REVISTAMATÉRIA V.28 N.2
ISSN 1517-7076 articles e20220337, 2023

Optimization of drilling parameters using GRA for polyamide 6 nanocomposites

Anand Thangavel[1], Ragupathy Kuppusamy[1], Ranganathan Lakshmanan[1]

[1]Agni College of Technology, Department of Mechanical and Automation Engineering, Chennai, India.
e-mail: anand.tvel@gmail.com; ragupathy86@gmail.com; ranganathanl1975@gmail.com

ABSTRACT

For drilling polyamide 6 (PA6) hybrid nano composites reinforced with copper nanoparticles and multi-walled carbon nano tubes (MWCNT), this work optimizes the process variables including reinforcing percentage, drill bit diameter, feed rate, and spindle speed. In this work, the Taguchi method was used to construct the experiments. L9 orthogonal arrays were used in the trials. Torque, surface roughness, and thrust force were the three different responses on which the influence of different process factors and their combinations were examined. The ideal values of the process factors have been found by employing the grey relational code produced by the grey relational analysis. The crucial process factors were identified using analysis of variance (ANOVA). To verify the test results, a confirmation test was carried out. The surface of the drilled holes was examined with a scanning electron microscope. The optimal drilling process parameters for PA 6 nanocomposites were 0.6 weight %, 500 rpm, 90 mm/min, and 6 mm in drill diameter. The weight percentage of the nano Cu particles (60.618%) clearly has a greater impact on drilling of Polyamide 6 hybrid nanocomposites reinforced with Cu nanoparticles and MWCNT than did the drill diameter (26.699%), speed (7.407%), and feed rate (5.271%). Verification of testing results at the best standard shows that the thrust force is reduced from 288.8 N to 281.4 N, the torque is decreased from 27.01 Nm to 24.52 Nm, and the surface polish is improved from 1.414 to 1.23 µm.

Keywords: Polyamide 6 (PA6); Multi Walled Carbon Nanotubes; Copper nano particles; Taguchi; Grey Relational Analysis.

1. INTRODUCTION

The crucial finishing step of machining involves gradually reducing the extra material from the completed blank to manufacture products with the specified dimensions and surface finish. A product can fundamentally fulfil its functional requirements, improve its performance, and extend its service life by being machined to a high degree of accuracy and finish. One of the most crucial methods is drilling, for removing metal in the manufacturing industry. In recent years, the manufacturing of machine tools increased dramatically on a global scale. The automotive and aerospace sectors are the main sources of demand for drilling operations. Each vehicle or aircraft requires the drilling of hundreds of holes, including those in the transmission shaft, camshafts, airbag propellant chambers, engine blocks and other internal engine elements.

Since many different elements have an impact on the stationary parent material and revolving drill bit, the mechanism used in drilling is quite complicated. The majority of authors in this field have focused on a specific variable that have a direct or indirect impact on burr development and hole quality, which is a significant problem when trying to assemble the components once drilling is complete in the desired location. The drill bit's wear, torque and thrust of drill are produced between the workpiece's material and the drill bit, because the production of a hole in a material is caused by the material being sheared [1].

The resistance of the material to the insertion of the cutting tool is indicated by the drilling torque and thrust force measurements. The energy needed for chip formation depends on the torque and thrust force. Mohammed S. Abd. Elwahed optimized the drilling procedure control parameters [2]. The process factors used were feed rate, spindle speed, and plate thickness; the response variables used were the delamination factor and torque. It was observed that the best combination for achieving the lowest delamination factor and torque is a low feed rate and rapid spindle speed.

In the machining of composite materials, drilling operations account for a sizeable portion. In polymer composites, proper cutting parameter selection is critical because tool wear generates high temperatures that are

Corresponding Author: Anand Thangavel Received on 20/12/2022 Accepted on 10/04/2023

DOI: https://doi.org/10.1590/1517-7076-RMAT-2022-0337

difficult to dissipate. If the cutting temperature approaches the melting temperature, the drill could become stuck with the thermoplastic material [3]. B.R.N. Murthy studied the impact of the tool size, feed rate, tool speed, and tool tip angle on the push force generated. The push force was most affected by the tool point angle, while the push force was least affected by the tool feed rate [4].

When analyzing the drilling parameters, the aspects of quality and productivity are equally significant. According to LIPIN and GOVINDAN [5], a machine tool's ideal speed depends on a number of processing factors, including the work piece's hardness, composition, stiffness, and tool life. Furthermore, it is clear that the feed rate is strongly influenced by the need for surfaces to be finished and the power supply. The input parameters, work piece or tool material, and machining condition have a substantial influence on the roughness of the drilled surfaces.

The impact of cutting power, cutting force, surface roughness, and temperature on turning of PVD-TiN and CVD-Al_2O_3-coated AISI H13 steel. The studies were carried out with dry cutting. According to this study, cutting speed and feed rate both have a significant impact on surface roughness and cutting force. Cutting power and temperature are also significantly influenced by cutting speed. When machining AISI H13 alloy with CVD-Al_2O_3-coated inserts as opposed to those with PVD-TiN-coated inserts, the abrasion and adhesion mechanism is more effective, according to SEM analysis [6].

According to the research done by NAS and KARA [7], electrical discharge machining (EDM) was used to test the machinability of a corrosion-resistant superalloy after it had undergone shallow (SCT) and deep (DCT) cryogenic treatment, and the performance of the EDM processing was examined as a result. The entire factorial experimental design was built using experimental characteristics such as pulse-on time, peak current, and material kinds. The Taguchi L18 approach was used to optimise the average surface roughness (Ra) and material removal rate (MRR) values. The ideal parameters for Ra and MRR were found to be cryogenic treatment, pulse-on time, and peak current, respectively, based on the Taguchi-based grey relational analysis. Peak current, with effects on average surface roughness and MRR of 74.79% and 86.43%, respectively, was the most significant factor for performance as determined by the ANOVA results. The ideal parameters for both Ra and MRR were assessed in terms of Taguchi-gray relational degrees.

On the cutting temperature, cutting tool vibration amplitude, tool wear, average surface roughness, and tool life in the turning of Vanadis 10 steel, the impacts of the environmentally friendly Minimum Quantity Lubrication system are examined. Cemented carbide tools covered with TiCN/Al_2O_3/TiN are utilized in the studies. The results of the experiments demonstrated that, as compared to dry machining, MQL provided notable improvements in terms of cutting temperature, cutting tool vibration amplitude, tool wear, and surface roughness. The Taguchi experimental design, ANOVA, and analyses of linear and quadratic regression are also applied to the experimental data. The cutting environment was identified as the parameter through statistical analysis that had the greatest impact on average surface roughness. In terms of vibration amplitude and tool wear, it was found that cutting speed was the most efficient [8].

This work examines the way to optimize the drilling process factors for polyamide 6 hybrid nano composites strengthened with MWCNT and copper nanoparticles. This work's primary goal is to examine the outcomes of various parameters of cutting on torque, thrust force and surface roughness. The Taguchi experimental design was employed. For the enhancement of several rebound characteristics, the grey relational analysis has been taken into consideration. The optimal parameters were found, and a validation test was conducted to defend the findings. ANOVA method was used to examine the relationship between the process specifications, torque, thrust force, and surface roughness responses.

2. EXPERIMENTAL WORK

2.1. Materials

MWCNT and Cu nanoparticle-reinforced polyamide 6 composites were used in this study. MWCNT with particle size of 25 nm, density of 2.1 g/cm^3, and average layer count of 35 was taken into consideration. The copper nanoparticles utilized 8.94 g/cm^3 density and a particle dimension of 20 nm.

2.2. Composite preparation

In a twin screw extruder, the materials were blended. The twin screw extruder employed has the following specifications: a rotating speed of 180 rpm, a screw diameter of 25 mm, an operating temperature of 250 °C, an L/D ratio of 40:1, and a melting pressure of 200 bars. The composite specimens were made from the blended material using a barrel temperature of for an injection moulding machine as 290 °C and a pressure of 10 MPa. MWCNT at 0.25 wt.% and Cu nanoparticles at 0.2, 0.4, and 0.6 wt.% were used to make the PA6 composites.

All the composites that were produced had the same amount of MWCNT since it exhibits better mechanical properties at this ratio.

2.3. Experimental procedure

In this study, the number of experiments was determined through design of experiments of Taguchi. There are four process parameters, each with three stages. The various parameters and the selected levels were displayed in Table 1. An L9 array was selected for the experiments. Figure 1 depicts the experimental setup of the drilling process.

The tests were undertaken in a dry environment using a radial drilling machine. The samples were cut to be 150 × 50 × 20 mm in size [9]. The tests used an HSS drill bit. The data generated by the experiment are collected and recorded using a data capture system. The torque and thrust force were assessed with a Kistler dynamometer. To gauge the surface roughness, a Mitutoyo Surftest SJ-210 Surface Roughness Tester 178-561-02A was utilized. To account for any potential experimental flaws, the tests were carried out three times. For the experiments carried out, the responses in terms of surface roughness, torque and thrust force were measured. The outcomes were on the list in Table 2.

Table 1: Process variables and levels.

PROCESS PARAMETERS	UNITS	LEVELS		
		1	2	3
Wt.% of nano Cu	%	0.2	0.4	0.6
Speed	rpm	500	1000	1500
Feed rate	mm/min	30	60	90
Drill dia.	mm	4	6	8

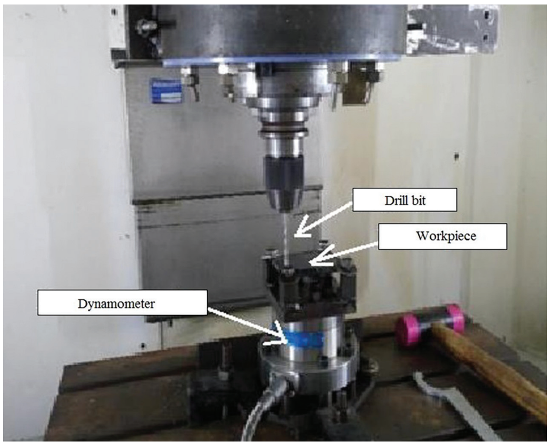

Figure 1: Experimental setup for drilling.

Table 2: Experimentally designed L9 orthogonal array.

EXP. NO	Wt.% of nano Cu	SPEED (rpm)	FEED RATE (mm/min)	DRILL dia. (mm)	THRUST FORCE (N)	TORQUE (N-m)	SURFACE ROUGHNESS (µm)
1	1	1	1	1	228	11.370	0.510
2	1	2	2	2	172	3.967	1.002
3	1	3	3	3	79.57	5.035	0.160
4	2	1	2	3	95.140	15.560	2.254
5	2	2	3	1	90.180	25.481	5.228
6	2	3	1	2	177.201	25.790	0.545
7	3	1	3	2	288.700	27.010	1.414
8	3	2	1	3	149.202	20.521	1.599
9	3	3	2	1	149.501	12.510	6.125

3. RESULTS AND DISCUSSIONS

3.1. Grey relational analysis

The grey system concept includes GRA as a key component. A "grey system" is a system that contains both known and unknown facts. Interval-valued unknowns are indicated by grey number that are used in the formal description of uncertainty with respect to the interval's width in the theory of grey systems representing how accurate the knowledge is [10]. There is a continuum between complete absence of data and thorough information created by information quantity and quality, ranging from black through grey to white. Hence there is ever some level of ambiguity, one is constantly in between two extremes, or in the middle. The conclusions of the grey analysis about system solutions are then very evident. For a system with no information, there is an extreme where no solution can be defined. On the other hand, an information-perfect system has a unique response. Grey systems will present a range of potential options in the centre. Grey analysis offers methods for identifying a good solution but does not try to determine the best one.

The mean of the relationship coefficients in grey that are obtained for the various process parameters is the relationship grade of grey, which is employed as a solo answer for the experimental design of Taguchi [11]. Figure 2 demonstrates it. The drilling process parameters of Polyamide 6 hybrid nanocomposites reinforced with nano Cu particles and MWCNT have been optimised with the current study using Taguchi's technique based grey relational analysis for multiple responses, including surface roughness thrust force, and torque.

It was determined the Signal to Noise Ratio (S/N ratio) for the responses obtained from the experiments conducted. The Smaller the better criterion was used (1). Where m denotes the quantity of experiments and x_{ij} is the summation of responses [12].

$$\frac{\mathrm{S}}{\mathrm{N}}\ \text{ratio}\ (\eta) = -10\ log_{10}\left(\frac{1}{m}\sum\nolimits_{i=1}^{m} x_{ij}^{2}\right) \tag{1}$$

The first step in pre-processing the data is to normalize the raw data in the grey relational analysis. The values in the same array are appropriately subtracted to bring their values in the range of 0 and 1. Since the normalization approach has an effect on the rank, it was looked at how sensitive it is to the sequencing results

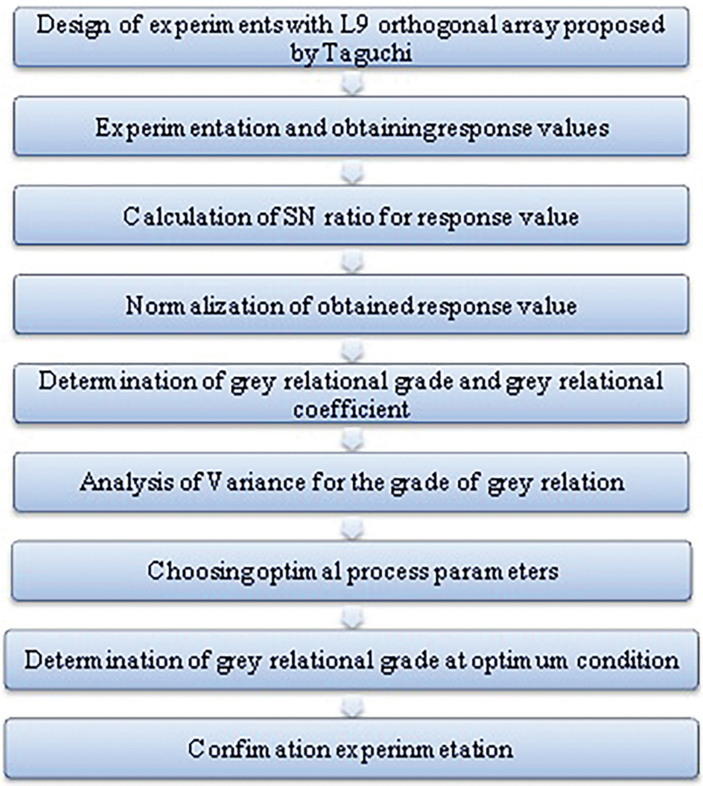

Figure 2: Grey relational analysis process to optimize multiple responses.

[13–15]. Therefore, it is recommended that when normalizing data, the S/N ratio value be involved. In terms of the smaller-is-better criterion, the normalised experimental results can be represented as

$$Z_{ij} = \frac{\max(x_{ij}, i = 1, 2, \ldots m) - x_{ij}}{\max(x_{ij}, i = 1, 2, \ldots m) - \min(x_{ij}, i = 1, 2, \ldots m)} \tag{2}$$

where Z_{ij} is the sequence following normalization and x_{ij} is the initial order regarding the findings of i^{th} experiment in the j^{th} test. The Values of S/N ratios and Normalized Values of S/N ratios were displayed in Table 3.

The normalized S/N ratio measurements are used to compute the coefficient of grey relation using Equation 3. Where n denotes the quantity of experimental data points $j = 1, 2,..., n$; $k = 1, 2,..., m$, $x_0(k)$ is the reference sequence, and $x_i(k)$ is the particular comparison sequence. The values shown as "min" and "max" represent $x_j(k)$'s minimum and maximum values. The distinction between $x_0(k)$ and $x_j(k)$ is deemed to be Δ_{oj} in absolute terms. The value of the distinguishing coefficient δ, which has a range of 0 to 1, is presumed to be 0.5, considering that all process parameters are given the same weight.

$$\mu(x_0(k), x_i(k)) = \frac{\Delta\min + \delta\ \Delta\max}{\Delta_{oj} + \delta\ \Delta\max} \tag{3}$$

Equation 4 is applicable for computing the grey relational grade.

$$\overline{\beta}_j = \frac{1}{k} \sum\nolimits_{i=1}^{n} \beta_{ij} \tag{4}$$

where $\overline{\beta}_j$ is the grade of grey relation relating to the test and k is the total amount of interpretation attributes corresponding to j^{th} experiment. Table 4 displays the grade value and grey relational coefficient for the tests. It is always preferable to have a better grey relationship grade. A greater grey relational grade denotes experimental data that more closely resemble the idealized normalized value [16]. Due to the greatest grey relational grade among the nine trials, experiment 7 exhibits the best multiple performance features.

The responses for the grey relationship grade means are shown in Table 5. By averaging the results from experiments 1 through 3, 4 through 6, and 7 through 9, the mean of the grey relationship grades for each level of the process parameters can be determined, including the wt.% of the nano Cu, spindle speed, feed rate, and drill dia.

Figure 3 depicts the effect of a process factor on a grey relational grade. The line of horizontal displays the mean for the grey relationship grade. The nigher the grey relationship grade is to the quality of the product, the larger it is. For best performance, a greater grey relationship grade is preferred [17]. The table provides the $A_3B_1C_3D_1$ optimum settings for better torque, thrust force, and surface roughness.

Table 3: Values of S/N ratios and Normalized Values of S/N.

EXPERIMENT NO.	S/N RATIO			NORMALIZED S/N RATIO		
	THRUST FORCE	TORQUE	SURFACE ROUGHNESS	THRUST FORCE	TORQUE	SURFACE ROUGHNESS
1	–47.159	–21.115	5.849	0.817	0.549	0.318
2	–44.711	–11.969	–0.017	0.598	0.000	0.503
3	–38.015	–14.040	15.918	0.000	0.124	0.000
4	–39.567	–23.840	–7.059	0.139	0.712	0.726
5	–39.102	–28.124	–14.367	0.097	0.970	0.957
6	–44.969	–28.229	5.272	0.621	0.976	0.336
7	–49.209	–28.630	–3.009	1.000	1.000	0.598
8	–43.475	–26.244	–4.077	0.488	0.857	0.632
9	–43.493	–21.945	–15.742	0.489	0.599	1.000

Table 4: Grey relational coefficient and grey grade.

EXPERIMENT NO.	GREY RELATIONAL CO-EFFICIENT			GREY GRADE
	THRUST FORCE	TORQUE	SURFACE ROUGHNESS	
1	0.732	0.526	0.423	0.560
2	0.554	0.333	0.502	0.463
3	0.333	0.363	0.333	0.343
4	0.367	0.635	0.646	0.549
5	0.356	0.943	0.920	0.740
6	0.569	0.954	0.430	0.651
7	1.000	1.000	0.554	0.851
8	0.494	0.777	0.576	0.616
9	0.495	0.555	1.000	0.683

Table 5: Response on means of grey grades.

SYMBOL	PROCESS PARAMETERS	GREY GRADE		
		LEVEL 1	LEVEL 2	LEVEL 3
A	Wt.% of nano Cu	0.456	0.646	0.717
B	Speed	0.654	0.606	0.559
C	Feed rate	0.609	0.565	0.645
D	Drill dia.	0.661	0.655	0.502

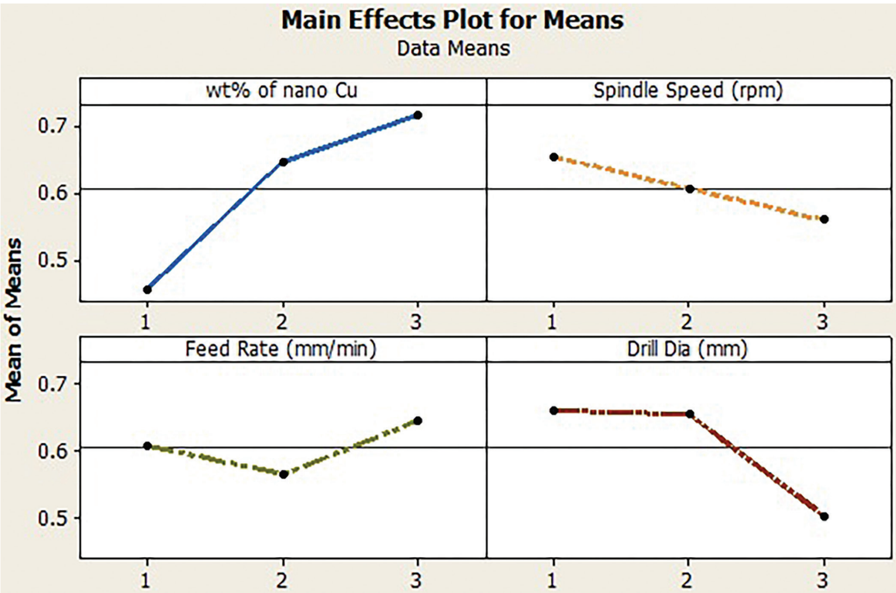

Figure 3: Main effect plots for means.

SEM was employed to examine the wreckage caused on the surface of the drilled holes. Figure 4 displays SEM images of the PA6 composites' drilled surfaces under various machining settings. Images of the drilled holes were obtained from various locations. Figures 4a and 4b show a fuzzy surface that was created owing to the composite material developing microscopic fissures. The drill bit encountered MWCNT along its journey, which caused the microcracks to emerge. The reinforcements were surrounded by a void when there were several microcracks. Smooth surface was found in Figure 4c, it is because the higher inclusion of copper nanoparticles has improved machinability. Figure 5 depicts the SEM image of the chip obtained during the drilling of PA 6 nanocomposites.

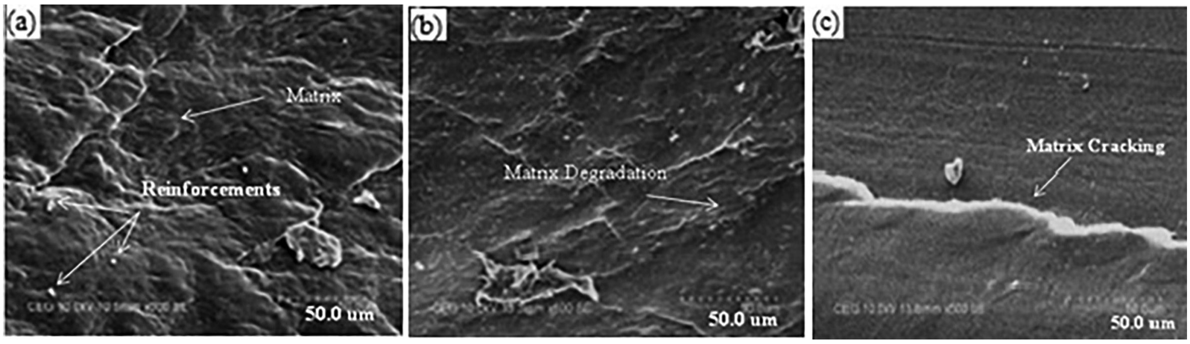

Figure 4: SEM images of drilled holes at different parameters for (a) 0.2 wt.% nano cu, 1500 rpm speed, 90 mm/min feed rate and 8 mm drill diameter (b) 0.4 wt.% nano cu, 1500 rpm speed, 30 mm/min feed rate and 6 mm drill diameter (c) 0.6 wt.% nano cu, 500 rpm speed, 90 mm/min feed rate and 6 mm drill diameter.

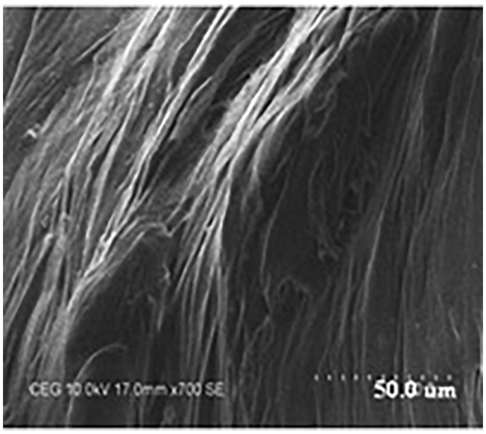

Figure 5: SEM image of chip obtained during drilling.

Table 6: ANOVA findings for the grade of grey.

PROCESS PARAMETERS	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	CONTRIBUTION (%)
A – wt.% of nano Cu	2	0.109633	0.054816	60.618
B – Spindle speed	2	0.013397	0.006698	7.407
C – Feed rate	2	0.009539	0.004770	5.271
D – Drill dia.	2	0.048289	0.024145	26.699
Residuals	0	0	0	–
Total	8	0.180858	0.090429	–

The mechanism for drilling polymer matrix composites is the drill applying thrust to the composite components. The mechanism of drilling hinges on the weight percentage of the reinforcements incorporated into the matrix as well as different process variables. It is challenging to get several performances in drilling because if one attribute raises its performance, the other one lowers it. To more clearly identify the best combinations of machining parameter levels, investigation of the relative significance of the process settings on the various performance aspects is still required [18]. Statistical ANOVA is used to analyze the data. Table 6 displays the ANOVA findings for the grey grade. To ascertain how each input component affects thrust force, torque, and surface roughness, analysis of variance is used. The % contribution ratio for each process variable is displayed in the table along with its significance level. To assess the effects of the control factors, percentage contributions were examined, with the largest percentage contribution representing the component that had the most impact on the outcome [19, 20].

Table 7: Performance comparison of the machining utilising the beginning and ideal levels.

	INITIAL PROCESS PARAMETER	OPTIMAL MACHINING PARAMETER	
		PREDICTION	EXPERIMENTAL
Setting level	$A_3B_1C_3D_2$	$A_3B_1C_3D_1$	–
Thrust force	288.7	–	281.4
Torque	27.01	–	24.52
Surface roughness	1.414	–	1.23
Grey relational grade	0.851	0.896	0.896

The drilling of Polyamide 6 hybrid nanocomposites reinforced with Cu nanoparticles and MWCNT is clearly influenced more by the wt.% of nano Cu particles (60.618%) than by the drill diameter (26.699%), speed (7.407%), and feed rate (5.271%). The findings showed that the torque, thrust force and surface roughness are all decreased when the copper nano particle weight percentage increases. For many applications, surface quality is taken into account in terms of dimensional precision, strength against fatigue, resistance to wear, and corrosive behaviour. Therefore, a key determinant of a material's capacity to be machined is its surface roughness. The S/N ratio table shows that turning experiments with 0.2 wt.% nano Cu particles reinforcement had greater S/N ratios of surface roughness values than turning experiments with 0.6 wt.% of nano Cu particles. When both inserts are compared in terms of surface roughness, turning tests carried out with the lower wt.% of nano Cu particles (0.2 wt.%) result in surface roughness values that are roughly 60–70% higher.

In general, as cutting speed increases, the thrust force and torque decrease. On the contrary, when the feed rate increased, these values increased. The key factor influencing the thrust force and cutting torque in this study, according to the ANOVA table, is the reinforcement percentage. Therefore, the thrust force and cutting torque S/N ratio values of the composites containing 0.2 wt.% and 0.6 wt.% of nano Cu particles have been compared. With the addition of more micro Cu particles, the cutting torque was lowered by up to 26.24% while the thrust force was decreased by up to 58.19%.

This is due to the copper nano particles' role as a solid lubricant, significantly reduce the coefficient of friction. Therefore the friction between the workpiece and the tool is dropped and prevents the workpiece from overheating. Thus the reduced coefficient of friction and prevention of overheating reduces the torque and thrust required to machine composite materials. Also, the size of the drill has a big impact on how well PA6 hybrid nano composites are machined. The drill diameter is directly related to the thrust force and cutting torque. Increased drill diameter lengthens the chisel edge, which accounts for 60–70% of the total thrust forces. Additionally, as tangential force grows along with drill diameter, other axial forces also rise.

After choosing the ideal processing-level parameters, the final stage is to apply Equation 5 to forecast and confirm the performance characteristics enhancement of drilling PA6 nanocomposites with regard to the selected initial parameter setting.

$$\hat{\alpha} = \alpha_m + \sum_{i=1}^{q} (\alpha_i - \alpha_m) \tag{5}$$

3.2. Confirmation experiment

To establish the quality features for drilling of Polyamide 6 nanocomposites reinforced with Cu nano particles and MWCNT, a confirmation experiment was carried out under optimum conditions. The verification of experimental findings at the optimum standard ($A_3B_1C_3D_1$) reveals that the torque is decreased from 27.01 Nm to 24.52 Nm, the thrust force is decreased from 288.8 N to 281.4 N, and the surface finish is increased from 1.414 to 1.23 µm, shown in the Table 7. These findings make it abundantly evident that the Taguchi technique-based grey relational analysis considerably improves the many performance facets of composite machining.

4. CONCLUSION

Surface roughness, torque and thrust force were the three performance criteria for which the best drilling settings were found using the grey relational analysis. The investigations were performed while use the L9 orthogonal array. The study's findings led to the following conclusions.

- Multiple response problems are optimized using the Taguchi-based grey relational analysis, and the technique is effective at estimating surface roughness, torque, and thrust force.

- 0.6 wt.% of nano Cu, feed rate 90 mm/min, Speed of the spindle 500 rpm, and drill diameter 4 mm were the optimum process parameter settings.
- Drilling of Polyamide 6 hybrid nanocomposites reinforced with Cu nanoparticles and MWCNT is clearly more affected by the weight percentage of the nano Cu particles (60.618%) than by the drill diameter (26.699%), speed (7.407%), and feed rate (5.271%)
- The thrust force is dropped from 288.8 N to 281.4 N, the torque is decreased from 27.01 Nm to 24.52 Nm, and the surface polish is improved from 1.414 to 1.23 m, according to verification of test results at the highest possible level.
- The wt.% of nano copper particles was the factor that had the highest influence on the grey relational grade for multi-performance qualities, according to the results of the ANOVA, followed by speed of the spindle, diameter of the drill and feed rate.
- The optimization procedure is made simpler by the grey relational analysis, which compresses multiple performance characteristics into a single performance characteristic.

5. BIBLIOGRAPHY

[1] LAUDERBAUGH, L.K., "Analysis of the effects of process parameter on exit burrs in drilling using a combined simulation and experimental approach", *Journal of Materials Processing Technology*, v. 209, n. 4, pp. 1909–1919, 2009. doi: http://dx.doi.org/10.1016/j.jmatprotec.2008.04.062

[2] ABD-ELWAHED, M.S., "Drilling process of GFRP composites: modeling and optimization using hybrid ANN", *Sustainability*, v. 14, n. 11, pp. 6599, 2022. doi: http://dx.doi.org/10.3390/su14116599.

[3] MIHOC, G.B., POP, A., GEAMAN, H., *et al*., "A review of the drilling processes of composite material". *Fascicle of Management and Technological Engineering*, v. 10, n. 20, pp. 4.5–4.12, 2022. doi: http://dx.doi.org/10.15660/AUOFMTE.2011-1.2138

[4] MURTHY, B.R.N., "Process parameter optimization to reduce the thrust force in CFRP composites drilling using RSM and Taguchi method", *AIP Conference Proceedings*, v. 2057, pp. 020006, 2019. doi: http://dx.doi.org/10.1063/1.5085577

[5] LIPIN, K., GOVINDAN, P., "A review on multi objective optimization of drilling parameters using taguchi methods", *A K G E C Journal of Technology*, v. 4, n. 1, pp. 11–21.

[6] AKGÜN, M., ÖZLÜ, B., KARA, F., "Effect of PVD-TiN and CVD –Al_2O_3 coatings on cutting force, surface roughness, cutting power and temperature in hard turning AISI H13 steel", *Journal of Materials Engineering and Performance*, v. 32, n. 3, pp. 1390–1401, Feb. 2023. doi: http://dx.doi.org/10.1007/s11665-022-07190-9

[7] NAS, E., KARA, F., "Optimization of EDM mahinability of hastealloy C22 super alloys", *Machines*, v. 10, n. 12, pp. 1131, 2022. doi: http://dx.doi.org/10.3390/machines10121131

[8] ÖZBEK, N.A., ÖZBEK, O., KARA, F., *et al*., "Effect of eco-friendly minimum quantity lubrication in hand machining of vanadis 10, ahigh strength steel", *Steel Research International*, v. 93, pp. 2100587, 2022. doi: http://dx.doi.org/10.1002/srin.202100587

[9] NOORUL HAQ, A., MARIMUTHU, P., JEYAPAUL, R., "Multi response optimization of machining parameters of drilling Al/SiC metal matrix composite using grey relational analysis in the Taguchi method", *International Journal of Advanced Manufacturing Technology*, v. 37, n. 3-4, pp. 250–255, 2008. doi: http://dx.doi.org/10.1007/s00170-007-0981-4.

[10] ANTIL, P., ANTIL, S.K., PRAKASH, C., *et al*., "Multi-objective optimization of drilling parameters for orthopaedic implants", *Measurement and Control*, v. 53, n. 9-10, pp. 1902–1910, 2020. doi: http://dx.doi.org/10.1177/0020294020947126

[11] SREENIVASULU, R., SRINIVASARAO, C., "Optimization of drilling parameters during machining of Al-Mg-Si Alloys by Taguchi method coupled with grey relational analysis and validated by FEA based deform – 3D", *Jixie Gongcheng Xuebao*, v. 71, n. 2, pp. 221–238, 2021.

[12] RANE, V.N., EDLABADKAR, A.P., CHAUDHARI, S.S., *et al*., "A review on optimization of drilling parameters using Taguchi methods", *Journal of Emerging Technologies and Innovative Research*, v. 2, n. 3, pp. 443–447, Mar. 2015.

[13] ROSS, P.J., *Taguchi techniques for quality engineering*, New York, McGraw-Hill, 1996.

[14] PEACE, G.S., *Taguchi methods*, New York, Addison Wesley, 1993.

[15] PALANIKUMAR, K., KARUNAMOORTHY, L., KARTHIKEYAN, R., "Multiple performance optimization of machining parameter on machining of GFRP composites using Carbide (K10) tool", *Materials and Manufacturing Processes*, v. 21, n. 8, pp. 846–852, 2006. doi: http://dx.doi.org/10.1080/03602550600728166

[16] RAJMOHAN, T., "Experimental investigation and optimization of machining parameters in drilling of fly ash-filled carbon fiber reinforced composites", *Particulate Science and Technology*, v. 37, n. 1, pp. 21–30, 2019. doi: http://dx.doi.org/10.1080/02726351.2016.1205686

[17] RAJMOHAN, T., PALANIKUMAR, K., "Optimization of machining parameters for multi-performance characteristics in drilling hybrid metal matrix composites", *Journal of Composite Materials*, v. 46, n. 7, pp. 869–878, 2012. doi: http://dx.doi.org/10.1177/0021998311412635

[18] KARATAS, M.A., GOKKAYA, H., NALBANT, M., "Optimization of machining parameters for abrasive water jet drilling of carbon fiber-reinforced polymer composite material using Taguchi method", *Aircraft Engineering and Aerospace Technology*, v. 92, n. 2, pp. 128–138, 2020. doi: http://dx.doi.org/10.1108/AEAT-11-2018-0282

[19] AKGÜN, M., KARA, F., "Analysis and optimization of cutting tool coating effects on surface roughness and cutting forces on turning of AA 6061 alloy", *Advances in Materials Science and Engineering*, v. 2021, pp. 6498261, 2021. doi: http://dx.doi.org/10.1155/2021/6498261

[20] ÖZBEK, N.A., ÖZBEK, O., KARA, F., "Statistical analysis of the effect of the cutting tool coating type on sustainable machining parameters", *Journal of Materials Engineering and Performance*, v. 30, n. 10, pp. 7783–7795, 2021. doi: http://dx.doi.org/10.1007/s11665-021-06066-8