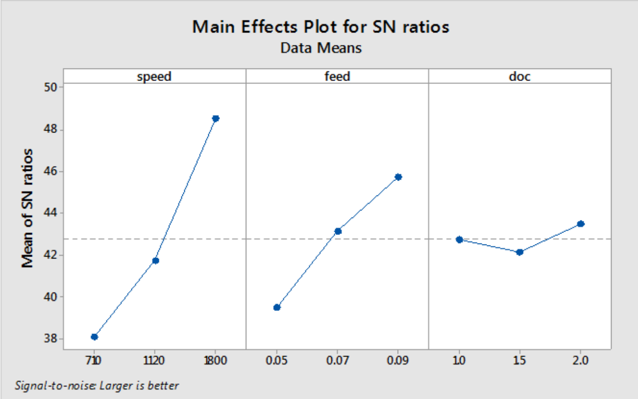

Fig.5: Main Effects Plot for SN ratios (MRR)

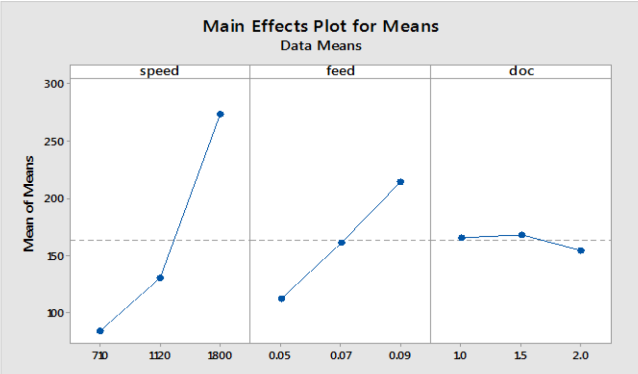

Fig.6: Main Effects Plot for Means (MRR)

Table 6: Obtained Eigen Values and Eigen Vectors

Eigen values	1.10578	0.89422
Eigen vectors	0.7071	0.7071
	0.7071	-0.7071
Ideal value	1.4142	0

Evaluation of Principal Components

To evaluate PC components response co-relation is to be eliminated. PCA is applied to derive two independent quality indices which are called principal components. These are denoted as 1 ψ (1st PC) and 2 ψ (2nd PC). Table 5 represents the values of these independent principal components for 9 experimental runs.

Principal components are determined in Table 6. These principal components are derived from the calculated values of normalized values of both performance characteristics-surface roughness and Material Removal Rate using the following formula:

$$\Psi(K) = \sum_{k=1}^{i} n(u) * \sigma(q)$$

Where,

Ψ (k) is the principal component corresponding to the kth experimental run, n(u) is the normalized value of corresponding quality characteristic. σ(q) is the qth element.

Table 7: Evaluation of Principal Component

Ψ1	Ψ2
0.14771	0.14477
0.69219	0.39901
0.99382	0.42017
0.34832	0.12469
0.86591	0.16099
1.05099	0.15490
0.50636	0.50637
0.95192	0.24587
1.16866	0.24534

Estimation of Quality Loss

Quality loss estimate can be calculated from the following equation:

$$\Delta = \text{ideal} - \Psi(k)$$

Table 8: Estimation of quality loss

Δ1	Δ2
1.26628	0.14771
0.72180	0.39902
0.420172	0.42017
1.065617	0.12469
0.548083	0.16100
0.363002	0.15491
0.907631	0.506369
0.46207	0.245867
0.245336	0.245335

Table 9: Ranking for Quality loss

S.No	Avg. Quality loss	S/N Ratios	Ranking
1	0.707000	3.0116	2
2	0.707000	5.0299	4
3	0.560411	7.5315	5
4	0.420172	4.5074	3
5	0.595154	9.0067	6
6	0.354540	11.7355	8
7	0.258954	3.0116	1

8	0.707000	9.0207	7
9	0.353970	12.2047	9

Taguchi's Lower-the-Better (LB) criterion is implemented to minimize this quality loss. The maximum possible number of the principal components to be computed is equal to the number of responses. The present study deals with two responses and hence two principal components $1^{st}\ \psi$ and $2^{nd}\ \psi$. Principal component and quality loss estimation for principal component are calculated also for considered responses. Based on Taguchi's lower the better criterion for minimizing quality loss, optimal setting of process parameter is determined. It is found that the rank is assigned; corresponding to 7^{th} experimental has got the least estimated average quality loss. This suggests that the optimal parameter setting can be found at this particular experimental run.

VI. CONCLUSIONS

From the results of the experiments and analysis of the test data conducted on AISI D3 steel during turning operation with CVD coated cemented carbide tool under MQL condition using castor oil as lubricating agent.

1. PCA technique integrated with Taguchi Methodology is successfully employed for the estimation of optimal process parameter setting which was found to be:
   Speed (level 3): 200 m/min
   Feed rate (level 1): 0.05 mm/rev
   Depth of cut (level 3): 2.0 mm

2. Combination of PCA with Taguchi's robust design is very simple method used for concurrent minimization of surface roughness and maximization of metal removal rate.

3. PCA was found useful in eliminating co-relational response by converting into individual responses which have been as treated as response variables for optimization.

4. This study can further be extended by using cutting tool insert style, different cutting fluids, nose radius etc as process parameters. Also an investigation can be done on tool wear rate, tool-chip interface temperature, cutting force, consumed power etc. as quality characteristics.

VII. REFERENCES

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AUTHORS

Sri. R. K. Suresh: Assistant Professor (Sr.) at SriKalahasteeswara Institute of Technology, Sri Kalahasti. He completed his Master of Technology from S.V.University, Tirupati. To his credit he has published in more than 15 International journals and presented papers in reputed International conferences.

B. Lohit: B.Tech Student at SriKalahasteeswara Institute of Technology, Sri Kalahasti. He has completed B.Tech in Mechanical Engineering with Distinction.