MULTI-RESPONSE OPTIMIZATION OF MACHINING PARAMETERS ON PHENOLIC BAKELITE HGW 2088 USING DESIRABILITY FUNCTION APPROACH

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ABSTRACT

The present investigation is, to determine the optimum parameter conditions in CNC turning process of Phenolic Bakelite HGW 2088 rod with multi response characteristics using Taguchi combined desirability function approach (DFA). The cutting speed (V), feed rate (F) and depth of cut (D) are the essential key process parameters that seriously affect the machining performance characteristics such as material removal rates (MRR) and surface roughness (SR). The experimental work was planned as per Taguchi's L9 orthogonal array design of experiments. A Taguchi combined desirability function analysis was employed to find out the optimum level of turning parameters with an objective to maximize the MRR and minimize the SR. Analysis of variance (ANOVA) was used to determine the significant effect of each process parameter on the multiple response characteristics. Experimental result shows that feed rate was the most influential parameter followed by depth of cut. The multiple response characteristics were improved drastically at the optimal level conditions as verified by the confirmation experiment.

KEYWORDS: Phenolic Bakelite HGW 2088, Turning Process, MRR, SR & Desirability Function Approach

Received: May 13, 2020; **Accepted:** Jun 03, 2020; **Published:** Aug 04, 2020; **Paper Id.:** IJMPERDJUN2020600

1. INTRODUCTION

Phenolic Bakelite HGW 2088 material is a thermoplastic material which is used widely across a range of applications, primarily where high mechanical properties are required. Typical applications include insulation of low voltage machines, installations and equipment as well as machined parts in various executions. The material is often used for bushings, guide rings for hydraulic, gliding bearings, etc. These kinds of rods are highly suitable for use when thermoplastics cannot handle the high pressure that the application requires. The remarkable properties of Phenolic Bakelite HGW 2088 material include good mechanical properties, high wear resistance, very good weatherability and resistance against salt water, good chemical and heat resistance. In general, plastic components are prepared with the aid of injection moulding process, blow moulding process and compression moulding process. The plastic materials are required to be machined in many occasions so as to impart required dimensional accuracy. The turning operations of plastic materials pose challenges owing to its inherent problems in imparting required Surface Roughness (SR) and improved Material Removal Rate (MRR). In this work, the machining of Phenolic Bakelite HGW 2088 material using Computer Numerical Controlled (CNC) turning machining has been considered for identifying the optimal input parameters setting so as to yield the better output responses. Taguchi method guided

towards findings a set of optimal parameters by minimizing the number of experiments in a cost effective way [1]. Taguchi combined desirability function approach can be applied to solve the multi response optimization problems [2]. Some literatures were reported the effect of input parameters in turning performance characteristics of plastic materials [3-6]. Panda et al. investigated the effect of input process parameters on SR and MRR during turning of nylon 6/6 using tungsten carbide insert. They concluded that increase in cutting speed and feed rate decreases the SR [3]. Sundara Bharathi et al. optimized the turning process parameters like spindle speed, feed rate and depth of cut on MRR and SR of Acrylonitrile Butadiene Styrene (ABS) material by using Taguchi coupled grey relational analysis (GRA). They reported that higher value of spindle speed and depth of cut increases the MRR and SR [4]. Jayaraman et al. had attempted the multi response optimization of turning parameters on AA6061-T6 using desirability function analysis. They revealed that feed rate is most significant parameter followed by depth of cut [5]. Raveendran et al. analyzed the influence of turning parameters such as cutting speed, feed rate and depth of cut on glass fibre reinforced plastic (GFRP) composites by using desirability function analysis. They observed that depth of cut is most dominant factor on multi responses followed by feed rate and cutting speed [6]. Kalipada Maity et al. studied the effect of cutting variables on tool wear and surface roughness during machining of Ti-6Al-4V titanium alloy using desirability function and analysis of variance (ANOVA). They concluded that the cutting speed was the most significant factor affecting the responses [7].

From the exhaustive literature, it has been found that there is only few research works concentrated on optimization of machining parameters on plastic materials. Hence, this research work aims to investigate the optimum level of machining parameters on turning behaviour of Phenolic Bakelite HGW 2088 material by using Taguchi combined desirability function analysis. Moreover, ANOVA was used to determine the significant effect of each machining parameter on output responses.

2. MATERIALS AND METHODS

2.1 Material

In this research work, Phenolic Bakelite HGW 2088 rod was selected as a work material. This material was procured from Micro Fine Chemicals, Chennai. This round rod made of woven Bakelite HGW 2088 consist of a base of cotton cloth fabric layers bonded with phenolic resin. Woven Bakelite is a material that can be used for applications up to 120°C. HGW 2088 rods display excellent wear resistance and weatherability. The physical and mechanical properties of the Phenolic Bakelite HGW 2088 material are provided in table 1.

Table 1: Physical and Mechanical Properties of Phenolic Bakelite HGW 2088

Sl. No	Property	Values
1	Appearance	Brown solid
2	Density	1.3 g/cm ³
3	Tensile Strength	50 N/mm ²
4	Flexural strength	120 N/mm ²
5	Compressive strength	100 N/mm ²
6	Thermal conductivity	0.2 W/m-K

2.2 Plan of Experiments

In the present study, three process parameters such as cutting speed, feed rate and depth of cut were selected for optimization [8]. The objective is to maximize the MRR and minimize the SR. The process parameters with three levels are provided in table 2. In order to reduce the number of experiments needed, to find the optimum level for the selected parameters, a standard Taguchi L9 (33) orthogonal array was considered to perform the experiments [9].

Table 2: Machining Parameters with their Levels

Machining Parameters	Unit	Level		
		1	2	3
Cutting speed (V)	rpm	800	1000	1200
Feed rate (F)	mm/rev	0.12	0.14	0.16
Depth of cut (D)	mm	1.0	1.2	1.4

2.3 CNC Turning Process

The Phenolic Bakelite HGW 2088 cylindrical rod of 25 mm diameter and 80 mm length was used for the experiments. The turning process was carried out in a CNC (ZOBBER XL) turning centre with a capacity of 7.2 kw spindle power and speed range of 50 - 4500 rpm at wet conditions. The uncoated carbide type insert was used as a cutting tool. The turning process was carried out as per Taguchi L9 orthogonal array by considering different level parameters as given in table 3. The photographic view of machined work piece materials is shown in figure 1. The material removal rate (MRR) is calculated by weight loss method. The weight of the work piece before and after machining is measured by electronic weighing machine with an accuracy of 0.001g. The surface roughness (SR) of the turned surfaces was measured by using Mitutoyo Talysurf SJ-210 surface roughness tester. SR was measured at two different locations on the each machined surface along the longitudinal direction, and the average values are considered for the responses. The estimated output responses are given in table 3.

Figure 1: Photographic View of Machined Work Pieces.

Table 3: L9 (3³) Orthogonal Array Design with Output Responses

Ex. No.	Input Parameters			Output Responses			
	V (rpm)	F (mm/rev)	D (mm)	MRR (g/min)	SRa ₁ (μm)	SRa ₂ (μm)	SRa _{avg} (μm)
1	800	0.12	1.0	7.571	2.760	2.757	2.759
2	800	0.14	1.2	9.710	3.365	3.334	3.350
3	800	0.16	1.4	7.463	3.517	3.35	3.434
4	1000	0.12	1.2	8.761	2.046	2.061	2.053
5	1000	0.14	1.4	9.576	3.291	3.291	3.191
6	1000	0.16	1.0	6.034	2.824	2.714	2.769
7	1200	0.12	1.4	8.141	3.189	3.184	3.187
8	1200	0.14	1.0	9.720	2.924	3.012	2.968
9	1200	0.16	1.2	8.452	3.314	3.102	3.208

3. RESULTS AND DISCUSSIONS

3.1 Desirability Function Analysis

Desirability function analysis can be used to convert the multi response characteristics into single response characteristics with the consideration of composite desirability (d_G) [10]. The following steps are carried out by the desirability function analysis:

Step 1: Compute the individual desirability index (d_i) for the measured output responses. There are three types of equations are available for evaluate the individual desirability index. [11]

Larger-the-better: If the objective function is to be maximum; equation (1) has been used.

$$d_i = \begin{cases} 1, & \hat{y} \leq y_{\min} \\ \left(\frac{\hat{y} - y_{\max}}{y_{\min} - y_{\max}} \right)^r, & y_{\min} \leq \hat{y} \leq y_{\max}, r \geq 0 \\ 0, & \hat{y} \geq y_{\max} \end{cases} \quad (1)$$

Nominal-the-best: If the objective function is a particular target, equation (2) was used.

$$d_i = \begin{cases} \left(\frac{\hat{y} - y_{\min}}{T - y_{\min}} \right)^s, & y_{\min} \leq \hat{y} \leq T, s \geq 0 \\ \left(\frac{\hat{y} - y_{\max}}{T - y_{\max}} \right)^t, & T \leq \hat{y} \leq y_{\max}, t \geq 0 \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

Smaller-the-better: If the objective function is to be minimum; equation (3) has been used.

$$d_i = \begin{cases} 1, & \hat{y} \leq y_{\min} \\ \left(\frac{\hat{y} - y_{\min}}{y_{\min} - y_{\max}} \right)^r, & y_{\min} \leq \hat{y} \leq y_{\max}, r \geq 0 \\ 0, & \hat{y} \geq y_{\max} \end{cases} \quad (3)$$

Here, $y_{\max}$ – is the maximum value of ‘y’, $y_{\min}$ – is the minimum value of ‘y’, T- denotes the target value, s, t, r – weight of responses. In the present study, MRR was considered as the larger-the-better characteristics and SR was considered as the smaller-the-better characteristics.

Step 2: Compute the composite desirability (d_G). The composite desirability values were estimated by combining the individual desirability index (d_i) of each responses and equation (4) was used. [11]

$$d_G = \sqrt[w]{d_1^{w_1} * d_2^{w_2} * \dots * d_i^{w_i}} \quad (4)$$

Where, d_i – is the individual desirability index and w_i - is the weight of response.

Step 3: In this step, after getting the composite desirability values, the optimal combination of parameters level can be determined. Generally, the highest value of the composite desirability (d_G) is considered to optimum level of parameters.

The calculated composite desirability with rank is provided in Table 4.

Table 4: Calculated Individual Desirability (d_i) and Composite Desirability (d_G)

Ex. No	Individual Desirability (d_i)		Composite Desirability (d_G)	Rank
	MRR	SR		
1	0.41698	0.48878	0.45145	3
2	0.99729	0.06083	0.24629	7
3	0.38768	0.00000	0.00000	8
4	0.73983	1.00000	0.86013	1
5	0.96093	0.17596	0.41120	4
6	0.00000	0.48154	0.00000	8
7	0.57162	0.17886	0.31975	6
8	1.00000	0.33744	0.58089	2
9	0.65600	0.16365	0.32765	5

According to the table 4, the experiment number 4 has a higher mean composite desirability (d_G) value of 0.86013. It identifies the better combination of optimal process parameters (cutting speed = 1000 rpm, feed rate = 0.12 mm/rev and depth of cut = 1.2 mm) with an objective to maximize the MRR and minimize the SR during turning process of Phenolic Bakelite HGW 2088 material.

3.2 Analysis of Parameters on Composite Desirability (d_G)

The mean response table for composite desirability (d_G) value is shown in table 5. From the table, the delta value is determined by difference between the maximum and minimum value of mean composite desirability (d_G). The larger delta value represents the most affecting parameter on the output responses which is assigned in rank 1. According to the Table 5, it can be observed that feed rate is the most influencing parameter on the multiple responses followed by the depth of cut and cutting speed.

Table 5: Response Table for Composite Desirability (d_G)

Level	V (rpm)	F (mm/rev)	D (mm)
1	0.2326	0.5438	0.3441
2	0.4238	0.4128	0.4780
3	0.4094	0.1092	0.2437
Max-Min	0.1912	0.4346	0.2344
Rank	3	1	2
Total mean of the composite desirability (d_G) = 0.35526			

Figure 2 shows the main effect plot of turning parameters like cutting speed (V), feed rate (F) and depth of cut (D) on the mean composite desirability (d_G). From figure 2, it was clearly observed that, the experiment runs 2, 1 and 2 have higher mean composite desirability (d_G) value with a better combination of optimum parameter level ($V_2F_1D_2$). The maximum MRR and minimum SR were achieved at medium level of cutting speed (1000 rpm), low level of feed rate (0.12 mm/rev) and medium level of depth of cut (1.2 mm).

Figure 2: Main Effect Plot of Mean Composite Desirability.

3.3 Analysis of Variance (ANOVA)

ANOVA is a statistical tool to determine the individual impact of process parameter on the output responses [12]. In the present study, ANOVA was used to find the percentage contribution of process parameters such as cutting speed, feed rate and depth of cut on the MRR and SR during turning process of Phenolic Bakelite HGW 2088 material. Table 6 shows the ANOVA table for mean composite desirability (d_G). From the table, it was clearly understood that the feed rate ($P=51.01\%$) is the most impact parameter on the multi response characteristics followed by depth of cut ($P=14.91\%$) and cutting speed ($P=11.64\%$). These results well agreed with the findings reported by Jayaraman et al. for the AA6061 T6 during turning process [5].

Table 6: ANOVA for Composite Desirability (d_G)

Source	DF	Adj.SS	Adj.MS	F	P (%)
V	2	0.06804	0.03402	0.50	11.64
F	2	0.29816	0.14908	2.20	51.01
D	2	0.08296	0.04148	0.61	14.19
Error	2	0.13535	0.06768	--	--
Total	8	0.58450	--	--	--

3.4 Effect of Parameters on MRR

Figure 3-5 shows the effect of turning parameters such as cutting speed, feed rate and depth of cut on MRR. For figure 3 displays the effect of cutting speed and feed rate on MRR. It can be observed that increase in cutting speed increases the MRR at low level of feed rate. However, the MRR is linearly decreases with increasing feed rate. The maximum MRR obtained at lower setting of cutting speed (800 rpm) and feed rate (0.12 mm/rev).

Figure 4: Surface Plot of MRR vs Cutting Speed & Feed Rate.

Figure 4: Surface Plot of MRR vs Cutting Speed & Depth of Cut.

Figure 5: Surface Plot of MRR vs Feed Rate & Depth of Cut.

Figure 4 reveals the effect of cutting speed and depth of cut on MRR. It can be understood that increase in cutting speed and depth of cut increases the MRR. However, the maximum MRR is achieved at low level of cutting speed (800 rpm)

with high value of depth of cut (1.4 mm). In figure 5 shows the effect of feed rate and depth of cut on MRR. It is clearly noticed that increase in depth of cut improves the MRR at minimum value of feed rate. The minimum MRR is attained by the higher level of feed rate (0.16 mm/rev) and low level of depth of cut (1 mm).

3.5 Effect of Parameters on SR

Figure 6-8 shows the effect of turning parameters such as cutting speed, feed rate and depth of cut on SR. In Figure 6 shows the effect of cutting speed and feed rate on SR. It is observed that increase in cutting speed increases the SR at medium level of feed rate (0.14 mm/rev). However, the SR is linearly reduces with decreasing feed rate. The minimum SR (2 μm) is obtained at lower setting of cutting speed (800 rpm) and low level of feed rate (0.12 mm/rev).

Figure 6: Surface Plot of SR vs Cutting Speed & Feed Rate.

Figure 7: Surface Plot of MRR vs Cutting Speed & Depth of Cut.

Figure 7 illustrates the effect of cutting speed and depth of cut on SR. It is clearly understood that increase in SR with increasing the cutting speed and depth of cut. However, the minimum SR is achieved at high level of cutting speed (1200 rpm) with lower value of depth of cut (1 mm). Similarly, lower level of cutting speed (800 rpm) and high level of depth of cut (1.4 mm) gives the minimum SR. In figure 8 shows the effect of feed rate and depth of cut on SR. It can be noticed that increase in depth of cut and feed rate improves the SR. However, the minimum SR (2 μm) is obtained by the

low level of feed rate (0.12 mm/rev) and low level of depth of cut (1 mm).

Figure 8: Surface Plot of SR vs Feed Rate & Depth of Cut.

3.6 Confirmation Experiments

The confirmation test was carried out by the optimum level of turning parameters and to verify the multi response characteristics during turning process of Phenolic Bakelite HGW 2088 material. The predicted value of composite desirability was determined by using equation (5). [13]

$$\alpha_{predicted} = \alpha_m + \sum_{k=1}^n (\alpha_i - \alpha_m) \quad (5)$$

Where, α_m - denotes the average composite desirability and α_i - denotes the mean value of the composite desirability at the optimum level of parameter and k- is the number of turning parameters. The obtained predicted and experimental value of mean composite desirability value is provided in table 7.

Table 7: Results of Confirmation Test

Response Parameters	Initial machining Parameters	Optimal Machining Parameters	
		Predicted	Experiment
Setting level	$V_1 F_1 D_1$	$V_2 F_1 D_2$	$V_2 F_1 D_2$
MRR (g/min)	7.571	--	8.761
SR (μm)	2.760	--	2.053
Composite desirability (d_G)	0.45145	0.73508	0.86013
Improvement of composite desirability (d_G) = 47.52%			

4. CONCLUSIONS

- In the present work, desirability function analysis was applied to improve the multi response characteristics such as MRR and SR during the turning process of Phenolic Bakelite HGW 2088 material using carbide insert.
- The main effect plot shows that the optimal level of turning parameters are cutting speed at level 2 (1000 rpm), feed rate at level 1 (0.12 mm/rev) and depth of cut at level 2 (1.2 mm) for achieving maximization of MRR (8.761 g/min) and minimization of SR (2.053 μm).

- ANOVA results revealed that, feed rate has the most influencing factor on multi response characteristics with contribution of 51.01% followed by depth of cut that contributes 14.19% and cutting speed at 11.64%.
- The medium level of cutting speed and feed rate obtained the higher mean composite desirability (d_G) value which results in improved the multi performance characteristics during the turning process.
- The confirmation tests were used to verify the optimal level of turning parameters that improves the percentage of composite desirability value is 47.52%.

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