Indian Journal of Engineering & Materials Sciences
Vol. 27, June 2020, pp. 776-782

Optimization of turning parameters of titanium chrome-molybdenum (Ti-Cr-Mo) alloy using taguchi method

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Received:12 March 2019 ; Accepted:24 October 2019

The traditional turning process has used in this study to develop a mathematical model from experimental data to predict the surface roughness of titanium chrome-molybdenum (Ti-Cr-Mo) alloy when the workpiece is machined with cutting parameters *i.e.* spindle rotational speed, feed rate and depth of cut. In order to determine the contribution of the cutting parameters, the analysis of variance (ANOVA) has been applied and Taguchi technique (smaller the better) has been used to optimize the parameters that affect the surface roughness. Mitutoyo SJ-400 roughness tester with cutoff length 0.8 mm has been used to measure the surface roughness of machined workpieces. Optimal parameters that are obtained to achieve minimum surface roughness value are 280 rpm rotational speed, 0.5mm/rev feed rate and 0.59 mm depth of cut.

Keywords: Taguchi method, Surface roughness, Titanium chrome-molybdenum, Analysis of variance (ANOVA)

1 Introduction

Turning is a main traditional machining process to machine the axis-symmetrical products especially cylindrical jobs. Such as increasing the demands of less wear, tear in rotating parts, closer tolerances products; there is much need to operate the machine on the optimum parameters so that desired surface roughness can be achieved. Nowadays, there are many advance machining processes are coming in the market, but traditional processes (turning, milling, drilling, *etc.*) methods are still used widely in the industry. Various types of alloys and materials are developed in everyday routine to fulfill the requirement of products which are used in areas such as the food industry, health sector, the automotive industry, and spacecraft industry. Kayir and Aytürk[1] conducted a study on the two different materials with a different type of cutting tools so that manufacturing efficiency and cost can be reduced. Turning is a commonly studied process in the industry as well as in the academic area to machine the cylindrical workpieces. Turning process is chip-based machining which is commonly used in the industry, therefore ample studies in academic and industry on topics which is related to the optimization of factors affecting turning operation such as material removal rate, minimum roughness, measuring of cutting forces, tool wear, tool temperature measurements, and vibration *etc.* Yallese *et al.*[2] developed the statistical model of cutting forces when AISIH11steel was turned in dry condition. They came out with the result after performing the 27 experiments on different parameters, the most important factor that affects the components of the cutting forces is the depth of cut. In another study by Gupta[3], calculate the surface roughness, tool wear, and power in turning operation by varying the parameters cutting speed, feed rate and cutting time. Data obtained by the experiments were analyzed and modeling equations were formed by using RSM, neural networks (NN) and Support Vector Regression (SVR) methods. Neural networks and SVR methods were shown better results than regression and RSM methods. Aouici *et al.*[4] conducted a study on AISI H11 steel (X38CrMoV5-1) with cutting tool CBN tools to machine the workpiece and studied the effect of cutting speed, feed rate and cutting time on the response parameters tool wear and values of the surface roughness. By applied ANOVA and RSM analysis tool, the researcher found that cutting time and feed rate was the most important factor in case of tool wear and surface roughness respectively. Suresh *et al.*[5]conducted experiments on AISI 4340 hardened steel by select the parameter cutting speed, feed rate, depth of cut and machining

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time and seen the effect on cutting forces, tool wear and surface roughness while machining on lathe machine and by using RSM method on experimental data, observed that high cutting speed, low feed rate, low depth of cut and short machining time are needed to minimize the cutting force and surface roughness and low feed rate and low cutting speed to minimize the tool wear. Chavoshi and Tajdari[6] studied the effect of hardness of workpiece and cutting speed on the surface roughness while feed rate and depth of cut were constant when machined AISI 4140 steel with CBN cutting tool. Mathematical models were developed by using regression and artificial neural networks methods. They concluded that surface roughness is mainly affected by the hardness of workpiece. In another study by Aruna *et al.*[7]optimized the cutting parameters when INCONEL 718 material was machined on a high-speed lathe with cermet cutting tools. Taguchi and RSM methods were used to determine the optimizing cutting parameters. It was found that surface roughness and tool wear is greatly influenced by the cutting speed. Sahoo[8] machined AISI 1040 steel material on CNC turning machine (lathe), applied ANOVA to see the most affecting parameter on the surface roughness of workpiece when it was machined by varying the parameters cutting speed, feed rate and depth of cut. A genetic algorithm was used to optimize the parameters to reduce the cutting time and tool wear. In another study by Ranganath *et al.*[9] used full factorial design to determine the effects of cutting speed, feed rate and depth of cut on the surface roughness of various material. RSM, Experimental and Taguchi method used to use to develop the mathematical model for obtained data. It is found that RSM gave better results. Researchers[10-16] used various techniques to optimize the machining parameters like Genetic Algorithm, simulated annealing method, multi-objective evolutionary algorithm etc.

To predict the optimum values of cutting parameters and operating conditions for the machining of titanium chrome-molybdenum (Ti-Cr-Mo) alloy which has high mechanical properties like resistant against corrosion and temperature and is mostly used in the medical field, aerospace and marine needs to be investigated so that the machining of titanium chrome-molybdenum (Ti-Cr-Mo) alloy can be done effectively. In order to fill this literature gap, the machining of titanium chrome-molybdenum (Ti-Cr-Mo) alloy is done with the insert of TiC coated carbide under dry machining conditions. To determine the effects of the cutting parameters used in the experiments on different surface roughness, ANOVA and Taguchi design method is used in the analysis.

2 Experimental Work, Taguchi Method and Design of Experiments

2.1 Machining Conditions and Roughness Measurements

The rough work material of Ti-Cr-Mo alloy bought from cast profile Ltd, Siddhi metal Mumbai. The first step has to make the workpiece of the diameter of 55 mm and a length 260 mm by removing the rough skin with an uncoated carbide insert. The workpiece material is Ti-Cr-Mo alloy with the chemical composition as given in Table 1. TiC coated carbide (SNMG 120408) tool is used for machine the workpiece. The tool holder used to hold the tool bit was SCLCR 1212F 09-M. The tests are conducted under dry machining conditions. The experimentation is performed on the standard lathe as depicted in Fig. 1. The objectives of these experimentsare to be determined the effect of speed, feed, and depth of cut on output response surface roughness. The levels of speed, feed, and depth of cut are three each which is given in Table 2. A total of 20 experiments is done

Table 1— Chemical composition of work piece material (Ti-Cr-Mo alloy) by weight.

Element	Ti	Cr	Mo
Composition (%)	93	3.0	3.0

Table 2 — Coded levels and corresponding actual values of the process parameters.

S.No.	Parameters	Unit	Levels		
			-1	0	1
1	Rotation speed of the work piece(A)	RPM	150	200	250
2	Feed Rate (B)	Mm/rev	0.1	0.2	0.3
3	Depth of cut (C)	mm	0.25	0.375	0.5

Fig. 1 — Experimental setup for turning the titanium chrome-molybdenum (Ti-Cr-Mo) cylindrical workpiece.

according to response surface methodology with the central composite design. The workpiece is held in a chuck and rotated, cutting has done for 1 minute for each experiment. After each experiment, the surface roughness (Ra) is measured with Mitutoyo SJ-400 surface roughness tester at cut-off length 0.8 mm as depicted in Fig.2.

The tool used is Tic coated carbide insert type. The geometry of the tool is: Rake angle 6°(+ve), 6°(+ve) clearance angle, 75°(+ve) major cutting-edge angle, 15°(+ve) included angle and 6°cutting edge inclination angles.

2.2 Taguchi Method

Taguchi technique is widely used in engineering, this technique measures the statistical performance by signal to noise ratio. The signal and noise ratio consider both mean and variability terms. This technique works on the ratio of the mean (signal) and 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 nominal is best (NB), lower the better (LB) and higher-the better (HB). All the values of normalizing data are lies between zero to one when the experimental data are normalized by suitable criteria; where zero represents the worst quality to be rejected and one represents the most satisfactory quality. Since S/N ratio is expressed as the mean (signal) to the noise (deviation from the target); if the ratio is the maximum that means deviation is minimum. Taguchi method always sets out to reduce the noise because the complete elimination of the noise factor is not feasible. Taguchi method offers much compact variance for the experiment with the optimum setting of process control parameters. That’s why Taguchi methods are used in the design of experiments with parametric optimization processes to get the desired results.

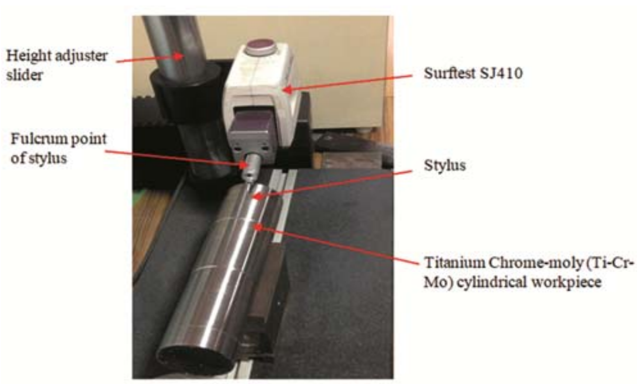

Fig. 2 — Surface roughness surftest (Mitutoyo SJ 410).

Nominal is the best characteristic:

$$\frac{S}{N} = 10 \log \frac{y}{s_y^2} \quad \dots (1)$$

Smaller the better characteristics:

$$\frac{S}{N} = -10 \log \frac{1}{n} \left(\sum y^2\right) \quad \dots (2)$$

Larger the better characteristics:

$$\frac{S}{N} = -10 \log \frac{1}{n} \left(\sum \frac{1}{y^2}\right) \quad \dots (3)$$

where, y is the average of observed data, s^2y the variance of y, n is the number of observations, and y the observed data. For each type of the characteristics, with the above S/N ratio transformation, the higher the S/N ratio the better is the result.

2.3 Design of Experiments

For the experimentation three factors with three levels are selected, Central composite design used to find the number of experiments. Three levels are coded with notation -1, 0, 1. There are 20 numbers of experiments; there are 6 center points. The factors and their levels have been selected on the basis of the tool, workpiece material, machine parameters and by studying different research papers, data handbooks and preliminary experimentation. The factors and levels are assigned as in Table 2.

3 Results and Discussion

ANOVA method is applied to analyze the experimental data so that the significant parameters and interaction between the parameters are identified. ANOVA also tells about the percentage contribution of each parameter. MINITAB statistical software is mainly used for the analysis of the experimental data for the Taguchi technique. MINITAB software calculated the signal to noise ratio from the provided experimental data. The software gives the signal to noise ratio for the surface roughness. S/N ratio has been calculated to find out the effects of different parameters and as well as their levels.

3.1 ANOVA for Surface Roughness

The ANOVA for surface roughness shows DF, SS, MS, F- value, P- value. From F-statistics it is clear that rotational speed and depth of cut are significant. Feed rate has not any significant effect on surface roughness. The ANOVA shows that the rank of rotational speed is one and rank of the depth of cut is two that means rotational speed and depth of cut has a significant effect on surface roughness. Table 3 shows the ANOVA for surface roughness. Table 4 represents the important other ANOVA parameters, which shows that the model is significant.

For the coefficient estimate for the factor, the 95% low and high confidence interval (CI) values are the lower and upper bound of the 95% confidence interval. These values in Table 5 represent the range that the true coefficient should be found in 95% of the time. If this range shows 0 (one limit is positive and the other negative) then the value of the coefficient of 0 could be true, indicating no effect of the factors. Lack of orthogonality in the design is measured by the variance inflation factor (VIF). If the value of VIF is one, it shows factor is orthogonal to all other factors. If factors are too correlated together the value of VIF is greater than 10 depending on the coefficients calculated in Table 5.

3.1.1 Final equation in terms of coded factors for surface roughness (µm)

$$SR = 0.98 + 0.42 * A + 0.12 * B + 0.19 * C + 0.14 * A * A + 0.11 * B * B + 0.033 * C * C + 0.029 * A * B - 0.016 * A * C - 0.15 * B * C \quad \dots(4)$$

where, A- Rotational Speed (rpm), B- Feed Rate (mm/rev) and C- Depth of Cut (mm).

3.2 Main Effect Plots for Surface Roughness

Figures 3, 4 and 5 show the main effect plots for surface roughness Ra (µm) in machining for smaller is better. Figure 3 shows the graph of the effect of rotational speed and feed rate on surface roughness

Table 4 — Other ANOVA parameters.

Std. Dev.	0.25	R-Squared	0.9239
Mean	1.18	Adj R-Squared	0.9009
C.V. %	16.59	Pred R-Squared	0.6970
PRESS	6.64	Adeq Precision	14.864

S.D.: standard deviation, C.V.: Coefficient of variation, *Predicted residual sum of squares.

Table 3 — ANOVA for surface roughness.

Source	Sum of squares	DF	Mean square	F value	Prob>F	Contribution	
Model	3.74	9	0.42	11.30	0.0004		Significant
A	2.38	1	2.38	64.61	0.0001	57.90%	
B	0.14	1	0.14	3.68	0.0841	3.40%	
C	0.49	1	0.49	13.32	0.0045	11.92%	
A^2	0.29	1	0.29	7.90	0.0185	7.05%	
B^2	0.11	1	0.11	2.96	0.1159	2.67%	
C^2	0.015	1	0.015	0.42	0.5337	0.364%	
AB	0.0006	1	0.0006	0.18	0.6805	0.014%	
AC	0.0003	1	0.0003	0.057	0.8154	0.007%	
BC	0.18	1	0.18	4.98	0.0498	3.40%	
Residual	0.37	10	0.037				
Lack of fit	0.3	5	0.061	4.7	0.0574		Not significant
Pure Error	0.065	5	0.013				
Cor Total	4.11	19					

Table 5 — Factor coefficients (coded form).

Factor	Coefficient Estimate	DOF	Standard error	95% CI Low	95% CI High	VIF
Intercept	32.62	1	2.14	28.05	37.18	
A	2.62	1	1.07	0.34	4.90	1.00
B	-3.75	1	1.07	-6.03	-1.47	1.00
C	-4.40	1	1.07	-6.69	-2.12	1.00
AB	0.89	1	1.31	-1.90	3.69	1.00
AC	0.36	1	1.31	-2.44	3.15	1.00
BC	0.020	1	1.31	-2.80	2.80	1.00
A^2	1.75	1	1.00	-0.39	3.88	1.05
B^2	6.30	1	1.00	4.16	8.43	1.05
C^2	4.60	1	1.00	2.47	6.74	1.05

DOF: Degrees of freedom, CI: Confidence interval, VIF: Variance inflation factor.

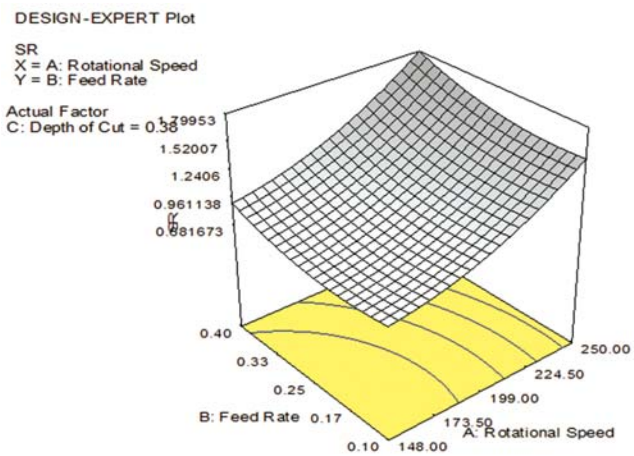

Fig. 3 — Effect of rotational speed and feed rate on surface roughness (µm).

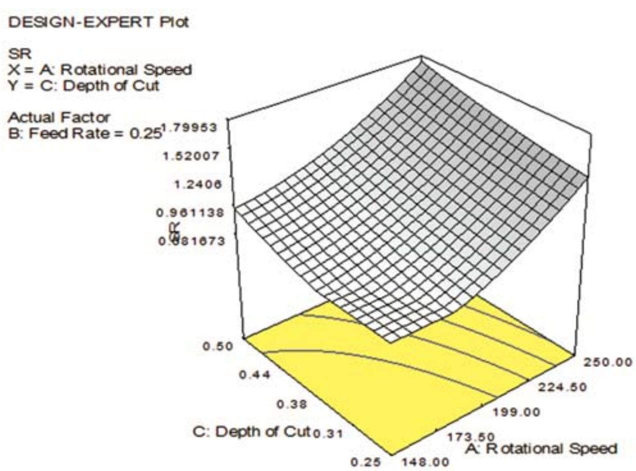

Fig. 4 — Effect of rotational speed and depth of cut on surface roughness (µm).

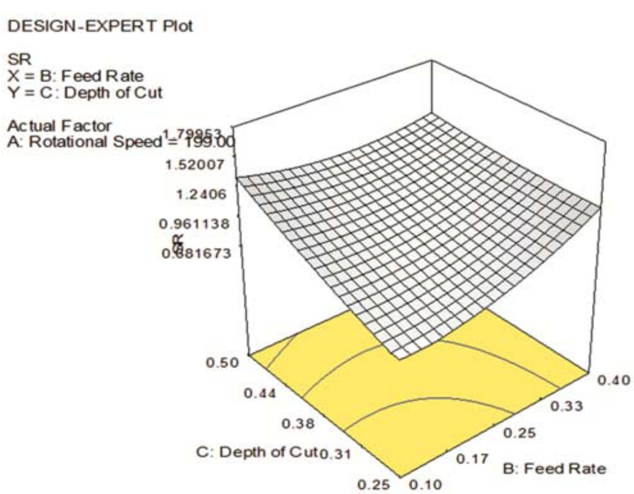

Fig. 5 — Effect of feed rate and depth of cut on surface roughness (µm).

Ra (µm). From the graph, it is clear that as the rotational speed of workpiece increases the surface roughness is also increases. When the increase in the value of feed rate also increases the surface roughness Ra (µm). Figure 4 shows the effect of rotational speed and depth of cut on the surface roughness Ra (µm). The graph shows that as the value of the depth of cut increase the surface roughness Ra (µm) increases. Figure 5 shows the effect of depth of cut and feed rate on surface roughness Ra (µm). The graph shows that as the depth of cut and feed rate values are increases the surface roughness Ra (µm) is increased. These three figures show the effect of parameters on the response (surface roughness Ra (µm)). Each factor has an individual and combined effect on the surface roughness of the cylindrical workpiece. The ANOVA shows the significant contribution of the process parameters on the response (surface roughness reduction). The maximum contribution is contributed by the rotational speed of the cylindrical workpiece. As the cylindrical workpiece rotational speed is increased, the surface roughness is minimized. They own the fact that relative velocity between the cutting tool and the workpiece is mandatory in order to cut (shear off) excess material from a workpiece to get the desired shape, size, finish, and tolerance. The cylindrical workpiece rotational speed is cutting speed of the workpiece. The higher velocity enhances material removal rate (MRR), which consequently improves productivity and reduces machining time substantially and improve the surface finish. This is also proved by the mathematical model which gives the maximum reduction in the surface roughness is influenced by the rotational speed in the present research work. The rotational speed of the cylindrical workpiece has a maximum contribution (57.90%) in the reduction in surface roughness. The feed rate and depth cut also play an important role in remove the material from the cylindrical workpiece surface. After the rotational speed of the cylindrical workpiece, the depth of cut is affecting the surface roughness. From Fig. 6 it is cleared that as the value of the depth of cut is increased after a certain level, the value of the surface roughness is increased. This happens because at a larger amount of depth of cut the cutting load and greater heat generation are produced which affects the surface characteristics of the cylindrical workpiece. The minimum surface roughness value is obtained at 0.5 mm depth of cut. The feed rate is also affecting the material removal rate of the process and also

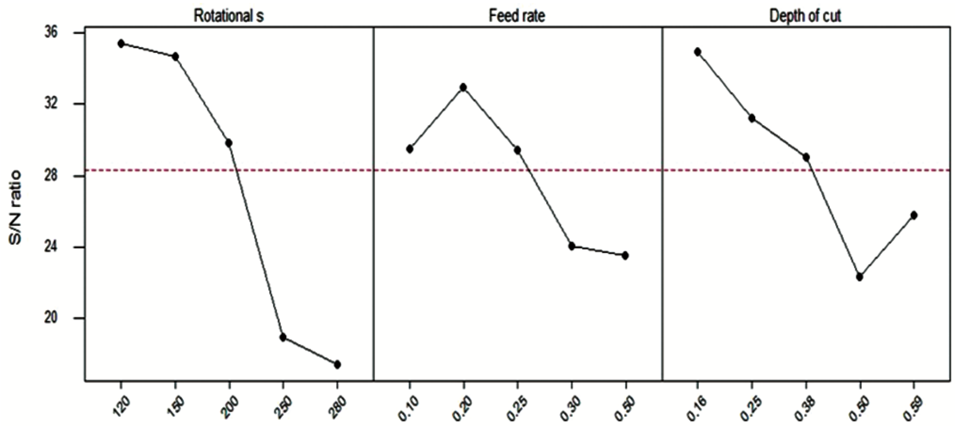

Fig. 6 — S/N Ratio (dB) graph for surface roughness height, Ra (µm).

affects the surface roughness. The feed rate, the rate at which metal is removed in the direction of that tool's travel, and it is differentiated from speed. From Fig. 6, it is cleared that as the feed rate increase at a certain limit the value of the surface roughness decreases. After 0.5 mm/rev feed rate, the value of the surface roughness increases. This reason behind that at higher feed rate increases the interaction time due to this the cutting of the material is not performed properly which increases the surface roughness value. The minimum surface roughness value is obtained at 0.5 mm/rev. Out of three graphs, the slope of rotational speed vs. feed rate has the largest slope and rotational speed vs. depth of cut has the second largest slope so rotational speed and depth of cut significantly affect the surface roughness Ra (µm) but feed has no significant effect on surface roughness Ra (µm).

3.3 S/N Ratio and Parametric Optimization for Surface Roughness Height, Ra

3.3.1 Smaller- the- better principle

Table 6 represents the experimental results and Signal-to-noise (S/N) ratio (η, dB) for surface roughness height, Ra (µm) during turning of Ti-Cr-Mo alloy. Utilizing smaller the better principle calculates the signal-to-noise ratio (dB) for surface roughness height, Ra (µm) represented. The summary statistic, η (dB) of smaller-the-better performance characteristic i.e. for surface roughness height, Ra(µm) is calculated with the expressed as follows:

$$\frac{S}{N} = -10log_e\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad \ldots (5)$$

i=1,2………n;

Table 6 — Experimental results and S/N ratio for surface roughness height, Ra (µm).

Sr. No.	Rotational speed (rpm)	Feed (mm/rev)	Depth of cut (mm)	SR (µm)	S/N ratio
1	150	0.10	0.25	0.45	45.00
2	250	0.10	0.25	1.12	27.69
3	150	0.30	0.25	0.72	36.52
4	250	0.30	0.25	2.03	15.79
5	150	0.10	0.50	0.98	30.36
6	250	0.10	0.50	2.11	15.02
7	150	0.30	0.50	1.17	26.81
8	250	0.30	0.50	1.89	17.22
9	120	0.25	0.38	0.76	35.44
10	280	0.25	0.38	1.87	17.43
11	200	0.20	0.38	0.86	32.97
12	200	0.50	0.38	1.38	23.51
13	200	0.25	0.16	0.78	34.92
14	200	0.25	0.59	1.23	25.81
15	200	0.25	0.38	0.92	31.62
16	200	0.25	0.38	1.11	27.87
17	200	0.25	0.38	1.16	26.98
18	200	0.25	0.38	0.91	31.84
19	200	0.25	0.38	0.89	32.28
20	200	0.25	0.38	0.98	30.36

where, n is the number of replications of i^{th} experiments, y_i is the response value or quality characteristics at i^{th} experiments.

3.3.2 S/N ratio (dB) for surface roughness height, Ra

Figure 6 shows the S/N ratio (dB) graph for surface roughness height, Ra. It is clear that the optimal parametric combination for smaller arithmetic mean value of surface roughness (SR) is at 280 rpm rotational speed, 0.5 mm/rev feed rate and 0.5 mm depth of cut.

4 Conclusions

In this study, ANOVA and Taguchi method (smaller is best) has used to determine optimum experimental parameter combinations. The mathematical model was developed to predict the roughness value with the help of dependent variables. The 3D graph is shown the effect of parameters on roughness with respect to the other machining parameters. After discussion on the experimental results, the following conclusions are drawn:

(i) The study of main effect plots of surface roughness indicates rotational speed and depth of cut are identified as the most significant parameters on surface roughness with 57.90% and 11.92% contribution respectively. Whereas the feed rate having contribution 3.40% respectively which is not much significant on surface roughness. Whereas the 'F' values (Table 3) of rotational speed and depth of cut are 64.61 and 13.32 respectively, hence these two parameters cannot be ignored rather consider as significant parameters on surface roughness Ra (μm).

(ii) For obtaining the minimum value of surface roughness, an optimal parametric combination for smaller arithmetic mean value of surface roughness height, Ra (μm) is at 280 rpm rotational speed, 0.5mm/rev feed rate and 0.59 mm depth of cut.

(iii) The mathematical models for surface roughness height, Ra (μm) are successfully proposed for the evolution of parametric value in advance for the effective turning of Ti-Cr-Mo alloy.

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