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Research Article

Surface Roughness of Al-5Cu Alloy using a Taguchi-Fuzzy Based Approach

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Abstract

The present paper investigates the application of traditional Taguchi method with fuzzy logic for multi objective optimization of the turning process of Al-5Cu alloy in CNC Lathe machine. The cutting parameters are optimized with considerations of the multiple surface roughness characteristics (Centre line average roughness R_a, Average maximum height of the profile R_z, Maximum height of the profile R_t, Mean spacing of local peaks of the profile S_a). Experimental results are demonstrated to present the effectiveness of this approach. The parameters used in the experiment were cutting speed, depth of cut, feed rate. Other parameters such as tool nose radius, tool material, workpiece length, workpiece diameter, and workpiece material were taken as constant.

Keywords: Multi-objective optimization; Taguchi method; Fuzzy logics, Surface roughness.

1. Introduction

Now a days the application of different optimization techniques in different machining processes is required vitally for the production of best quality product (low cost, high quality) in less time. Taguchi's method is one of the best method to control the product quality at the product design stage instead of controlling it at the manufacturing stage.

In engineering industries metal cutting processes are the most important and widely used manufacturing processes. The metal cutting process involves cutting tool and workpiece material composition and mechanical properties of cutting tool and the workpiece, and the other process parameter settings that influence the efficiency of the process and quality of the output (Montgomery, 1997). The surface quality of any machined product is mainly responsible for evaluating the productivity of the machine tools, used for the production of the product. Hence, a good surface quality is essentially required for the functional behavior of the mechanical parts of the product (Benardos and Vosniakos, 2003). Surface roughness has influenced resistance to wear and corrosion, fatigue strength, coefficient of friction, lubrication of the machined parts (Feng and Wang, 2002). Thus In today's manufacturing industries, special attention is given to proper dimensional accuracy and surface finish. Thus, a good surface finish indicates a good machining performance (Reddy and Rao, 2005). Turning is the most common process of removing extra metal from the workpiece in order to produce a finished product of required dimension and surface finish, with the help of cutting tools that moved past to the workpiece in a machine tool. The operators working on lathe use their own experience and different related guidelines for performing machining operation on the workpiece. An improper decision may cause high production costs and low machining quality. Therefore the proper selection of cutting tools and process parameters in order to achieve high cutting performance is required (Nian et al., 1999). Jayant et al. (2008) optimized the cutting parameters in turning operation of hardened steel AISI 4140 with carbide insert cutting tool under semi finishing and finishing conditions using Taguchi's methodology. The effect of the process parameters on the response parameters were analyzed and an optimal combination of process parameters were obtained. Aggarwal et al. (2008) using response surface methodology (RSM) and Taguchi's technique, investigated the effect of cutting speed, feed rate, depth of cut, nose radius and cutting environment in CNC turning operation of AISI P-20 tool steel. Taguchi's L_{27} orthogonal array were used for conducting the experiments. The effects of feed rate and nose radius were found to be insignificant compared to other factors. It was found that RSM technique seems to have an edge over the Taguchi's technique. Kirby et al. (2006) optimized the surface finish by using Taguchi method in a turning operation. The process parameters were: spindle speed, feed rate, depth of cut and tool nose radius. A confirmation experiment was done to verify the experimental results. Gauri and Chakraborty (2009) used principal component analysis (PCA)-based approach for multi objective optimization. It was found that the principal component analysis based optimization technique is better than the constrained optimization and MRSN ratio-based methods. Yang and Chen (2001) used Taguchi method, L_{18} orthogonal array for optimizing the surface roughness in end milling operation. Sukthomya and Tannock (2005) used Taguchi's Design of Experiments to identify the optimum setting of Neural Network parameters in a multilayer perceptron (MLP) network trained with the back propagation algorithm.

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Nalbant et al. (2007) also used Taguchi method to find the optimal cutting parameters for surface roughness in turning operation of AISI 1030 steel bars using TiN coated tools. Three cutting parameters namely, insert radius, feed rate and depth of cut are optimized with surface roughness as response parameter. Tosun and Ozler (2004) investigated and optimized the effect of cutting parameters on multiple performance characteristics, such as tool life and surface roughness in hot turning operation. Taguchi's design of experiment was used for performing the experiments. Singh and Kumar (2006) obtained an optimum combination of turning process parameters (cutting speed, feed rate and depth of cut) in machining EN24 steel with TiC-coated tungsten carbide inserts. The effects of the selected turning process parameters on feed force as response parameter was investigated. Palanikumar (2006) used Taguchi method and Pareto ANOVA analysis to optimize the cutting parameters in turning operation of glass fiber reinforced plastic (GFRP) composites by using a poly crystalline diamond (PCD) cutting tool to minimize the surface roughness. From the experimental results it was found that feed rate is the most significant process parameter followed by cutting speed. Aggarwal, Singh, Kumar, and Singh (2008a, 2008b) comparatively used response surface methodology and Taguchi method, and concluded that the low temperature cutting conditions reduce the consumption of power as compared to dry and wet cutting conditions. Lin, Wang, Yan, and Tarng (2000) optimized the electrode wear rate and material removal rate of an electrical discharge machine by finding the optimum machine parameter of work-piece polarity, pulse on time, duty factor, voltage, current and dielectric fluid using Taguchi method with fuzzy logics. Paiva Anderson, Ferreira, and Baletrassi (2007) optimized AISI 52100 hardened steel by considering 3 inputs such as cutting speed, feed, depth of cut, by combining Response Surface Methodology with Principal Component Analysis, in turning operation to optimize several response parameters such as cutting tool life, processing cost, cutting time, surface roughness, metal removal rate. Similarly Nian, Yang, and Tarng (1999) optimized the turning process on lathe by considering several performance characteristics.

In the present paper, the Taguchi method with fuzzy logic is used to determine the optimum machining parameters for CNC Lathe machine turning operation for optimization of surface roughness parameters such as centre line average roughness (R_a), Average maximum height of the profile R_z, Maximum height of the profile R_t, Mean spacing of local peaks of the profile S_a . Taguchi's L_9 orthogonal array design was used for the three factors that is, cutting speed, feed, depth of cut, each at three levels to find out the optimum 9 combination of factors and levels of Al-5Cu alloy. The single-response optimization was conducted using Taguchi method. For a multi-response case, fuzzy logic unit (FLU) was employed to transform the four correlated responses to a single response. The effects of the process parameters such as feed rate (f), cutting speed (v) and depth of cut (d) on surface roughness parameters was also analyzed in this investigation.

2. Proposed fuzzy based Taguchi method

Taguchi methods are the statistical methods developed by Genechi Taguchi to improve the quality of any product. Taguchi had simplified the design of experiment by introducing orthogonal array and statistical analysis for the evaluation of the experimental data. Taguchi defined a signal-to-noise ratio which is the evaluation of the stability of performance of an output. For multi objective optimization this method is not useful. Therefore number of theories such as utility theory, grey relational analysis theory, desirability function approach were combined with Taguchi method in previous research work. But for these theories individual priority weights are required to assign for each response parameters. The assignment of these priority weights are based upon the assumption which may lead to uncertainty in the solution. To overcome this limitation fuzzy theory was combined with Taguchi method.

In the present investigation following steps were taken:

i. Assortment of ranges and levels of the process parameters.
ii. Design of experiment using Taguchi’s L9 orthogonal array.
iii. Performing the experiment.
iv. Computation of S/N ratio for each response parameter.
v. Use of fuzzy logic for the conversion of S/N ratio into MPCI (multi performance characteristics index) considering triangular membership function.
vi. Selection of the optimum process parameters based on maximum MPCI value.

3. Experimental Set up

The experiment was carried out in a ‘FLEXTURN SIEMENS 802D’ CNC Lathe manufactured by MTAB Engineers Pvt. Ltd. The machining was carried out in dry environment without any cutting fluid. CNC part programs were used for doing the turning operation in CNC Lathe machine. The surface roughness parameters were measured in a 3D profilometer.

Fig.1. Photograph of the experimental setup

Table 1. Technical Specification of the CNC Lathe Machine

Capacity	
Chuck Size	100 mm
Maximum Turning Diameter	80 mm
Maximum Turning Length	195 mm
Bed	Slant Bed 45 Deg
No. of Axes	2
Distance Between Centres (Aprox.)	300 mm
Accuracy	
Positioning	0.010 mm
Repeatability	± 0.005 mm
Spindle	

Spindle Speed Range	150-4000 RPM
Spindle Motor	AC Servo
Spindle Motor Capacity	3.7 KW
Spindle Type	Cartridge
CNC Details	
Control	Siemens/Fanuc/Mitsubishi
Machine Dimensions	
L x W x H (Approx.)	1700 mm x 1100 mm x 1650 mm
Lubrication	Automatic Lubrication System

3.1 Selection of process parameters

Surface roughness depends on several factors such as the geometry of the cutting tool, tool material, workpiece material, machine tool rigidity and several cutting conditions such as cutting speed, feed rate and depth of cut. Factors such as wear of the cutting tool, chip formations and properties of the cutting tool and workpiece material are some of the uncontrollable parameters in actual machining [21]. Machine tool vibration or chatter, cutting tool wear, irregular chip formation, work piece material surface defects are responsible for the surface defects during machining operations [22, 23]. So it is very difficult to consider all factors that control surface roughness. From the literature it is clear that cutting speed, feed, depth of cut are the three primary machining parameters that affect the surface roughness and thus these three parameters are taken into consideration in the present study.

3.2 Selection of response parameters

Although all the previous studies concentrated on the centre line average roughness, R_a. But to describe the quality of a multi scale rough surface centre line average roughness, R_a is not sufficient. So in the present investigation three more roughness parameters are taken into consideration, such as R_z, R_t, S_a.

3.3 Work material

Pure aluminum 320 gm and 5% pure copper (16 gm) were melted in muffle furnace at a temperature of 950°C and it was kept in the furnace for 20 minutes to have an uniform distribution of Cu in Al melt. It makes the Al-Cu alloy called Duralium. Duralium is the trade name of one of the earliest type of age-hardenable aluminium alloys. It was first used in rigid airship frames, and then it was quickly spread throughout the aircraft industry. It is also being used in precision tools because of its light weight and strength. The molten metal was then poured in the metallic mold of length 50 mm and diameter of 18 mm and thus specimens were prepared for performing the turning operation in CNC Lathe.

3.4 Cutting tool used

Commercially available high speed steel cutting tool have been used in the present investigation.

3.5 Design of experiment

Three levels, of equal spacing within the range of the parameters have been selected (table 2). In the present investigation, Taguchi's L_9 Orthogonal Array design has been taken into consideration for the experimentation. The design of experiment and the measured roughness parameters are listed in table 3 and table 4 respectively.

Table 2. Selected levels for cutting

Parameter	Notation	Unit	Level of factors		
			Level 1	**Level 2**	**Level 3**
Cutting Speed	N	rpm	500	550	600
Feed	f	mm/min	6.4	8.0	9.6
Depth of Cut	d	mm	0.2	0.4	0.6

Table 3. Design of Experiment

Sl No.	L_9 Orthogonal Array		
	N	f	d
1.	500	6.4	0.2
2.	500	8.0	0.4
3.	500	9.6	0.6
4.	550	6.4	0.4
5.	550	8.0	0.6
6.	550	9.6	0.2
7.	600	6.4	0.6
8.	600	8.0	0.2
9.	600	9.6	0.4

Table 4. Experimental results

Sl No.	Measured Roughness Parameters			
	R_a μm	R_z μm	R_t μm	S_a μm
1.	0.41200	2.9067	3.2400	2.6567
2.	0.56367	3.3733	3.8400	2.7000
3.	0.56833	3.4767	3.9667	2.8667
4.	0.52467	2.9367	3.4833	2.6733
5.	0.43267	2.6367	2.8400	3.2100
6.	0.49967	3.1433	3.6000	3.1500
7.	0.54867	3.7800	5.3900	3.4167
8.	0.51833	3.2933	4.5733	2.8633
9.	0.51900	3.0667	3.6000	3.3033

Table 5 shows the experimental results for surface roughness parameters (Ra, Rz,Rt and Sa) and their S/N ratios based on the experimental parameter combinations(Table 3).To consider these four different performance characteristics in the Taguchi method, the S/N ratios corresponding to the surface roughness parameters are proposed by the fuzzy logic unit.

Table 5. Experimental results for output variables and their S/N ratio

Sl No.	R_a		R_z		R_t		S_a	
	μm	S/N	μm	S/N	μm	S/N	μm	S/N
1	0.41200	7.70206	2.9067	-9.2680	3.2400	-10.2109	2.6567	-8.4869
2	0.56367	4.97950	3.3733	-10.5611	3.8400	-11.6866	2.7000	-8.6273
3	0.56833	4.90799	3.4767	-10.8233	3.9667	-11.9686	2.8667	-9.1476
4	0.52467	5.60228	2.9367	-9.3572	3.4833	-10.8398	2.6733	-8.5410
5	0.43267	7.27686	2.6367	-8.4212	2.8400	-9.0664	3.2100	-10.1301
6	0.49967	6.02633	3.1433	-9.9477	3.6000	-11.1261	3.1500	-9.9662
7	0.54867	5.21378	3.7800	-11.5498	5.3900	-14.6318	3.4167	-10.6721
8	0.51833	5.70787	3.2933	-10.3526	4.5733	-13.2046	2.8633	-9.1373
9	0.51900	5.69665	3.0667	-9.7334	3.6000	-11.1261	3.3033	-10.3790

4. Fuzzy logic implementation on surface roughness

Fuzzy logic is a mathematical theory of inexact reasoning that allows modelling of the reasoning process of human in linguistic terms. It is very suitable in defining the relationship between system inputs and desired outputs. A fuzzy logic system comprises a fuzzifier, membership functions, fuzzy rules, inference engine, and a defuzzifier. First, the fuzzifier uses membership functions to fuzzyfy the S/N ratios. Next, the inference engine performs a fuzzy reasoning on fuzzy rules to generate fuzzy values. Finally, the defuzzifier converts the fuzzy value into a COM(comprehensive output measure).
In the present work, fuzzy reasoning is based on the four-input-one output fuzzy logic unit. The fuzzy rule base consists of a group of if-then control rules with the three inputs, x_1,x_2 ,x_3 and x_4 and one output y, i.e.,

- Rule 1: if x_1 is A_1 and x_2 is B1 and x_3 is C_1 and x_4 is D_1 then y is E_1 else
- Rule 2: if x_1 is A_2 and x_2 is B_2 and x3 is C_2 and x_4 is D_2 then y is E_2 else
- ... ...
- Rule *n*: if x_1 is A_n and x_2 is B_n and x_3 is C_n and x_4 is D_n then y is E_n.

A_i, B_i, C_i ,D_i and E_i are fuzzy subsets defined by the corresponding membership functions, i.e., μ_{A_i}, μ_{B_i} , μ_{C_i} ,μ_{D_i} and μ_{E_i} . In this paper three fuzzy subsets(Small, Medium, Large) are assigned to the four inputs (Fig.2 for R_a, R_z, R_t and S_a).

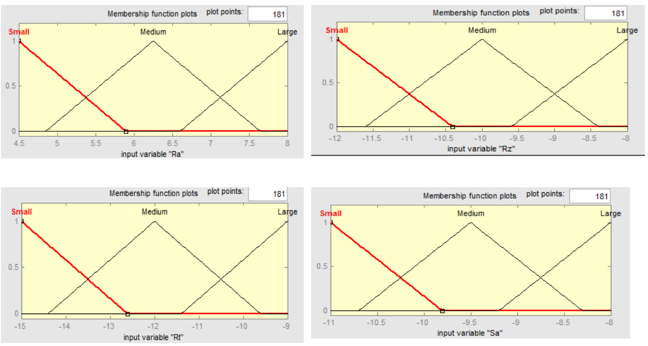


Fig.2. Membership functions for Ra, Rz, Rt, and Sa

Seven fuzzy subsets are assigned to the only output comprehensive output measure (COM)(Fig.3).

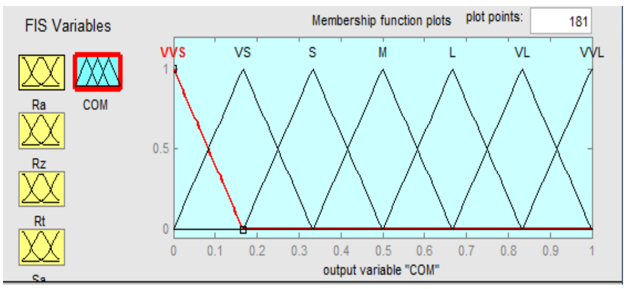


Fig.3. Membership functions for the COM

Various degree of membership to the fuzzy sets is calculated based on the values of x_1,x_2 , x_3 ,x_4 and y. Eighty One (81) fuzzy rules (Table 6) are derived directly based on the fact that smaller is the S/N ratio, the better is the performance characteristic. By taking the max-min compositional operation (Zimermann, 1985), the fuzzy reasoning of these rules yields a fuzzy output. Supposing that x_1,x_2 ,x_3 and x_4 are the four input values of the fuzzy logic unit, the membership function of the output of fuzzy reasoning can be expressed as

$$\mu_{C_0}(y)=[\ \mu_{A_1}(x_1)\ \wedge\ \mu_{B_1}(x_2)\ \wedge\ \mu_{C_1}(x_3)\ \wedge\ \mu_{D_1}(x_4)]\vee[\mu_{A_2}(x_1)\ \wedge\ \mu_{B_2}(x_2)\ \wedge\ \mu_{C_2}(x_3)\ \wedge\mu_{D_2}(x_4)]\vee\ \ldots\ \ldots\ \ldots\ \vee\ [\mu_{A_n}(x_1)\ \wedge\ \mu_{B_n}(x_2)\ \wedge\ \mu_{C_n}(x_3)\ \wedge\ \mu_{D_n}(x_4)]$$

where $\wedge$ is the minimum operation and $\vee$ is the maximum operation.
Finally, a defuzzification method, called the center-of-gravity method (Zimermann, 1985), is adopted here to transform the fuzzy inference output μ_{C_0} into a non-fuzzy value y_0, i.e.,

$$y_0 = \frac{\sum y\mu_{C_0}(y)}{\sum \mu_{C_0}(y)}$$

In this paper, the non-fuzzy value y_0 is called COM. Based on the above discussion, the smaller is the COM, the better is the performance characteristic.

Table 6. Fuzzy rule table

SL. No.	Ra	Rz	Rt	Sa	COM
1.	S	S	S	S	VVS
2.	S	S	S	M	VS
3.	S	S	S	L	S
4.	S	S	M	S	VS
5.	S	S	M	M	S
6.	S	S	M	L	M
7.	S	S	L	S	M
8.	S	S	L	M	M
9.	S	S	L	L	M
10.	S	M	S	S	S
11.	S	M	S	M	M
12.	S	M	S	L	M
13.	S	M	M	S	M
14.	S	M	M	M	M
15.	S	M	M	L	M
16.	S	M	L	S	M
17.	S	M	L	M	M
18.	S	M	L	L	M
19.	S	L	S	S	S
20.	S	L	S	M	S
21.	S	L	S	L	M
22.	S	L	M	S	M
23.	S	L	M	M	M
24.	S	L	M	L	M
25.	S	L	L	S	M
26.	S	L	L	M	M
27.	S	L	L	L	L
28.	M	S	S	S	S
29.	M	S	S	M	M
30.	M	S	S	L	M
31.	M	S	M	S	M
32.	M	S	M	M	M
33.	M	S	M	L	M
34.	M	S	L	S	M
35.	M	S	L	M	M
36.	M	S	L	L	M
37.	M	M	S	S	M
38.	M	M	S	M	M
39.	M	M	S	L	M
40.	M	M	M	S	M
41.	M	M	M	M	M
42.	M	M	M	L	M
43.	M	M	L	S	M
44.	M	M	L	M	M

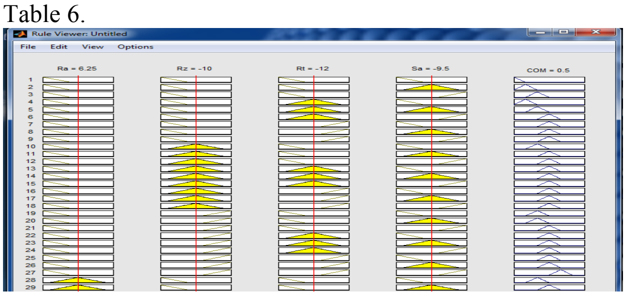
45.	M	M	L	L	M
46.	M	L	S	S	M
47.	M	L	S	M	M
48.	M	L	S	L	M
49.	M	L	M	S	M
50.	M	L	M	M	M
51.	M	L	M	L	M
52.	M	L	L	S	M
53.	M	L	L	M	M
54.	M	L	L	L	VL
55.	L	S	S	S	S
56.	L	S	S	M	S
57.	L	S	S	L	M
58.	L	S	M	S	M
59.	L	S	M	M	M
60.	L	S	M	L	M
61.	L	S	L	S	M
62.	L	S	L	M	M
63.	L	S	L	L	L
64.	L	M	S	S	M
65.	L	M	S	M	M
66.	L	M	S	L	M
67.	L	M	M	S	M
68.	L	M	M	M	L
69.	L	M	M	L	L
70.	L	M	L	S	M
71.	L	M	L	M	L
72.	L	M	L	L	L
73.	L	L	S	S	L
74.	L	L	S	M	M
75.	L	L	S	L	L
76.	L	L	M	S	L
77.	L	L	M	M	L
78.	L	L	M	L	L
79.	L	L	L	S	VL
80.	L	L	L	M	VL
81.	L	L	L	L	VVL

Table 7 shows the MATLAB generated fuzzy logic unit results for the COM using the experimental combinations of Table 3.

Table 7. Results for the COM

Run No.	Comprehensive output measure(COM)
1	0.723
2	0.471
3	0.440
4	0.591
5	0.703
6	0.500
7	0.222
8	0.500
9	0.500

Fig. 4 shows the fuzzified rule viewer for COM, which can accept any value of 4 multiple output responses of Ra, Rz, Rt and S_a.The results for 81 experimental runs are shown in Table 6.



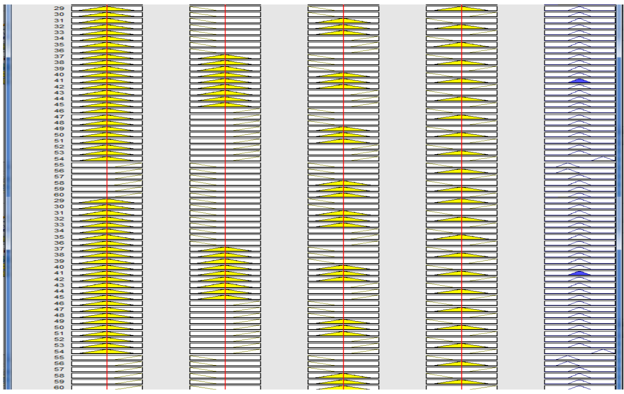


Fig.4. The fuzzy rule COM graph for 4 input combinations

Fig. 5 shows the surface view of COM for Ra, Rz, Rt, Sa parameters.

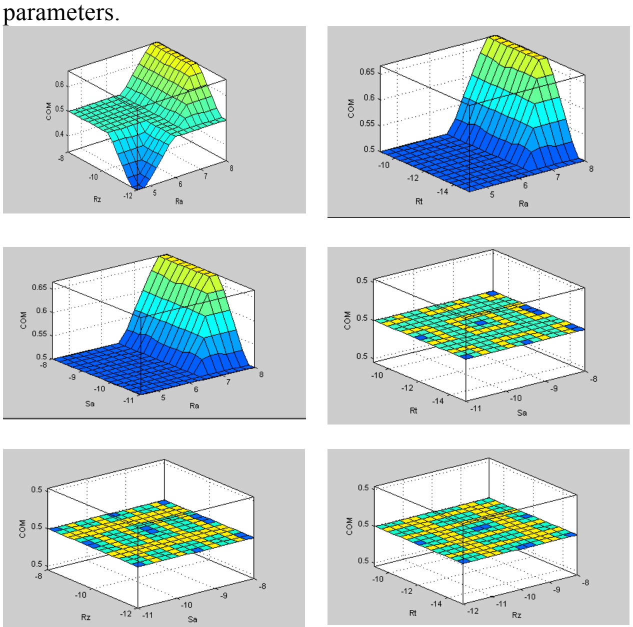


Fig. 5. The surface graph for COM for all combinations of surface roughness parameters.

5. Conclusion

The present investigation considers aforesaid multiple surface roughness characteristics for simultaneous optimization (minimization) of multiple roughness characteristics within experimental domain. The following conclusions may be drawn from the result obtained from the experiments and the analysis of the experimental data with multi-response optimization in CNC Lathe operation.

i. The factor/level combination of $N_2f_1d_1$ for R_a, N_2 f_2 d_1 for R_z, N_2 f_2 d_2 for R_t, and N_1 f_1 d_2 for S_a are the optimum parameters when these four responses are considered individually.

ii. When all the four responses are considered in multi-response problem using Taguchi-fuzzy approach N_1 f_1 d_1 is the recommended optimum condition.

iii. For finding the optimum parameters using fuzzy based Taguchi method, has been found fruitful.

iv. To solve a multi-response optimization problem, this approach is quite efficient.

v. Confirmatory test has validated the setting of the parameters determined by fuzzy based Taguchi method.

vi. Thus the said approach can be recommended for undergoing continuous improvement of quality.

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