Optimization of Process Parameters in Ti-6Al-4V During CNC Turning

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Abstract: Titanium alloy are one of the most prominently used materials in bio-medical field due their high tensile strength, corrosion resistance and light weight property. This paper deals with the experimental study to determine the effects that various cutting parameter have on the surface roughness and Material Removal Rate (MRR) while turning of Ti-6Al-4V metal on CNC Lathe machine. The design of experiment (D.O.E) has been developed with the help of Taguchi method and Principal components Analysis (PCA) has been used for the optimization of the process parameters involved in the experiment. Analysis of Variance (ANOVA) is utilized to study the contribution of each parameter. Four parameters have been chosen as process variables: cutting speed, feed, depth of cut and nose radius each working combined at three different levels. The experiment plan is designed using Taguchi's L9 Orthogonal Array (OA) as the degree of freedom of the variables available is nine. The effects of various parametric combinations on the turning process are studied and an optimization strategy for a pre-decided set of parameter combination is developed in order to get a better surface finish and high MRR of the turned product. The PCA method of multivariate analysis is used to obtain a single optimal solution of process parameters combining the solutions of Taguchi analysis.

Key words: Titanium alloy · CNC Lathe Machine · Taguchi D.O.E · PCA Analysis

INTRODUCTION

Metal plays an important role in modern medical science as far as fractured bones, joints and hip replacements are considered. For over a century now the use of metals such as steel, cobalt chromium alloy (Co28Cr6Mo), titanium alloy (Ti6Al4V) and many other materials have been prominent in the medical field. In modern industry, the goal is to manufacture low cost, high quality product in short time. Automated and flexible manufacturing systems are employed for that purpose along with Computerized Numerical Control (CNC) machines that are capable of achieving high accuracy and very low processing time. In the past various research work has been conducted by researchers with the objective been optimization of process parameters of machining metals to best fit an industrial application in terms of capital investment & quality required. The present research work deals with optimization of process parameters of machining a titanium alloy on CNC lathe & the main objective being machining of titanium alloy in order to suit the various medical application. We chose to

work with Titanium alloy because of its light weight, high fatigue strength & non-corrosive nature. Titanium alloy is mainly used in medical transplant of bone joint & aerospace industry. The major issue with these implants are cost of implants because cost of these material and machining is very high the reason being high surface finish. In our search for the metal which would best suit the medical application, we studied numerous journal paper & one among them was a paper published by Matej Balazic & Janez Kopac from university of Ljubljana their study focussed on the various properties of titanium alloys that makes it fit for medical application. The various behavior of titanium alloy during machining under different cutting conditions & different tools were studied & it was concluded that turning Ti-6Al-4V lubricant one can achieve a 40% longer tool life expectancy than at dry turning. The cutting speed used with coated carbide tool is around 60m/min which is the optimal setting for tool material combination [1]. In another study conducted by Dileep Kumar et al. to study the effects of tool nose radius on surface finish in optimization of machining parameters of turning process of an aerospace material.

They combined Taguchi method & Grey relational analysis for optimization of surface roughness & MRR. The experiment was designed using Taguchi L9 orthogonal array & CNC lathe was used to machine the workpiece. The minitab software were used to analyze it. The result showed that feed rate & nose radius are the most important parameters that affects the surface finish [2]. A study conducted by Manpreet Singh *et al.*in order to review the literature on machining of different materials with CNC they studied a number of journal papers on turning process on CNC lathe & concluded that many researchers have taken input parameters as speed , feed & depth of cut (DOC) or nose radius, environment factors etc. For better surface roughness speed , feed & nose radius played vital role whereas for MRR DOC, feed & speed played vital role [3]. In a study conducted by Ilhan Asiltürk *et al.* titled Optimisation of parameters affecting surface roughness of Co28Cr6Mo medical material during CNC lathe machining by using the Taguchi and RSM methods. design. To achieve the minimum surface roughness, the optimum values estimated for spindle rpm, feed rate, depth of cut and tool tip radius were 318 rpm, 0.1 mm/rev, 0.7 mm and 0.8 mm respectively [4]. A study was conducted by Aouici *et al.* regarding effect of feed rate, cutting speed & cutting time using RSM & ANOVA. They made use of CBN tool to machine AISI H11 steel & under these cutting forces they analyzed the tool wear & values of surface roughness. They concluded that most influential factor in tool wear is cutting time interval whereas for surface roughness, the feed rate was most influential parameter [5]. The study conducted by Sayak Mukherjee *et al.* to optimize the material removal rate during turning of SAE 1020 material in CNC lathe where they made use of Taguchi method employing L25 orthogonal array for 3 parameters namely speed, feed & depth of cut with 5 different levels. The study produced a predictive equation for determining MRR with given set of parameters in CNC lathe. Thus it was found that with the proposed optimal parameters it is possible to increase the efficiency of machining process & decrease the production cost [6]. Sujan Debnath *et al.* studied the influence of cutting fluid conditions & cutting parameters in turning process of mild steel bar using coated carbide tool insert on CNC lathe to determine their effects on surface roughness & tool wear. They made use of Taguchi orthogonal array to minimize the number of experiments. It was found that effect of feed rate is most dominating factor which contributed to about 34.3% of surface roughness of workpiece [7]. In a study conducted by B. Singarvel *et al.* in multiple objective optimization of

turning EN25 steel. They estimated the optimal machining parameters using Taguchi based utility concept coupled with Principal Component Analysis (PCA).This method has been used for imultaneous minimization of surface roughness, cutting force & maximization of MRR. PCA is used to find the weight factor involved in all objectives, $W_{Ra} = 0.035$, $W_{cutting\ force} = 0.448$, $W_{MRR} = 0.515$. ANOVA employed on SN ratio to determine their individual contribution in percentage. It was found that the optimal cutting speed equals 244m/min, Feed rate = .1mm/rev, depth of cut = 1mm [8]. Experiments carried out by D. Manivel *et al.* in order to optimize the surface roughness & tool wear in hard turning of austempered ductile iron (grade 3) where they made use of Taguchi method and L18 orthogonal array by choosing the cutting parameters as cutting speed, feed rate, depth of cut with 3 levels & 2 levels of nose radius. It was found that the cuuting speed is the most dominating factor that affects the surface roughness & tool wear. The optimal cutting condition were predicted using signal to noise ratio & regression analysis [9]. In a study conducted by Mihir Patel *et al.* titled optimization of TC process parameters using PCA based taguchi method to optimize the multiple responses of CNC processes. The workpiece used was E250 B0 of standard IS:2062, tool material CVD coated cemented carbide. They made use of Taguchi L16 orthogonal array with process parameters as speed, feed, depth of cut & tool nose radius. Quality responses are MRR & R_a. From the experiment concluded that the optimal parameters are speed=1400 rpm, feed=0.06mm/rev, DOC=1.4mm & nose radius= 1.2mm. After multi optimization the improvement of R_a ratio from initial condition is 11% & MRR reduced by 7% from individual optimal condition [10]. A study conducted by Meenu Gupta *et al.* in order to investigate the surface roughness & MRR for turning Of UD-GFRP using PCA & Taguchi method. The parameters such as node radius, feed rate, depth of cut, cutting speed, tool rake angle & cutting environment are selected to investigate their effect on the output response. PCA has been used to transform correlated responses inro uncorrelated quality indices. It was determined that surface increases as feed rate increases also it was found that the order of significant parameters lead by feed rate = 0.2 are depth of cut = 1.4 , cutting speed = 159.66 m/min produced the an optimal value of surface roughness equivalent to R_a = 1.498mic. metre & Optimal MRR = 330.267mm³/sec. [11]. A study conducted by Suha K. Shihab *et al.* regarding application of grey relational analysis along with PCA for multi-response optimization of hard turning. They investigated the effect of cutting

speed, feed rate, depth of cut & different cutting situations on machining force components & R_a on hard turning of AISI 52100. They used L9 orthogonal array as DOE & conducted experiment on CNC lathe. It was concluded that optimal conditions for hard turning are cutting speed =100m/min, feed rate= 0.1mm/rev, DOC=0.2mm & cryogenic cooling condition is required & DOC is a major control factor [12]. Sanjit Moshat *et al*. conducted an experiment on multi objective optimization for end milling operation in CNC end milling using PCA based hybrid taguchi method. Input parameters were depth of cut, speed & feed rate. For quality parameters surface roughness & material removal rate was chosen. L_9 orthogonal array of taguchi was used in this experiment. They found that PCA based hybrid Taguchi method is the best way to optimize the multi objective quality parameters [13]. Kopac & Krajnik investigated the robust design of flank milling parameters with optimization of the milled surface roughness, material removal rate & the cutting speed in the machining of an Aluminum alloy casting plate for injection moulds. He made use of Grey Taguchi method which combined the design of experiment, orthogonal array with grey relational analysis. They concluded with the optimal data of milling parameters for multiple process responses [14]. An investigation was carried out by Anish Nair *et al*. for multiple surface roughness characteristics optimization in CNC end milling of Aluminum using PCA. They choose workpiece as 6061-T4 Aluminum & cutting tool as CVD coated carbide tool. Taguchi L25 OA was used for experimentation. They concluded that PCA based Taguchi method is efficient for solving multi attribute problems [15].

In the past various research work has been conducted by researchers with the objective been optimization of process parameters of machining metals to best fit an industrial application in terms of capital investment & quality required. The present research work deals with optimization of process parameters of machining a titanium alloy on CNC lathe & the main objective being machining of titanium alloy in order to suit the various medical application. With reference to above literarture work, we chose the different process parameters & the output responses to be optimized. We made use of Taguchi DOE to optimize individual output responses & have combined PCA analysis to obtain a single optimized value from the multivariate output responses.

Experimental Setup: In this experiment we have considered depth of cut, spindle speed and feed rate as

the machining parameters whereas surface roughness & material removal rate is chosen as the response variables. A rod of Ti-6Al-4V with diameter 25 mm and length 360 mm is used for the experiment. The work piece is initially prepared on a conventional lathe machine by providing an initial facing and making a holding portion. CNMG inserts are used for the machining purpose. It is observed that carbide tools are most suited for machining Titanium alloys . Three inserts of different nose radius and same grade are selected (Made: SUMOTO). CNMG 12 04 O4 H13A, CNMG 12 04 08 H13A, CNMG 12 04 12 H13A are the inserts used.

Fig. 1: CNC lathe Machine

Fig. 2: Titanium alloy

Fig. 3: CNMG Tool

Table 2: Chemical Composition

Element	Percentage
Ti	89.55
Al	6.40
V	3.89
Fe	0.16
C	0.002

Table 3. Physical Properties

Thermal Conductivity	6.7 W/mk
Hardness (HRC)	36
Ultimate Tensile Strength	950 Mpa
Poisson's ratio	0.342
Modulus of Elasticity	113 GPa
Density	4.43 g/m^3

Fig. 4: R_a Tester

$$MRR = (W_i-W_f)/t \ (mm^3/sec).$$

where W_f & W_i are final & initial diameter in mm, t = machining time.

Surface roughness is component of surface texture which is quantified by the deviation in the direction of normal vector of real surface from its ideal form. The surface roughness is measured using Mitutoyo Surface roughness tester SJ-210-Series 178 with stylus tip radius 2μm & detect measuring force= 0.75Mn.(Fig. 4).

Table 1: Design of Experiment- Inputs

Levels	Speed (RPM)	Feed (mm/rev)	D.O.C (mm)	TNR (mm)
Level1	400	0.05	0.3	0.4
Level2	600	0.15	0.5	0.8
Level3	800	0.25	0.7	1.2

Titanium Alloy and It's Properties: The high strength, low weight, excellent corrosion resistance possessed by titanium alloys have led to a wide range of great applications which requires high level of reliable performance in surgery, medical, aerospace, automotive, chemical plant & other major industries.

More than 1000 tonnes of titanium made device of every characteristics & function are implanted in patients all over world every year. Requirement for joint replacement is rising as people live longer or damage themselves in serious accidents. Moreover titanium is only of few materials that coincidentally match the requirements for implantation in the human body. Medical grade titanium alloys (grade V) have a significantly higher strength to weight ratio than stainless steels. The wide range of alloys reaches from high ductility commercially pure titanium used where extreme formability is essential, to fully heat treatable alloys with strength above 1300MPa.

The natural selection of titanium for implantation is determined by a combination of most desirable characteristics including immunity to corrosion, bio-compatibility, strength, low modulus and density and the capacity for joining with bone. The mechanical and physical properties of titanium alloys are combined to provide best implants which are highly damage tolerant. The human anatomy naturally limits the shape and allowable volume of implants. The lower modulus of titanium alloys compared to steel is a positive factor in reducing bone resorbtion. Two further parameters define the importance of the implantable alloy, the notch sensitivity, - the ratio of tensile strength in the notched vs un-notched condition and the resistance to crack propagation, or fracture toughness. Fracture toughness of all high strength implantable alloys is above 50MPa.m-½ with critical crack lengths well above the minimum for detection by standard methods of non-destructive testing. Other uses are dental Implants Maxillofacial and Craniofacial Treatments , Cardiovascular Devices, External Prostheses, surgical Instruments.

Problems with Turning Operation and Ti-6Al-4V Alloy: The turning operation is influenced by many parameters. Some of the major issues associated with the quality characteristics of the turned parts includes surface roughness, tool wear, burrs, tool vibrations, etc. The machining parameters such as cutting speed, feed rate, depth of cut, features of tools, work piece material and coolant conditions highly affects the performance characteristics. So it is necessary to select the most appropriate machining parameters in order to improve cutting efficiency, cost optimization and produce good quality components.This work is focused on turning of a titanium alloy, Ti-6Al-4V. Ti-6Al-4V is known as the "workhorse" of the titanium industry, it offers a unique combination of high strength, light weight and corrosion

resistance which have made it an important material in bio-medical applications. Despite of its advantages the machinability of Ti-6Al-4V have many challenges. Its low thermal conductivity and work hardening effect reduces the tool life and reduced quality of the product. Formation of built-up-edge at low cutting speed and high chemical reactivity with tool materials at high temperatures, etc. will cause further problems during machining.

MATERIALS AND METHODS

Taguchi Design of Experiment (DOE): In order to reduce the number of experiments conducted to optimize the process parameters of any project a japanese scientist Genichi Taguchi devices a special method which makes use of orthogonal arrays(OA). These standard arrays provide us with a handy method for conducting the minimal number of experiments which ultimately gives the complete information of the factors which affect the performance parameter. The crux of the orthogonal arrays method lies in choosing the level combinations of the input design variables for each experiment. There is a variety of standard orthogonal arrays available but each one of them is meant for a particular number of independent design variables and levels. consider the example wherein one wish to conduct an experiment to determine the effect of 4 different independent variables with each variable possessing 3 set values (level values), here a L9 orthogonal array would be the right choice. The interaction between any two factor is assumed to be nil. The assumption holds right for large amount of cases but there are certain cases where it fails.One good example of one such interaction is the interaction between the material properties and temperature.

SMALLER-THE-BETTER:

$n = -10 \, \text{Log}_{10} \, [$ mean of sum of squares of measured data$]$

LARGER-THE-BETTER:

$n = -10 \, \text{Log}_{10} \,$ [mean of sum squares of reciprocal of measured data]

NOMINAL-THE-BEST:

$n = 10 \, \text{Log}_{10} \dfrac{\text{Square of mean}}{\text{variance}}$

Taguchi's Signal-to-Noise ratios (S/N), which are log functions of desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results.

Principal Component Analysis (PCA): Principal component analysis (PCA) is one among the most widely utilized multivariate techniques in statistics. Usually it is used to minimize the dimensionality of data and thus examine its underlying structure and the covariance/correlation structure of a set of variables. Where as the singular value decomposition gives a simple means for identification of the principal components (PCs) for classical PCA, the solutions thus achieved may lack certain desirable properties such as robustness, smoothness and sparsely. New techniques for PCA can be developed by altering the optimization problems to which principal component loadings are the optimal solutions.

- Obtain the required data.

Let $Z_a(b)$ represents the response. Where a = (1, 2........m) & b = (1, 2......n) where m, n are no of experiments & quality characteristics respectively.

- Normalize the quality characteristics:

The normalized value for MRR and R_a is obtained using the formula mentioned below. (a) LB (Lower-the-better) = min of X_i (k)/ X_i(k) (surface roughness R_a).

HB (Higher-the-better) = X_i(k) / max of X_i (k) (MRR):

- Covariance matrix is calculated.
- Eigen value & eigen vector of covariance matrix is calculated.
- Feature vector is formed i.e., eigen values are arranged in their descending order.
- Derive the new data set.

The turning operation was carried out in CNC lathe machine using Taguchi L9 OA shown above the machined work piece was tested for its output responses which are surface roughness & MRR shown below.

Table 4: Observation

Experiment No.	Control factors			
	Speed (RPM)	Feed (mm/rev)	Depth of cut (mm)	Nose radius (mm)
1	400	0.05	0.3	0.4
2	400	0.15	0.5	0.8
3	400	0.25	0.7	1.2
4	600	0.05	0.5	1.2
5	600	0.15	0.7	0.4
6	600	0.25	0.3	0.8
7	800	0.05	0.7	0.8
8	800	0.15	0.3	1.2
9	800	0.25	0.5	0.4

Table 5: Output responses

Experiment no.	Surface roughness (micro meter)					MRR(g/min)
	1	2	3	4	Mean	
1	1.25	1.06	1.15	1.27	1.1825	1.940
2	1.22	1.24	1.24	1.22	1.23	5.842
3	1.43	1.35	1.28	1.33	1.3475	7.920
4	0.71	0.72	0.71	0.68	0.705	3.070
5	0.93	0.85	0.84	0.97	0.89	11.606
6	2.40	2.49	2.42	2.38	2.4225	17.910
7	0.38	0.46	0.39	0.43	0.4151	5.050
8	1.21	1.22	1.18	1.30	1.2275	14.840
9	2.84	2.95	3.02	2.97	2.945	24.210

RESULT AND DISCUSSION

The different input parameters utilized in the experiment is fed into Minitab 17 software along with the output parameters i.e. MRR and surface roughness. Response table is obtained for the different values of MRR and surface roughness. The response table obtained is for mean and signal to noise ratio. The mean response table is basically the average value of performance characteristics for each parameter at different levels. The s/n ratio response table shows the effect of noise on signal under different levels of experiment. On the basis of response table rank is provided to each parameter showing their contribution in the machining process. The mean and S/N response table for MRR is shown in Table 8 and Table 9 while for surface finish it is shown in Table 10 and Table 11.

Table 6: Response table for S/N ratio of MRR:

Level	Speed	Feed	DOC	TNR
1	13.021	9.855	18.082	18.243
2	18.699	20.018	17.585	18.153
3	21.725	23.572	17.778	17.049
Delta	8.704	13.717	0.498	1.195
Rank	2	1	4	3

Table 7: Response table for Mean of MRR

Level	Speed	Feed	DOC	TNR
1	5.234	3.353	11.563	12.585
2	10.862	10.763	11.041	9.601
3	14.700	16.680	8.192	8.610
Delta	9.466	13.327	3.371	3.975
Rank	2	1	4	3

Main Effects Plot for SN ratios
Data Means
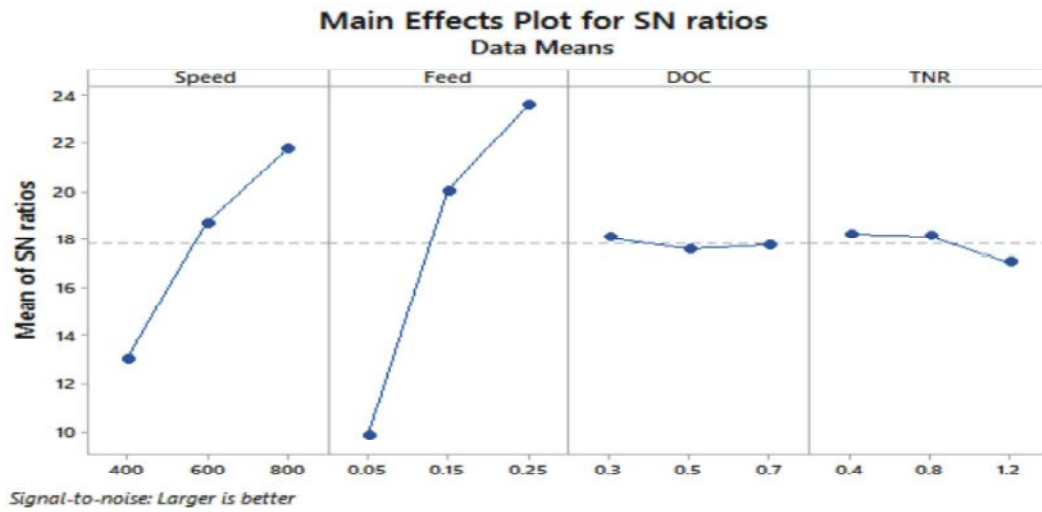
Fig. 5: S/N ratio response graph for MRR

Main Effects Plot for Means
Data Means
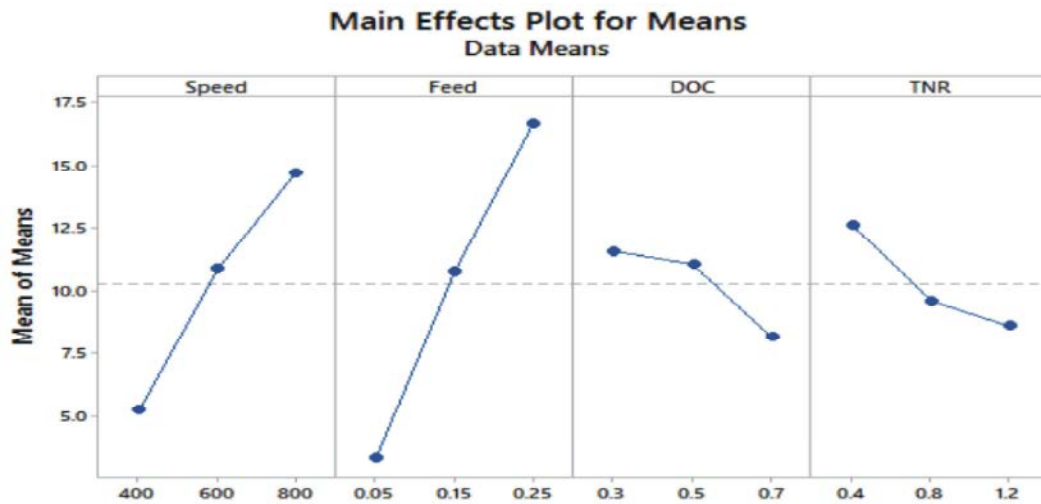
Fig. 6: Mean response graph for MRR

Table 8: Response table for S/N ratio of R_a

Level	Speed	Feed	DOC	TNR
1	3.0731	1.9959	-1.1744	-0.6148
2	-0.8797	-2.7145	-1.2366	-0.4449
3	-6.5525	-3.6406	-1.9482	-3.2995
Delta	9.6256	5.6365	0.7739	2.8545
Rank	1	2	4	3

Table 9: Response table for mean of R_a

Level	Speed	Feed	DOC	TNR
1	0.7675	0.8867	1.5292	1.3558
2	1.1183	1.6267	1.3417	1.0933
3	2.2383	1.6108	1.2533	1.6750
Delta	1.4708	0.7400	0.2758	0.5817
Rank	1	2	4	3

Main Effects Plot for SN ratios
Data Means
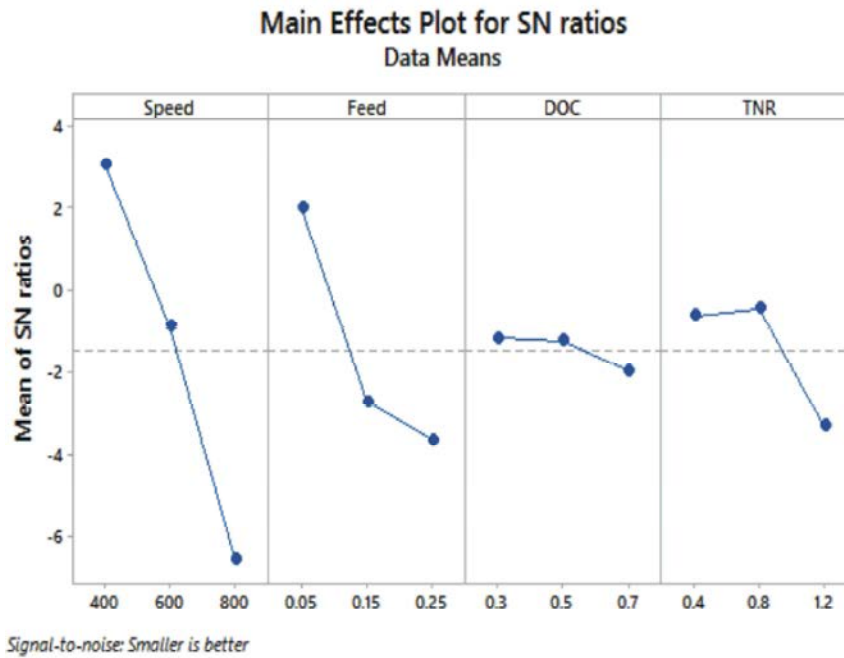
Fig. 7: Response graph for S/N ratio of R_a

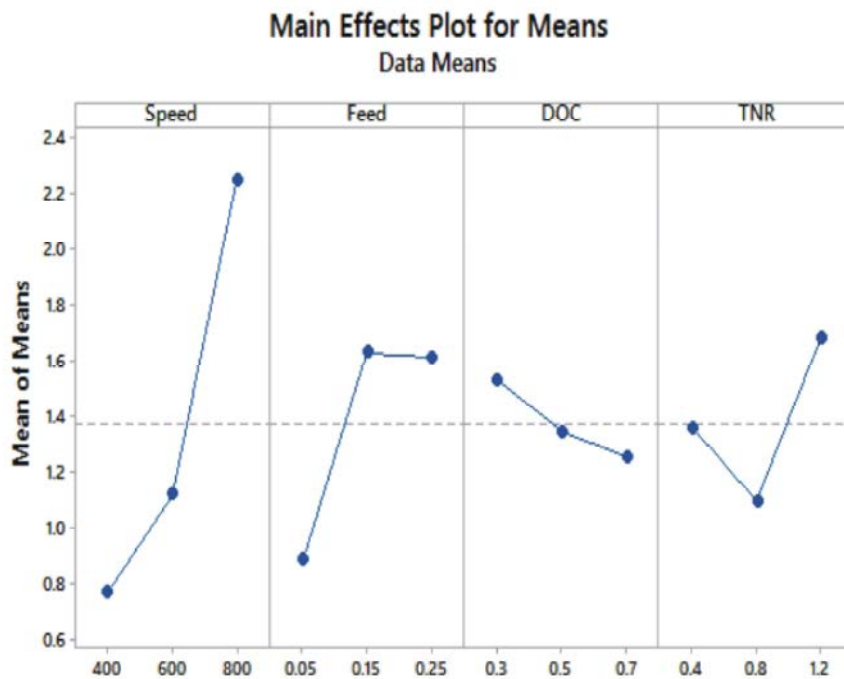## Main Effects Plot for Means
Data Means

Fig. 8: Response graph for means of R_a

The optimal value for MRR is shown in Fig. 5 and 6. The optimal value for high MRR is is found to be Speed: 800 RPM, Feed: 0.25mm/rev, DOC: 0.7mm, TNR: 1.2mm. Similarly optimal value of surface roughness is shown in Fig. 7 and 8. The optimal value required is least value of surface roughness in order to get the surface with highest degree of surface finish. From the fig. optimal condition to obtain the minimum surface roughness while machining titanium alloy is found to be Speed: 400 RPM, Feed: 0.05mm/rev, DOC: 0.3mm, TNR: 0.4mm. The Taguchi method of analysis provides us two optimal solution for MRR and R_a respectively and in order to obtain a single

optimal process parameters value a multi variant optimization technique (PCA) is used. The analysis for PCA is shown below.

The two output parameters MRR and R_a are fed into Minitab 17 software to obtain the eigen value and eigen vetor of them

Table 10(a): Eigen analysis of the correlation matrix

Eigen value	1.7309	0.2691
Proportion	0.865	0.135
Cumulative	0.865	1.000

Table 10(b): Eigen vectors

Variable	PC1	PC2
MRR(g/min.)	0.707	-0.707
R_a(Mic.Met.)	0.707	0.707

The above table shows the eigen values and eigen vactor of output parameters MRR and surface roughness respectively which was found using minitab software. From the table it is found that the eigen value of MRR is greater then 1 and it contributes to about 86.5% and hence it is the parameter which needs to be optimised through PCA by determining its quality loss, the calculations are shown below. The eigen value of R_a is less then 1 and hence can be neglected. The surface roughness data is normalized by dividing the least value of surface roughness from each value and in case of MRR we divide every value by the highest value of MRR. The normalized value of surface roughness and MRR along with quality loss is shown in Table 9. And Table 10 shows eigen value and eigen vector along with their proportionate contribution.

Table 11: Normalized value of MRR and R_a

Nor. MRR	Nor. R_a	PC 1	PC 2	Quality loss
0.0801	1	0.7636	0.6504	0.6504
0.2413	0.5886	0.5866	0.2456	0.8274
0.3271	0.3509	0.4792	0.0168	0.9348
0.1268	0.4623	0.4164	0.2372	0.9976
0.4793	0.3373	0.5772	-0.1004	0.8368
0.7397	0.3380	0.7619	-0.2841	0.6521
0.2085	0.3079	0.365	0.0702	1.049
0.6129	0.1409	0.5329	-0.3337	0.8811
1	0.1713	0.8281	-0.5859	0.5859

The values of principle component 1 & 2 i.e., PC1 & PC2 are determined by;

$$y_i = \sum\nolimits_{j=1}^{n} X_i(j)\beta_{kj}$$

where, y_i is the principal component score of the k th element in the i th series. Xi (j) is the normalized value of the j th element in the i th sequence and β_{kj} is the j th element of eigenvector β_k.

The quality loss function is obtinted for PC1 (AS PC2 is neglected due to it's megre contribution)

Quality loss = {Ideal value – individual entries in PC1 column}

Now this quality loss function is analyzed again using Taguchi method to obtain the response table for the same. The quality loss function is optimized using smaller the better critiria of S/N Ratio because quality loss is always to be minimized.
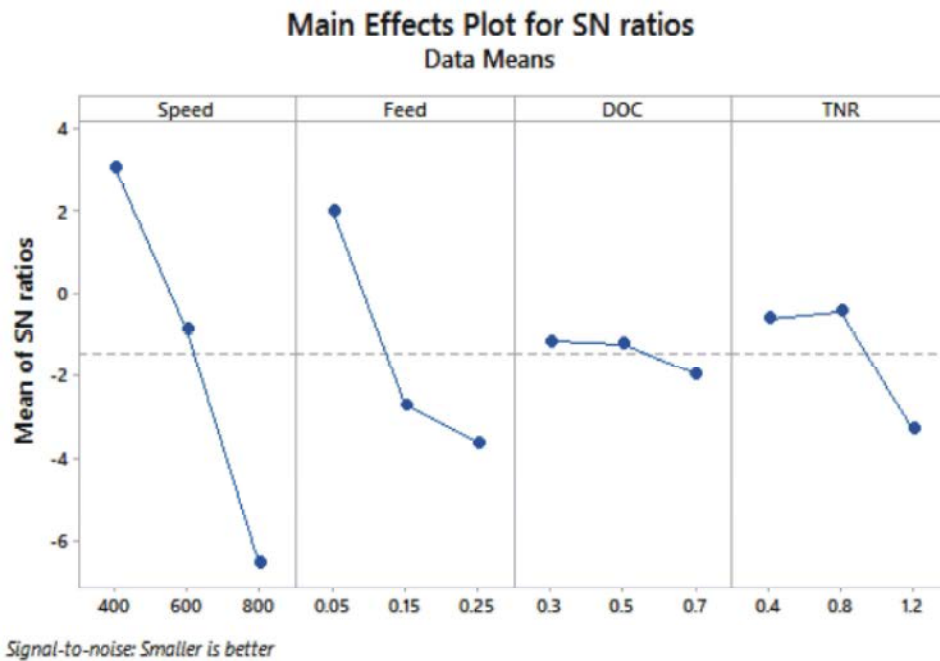
Table 12: S/N ratio response table

Level	Speed	Feed	DOC	TNR
1	0.8042	0.8990	0.7279	0.6910
2	0.8288	0.8484	0.8036	0.8428
3	0.8387	0.7243	0.9402	0.9378
Delta	0.0345	0.1747	0.2123	0.2468
Rank	4	3	2	1

Table 13: Mean response table

Level	Speed	Feed	DOC	TNR
1	1.9892	1.1139	2.8499	3.3092
2	1.7607	1.4309	2.1034	1.6480
3	1.7758	2.9810	0.5726	0.5687
Delta	0.2285	1.8670	2.2773	2.7405
Rank	4	3	2	1

Main Effects Plot for SN ratios
Data Means

Signal-to-noise: Smaller is better

Fig. 9: S/N ratio response graph

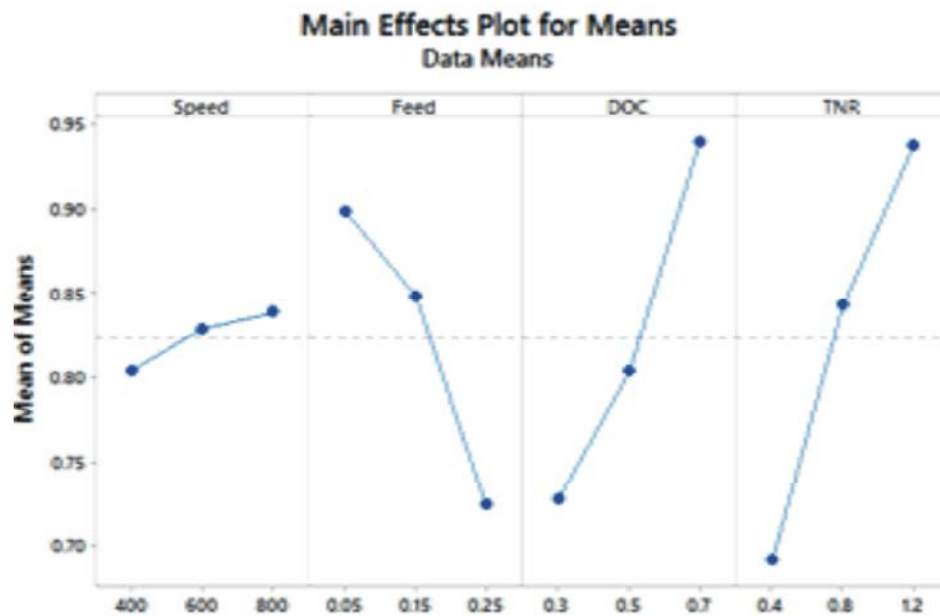## Main Effects Plot for Means
Data Means

Fig. 10: Mean response graph

By the use of PCA reaches finally to one optimize parameter as shown above in the response table and response graph. The above parameter is the best at which if the machining is done the result will always be optimized. And the value of optimum process parameter is as follow Speed: 400 RPM, Feed: 0.25mm/rev, DOC: 0.3mm, TNR: 0.4mm.

CONCLUSION

The above study shows that the combination of Taguchi and PCA together forms a strong and powerful tool to optimize the multivariate responses and obtain the best optimal values of process parameters to machine the medical materials and obtain the lower surface roughness and high MRR.

The output responses were analysed using minitab software to obtained the value of SN ratio and mean value for MRR and R_a .With the help of these value the response table for SN ratio and mean value are obtained and the mean effect plot against various process parameter for SN ratio and mean value is also obtained for MRR and R_a.When these plots were analyzed it was found that the optimal parameter setting for maximum MRR and minimum surface roughness were found to be as follows.

Speed :800rpm and 400rpm, feed:0.25mm and 0.05mm, DOC:0.7mm and 0.3mm, TNR:1.2mm and 0.4mm.

In order to obtain a single optimumal result which is the combination of the two optimal solution obtained by taguchi we applied Principle component analysis (PCA) using Minitab software. Meanwhile we found out eigen values, eigen vectors, normalized values & quality loss in the process. With the help of these value the response table for SN ratio & mean value were obtained and the mean effect plot against various process parameters for SN ratio & mean value is also obtained for quality loss. When these plots were analyzed optimal parameter setting for minimum quality loss were found, which are as follows: Speed:400rpm, Feed:0.25mm/rev, DOC:0.3mm, TNR=0.4mm

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