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FULL LENGTH ARTICLE

Taguchi design optimization of machining parameters on the CNC end milling process of halloysite nanotube with aluminium reinforced epoxy matrix (HNT/Al/Ep) hybrid composite

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Abstract This paper introduces the application of Taguchi optimization methodology in optimizing the cutting parameters of end-milling process for machining the halloysite nanotubes (HNTs) with aluminium reinforced epoxy hybrid composite material under dry condition. The machining parameters which are chosen to be evaluated in this study are the depth of cut (d), cutting speed (S) and feed rate (f). While, the response factors to be measured are the surface roughness of the machined composite surface and the cutting force. An orthogonal array of the Taguchi method was set-up and used to analyse the effect of the milling parameters on the surface roughness and cutting force. The result from this study shows that the application of the Taguchi method can determine the best combination of machining parameters that can provide the optimal machining response conditions which are the lowest surface roughness and lowest cutting force value. For the best surface finish, A1–B3–C3 (d = 0.4 mm, S = 1500 rpm, f = 60 mmpm) is found to be the optimized combination of levels for all the three control factors from the analysis. Meanwhile, the optimized combination of levels for all the three control factors from the analysis which provides the lowest cutting force was found to be A2–B2–C2 (d = 0.6 mm, S = 1000 rpm, f = 40 mmpm).

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Introduction

The composite materials with low density and high strength stand are mostly preferable for most applications in the industry world [1]. The unique properties such as the high specific stiffness and strength, high mechanical strength, high damping, good corrosive resistance and low thermal expansion of the fibre-reinforced composite materials have enabled their use in automotive, machine tool industries, aerospace, sporting equipment industries [2]. However, composite materials could be very difficult to machine because of their non-homogeneous, anistropic and reinforced by very abrasive materials. So, the machined composite work piece may experience a significant damage and high wear rate of cutting tools. After all, the machining of composite materials is depending on several conditions such as the material properties, relative content of the reinforcement and the matrix materials, and the response to the machining process [3].

Hybrid polymer composites

In polymer composites, hybrid composite is considered as a kind of reinforcing material which is incorporated in a mixture of different matrices, or two or more reinforcing and filling materials present in a single matrix, or both approaches [4]. When a composite has more than two reinforcing phases, these two reinforcing phases might experience deviations either positive or negative from the properties predicted by the rule of mixtures and these deviations are known as hybrid effects [5].

In this study, the hybrid polymer composite material consists of a type of nanoclay material, halloysite nanotube (HNT) and a type of metal filler, aluminium filler. The halloysite nanotubes (HNTs) possess the characteristics of enhancing thermal stability, impeding the crack growth and improving the strength and toughness of the epoxy matrix composites [6]. Meanwhile, the aluminium powder filler has been proven to exhibit the qualities of improving machinability and thermal of the epoxy matrix composites [7]. The incorporation of HNTs into hybrid composites can be considered as the new hybrid epoxy composites which have huge potentials to contribute in various applications such as rapid tooling, aerospace, defence and automobile applications.

Taguchi method

Design of experiments is a powerful analysis tool for modelling and analysing the influence of control factors on performance output. The traditional experimental design is difficult to be used especially when dealing with large number of experiments and when the number of machining parameter is increasing [8]. The most important stage in the design of experiment lies in the selection of the control factors [9]. Therefore, the Taguchi method, which is developed by Dr. Genichi Taguchi, is introduced as an experimental technique which provides the reduction of experimental number by using orthogonal arrays and minimizing the effects out of control factors [8]. Taguchi is a method which includes a plan of experiments with the objective of acquiring data in a controlled way, executing these experiments and analysis data in order to obtain the information about behaviour of the given process [1,10,11]. Besides that, it is a set of methodologies that took into account of the inherent variability of materials and manufacturing process during the design stage [12]. It is almost similar to the design of experiment (DOE) but the Taguchi design's balanced (orthogonal) experimental combination offers more effective technique than the fractional factorial design [12]. This technique has been applied in the manufacturing processes to solve the most confusing problems especially to observe the degree of influence of the control factors and in the determination of optimal set of conditions [1].

In the Taguchi definition, the quality of a product is defined in terms of the loss imparted by the product to the society from the time it is shipped to the customer [13]. The losses due to the functional variation are known as losses due to the deviation of the product's functional characteristics from its desired target value. Besides that, the noise factors are the uncontrollable factors which cause the functional characteristics of a product that do not achieve its targeted values [13]. The noise factors can be classified as the external factors (temperature and human errors), manufacturing imperfections and product deterioration. The main purpose of quality engineering is to make sure that the product can be robust with the respect of all possible noise factors [13]. So, the Taguchi method could decrease the experimental or product cycle time, reduce the cost while increasing the profit and determines the significant factors in a shorter time period as it can ensure the quality in the design phase [8,12].

The procedure of Taguchi's design as shown in Fig. 1 can be categorized into three stages viz. system design, parameter design and tolerance design [12]. Parameter design, considered as the most important stage, can determine the factors affecting quality characteristics in the manufacturing process. The first step in Taguchi's parameter design is selecting the proper orthogonal array (OA) according to the controllable factors (parameters). Then, experiments are run according to the OA set earlier and the experimental data are analysed to identify the optimum condition. Once the optimum conditions are identified, then confirmation runs are conducted with the identified optimum levels of all the parameters [12].

The use of parameter design in Taguchi's technique is an engineering method of focusing on determining the parameter settings producing the best levels of a quality characteristic with minimum variation for a product or process. The main

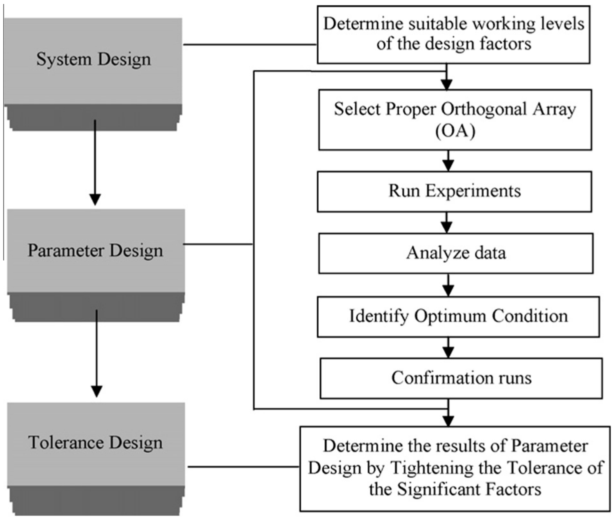

Fig. 1 Taguchi design procedure [12].

objective of quality engineering is to make products that are robust in respect of all noise factors [8]. So, Taguchi created standard orthogonal array to accommodate as many factors as possible into control factor selection stage to identify non-significant variables in the earliest opportunity. Taguchi used the signal-to-noise (S/N) ratio as the measurable value of the quality characteristics of the choice. This shows that the engineering systems can behave in a way such that the manipulated production factors can be divided into three categories [8]:

1. Control factors, (factors that affect the process variability as measured by the S/N ratio).
2. Signal factors (factors that do not influence the S/N ratio or process mean).
3. Factors (factors that do not affect the S/N ratio or process mean).

The experimental observations are future transformed into signal-to-noise (S/N) ratios. Signal-to-noise (S/N) ratio was used by Taguchi as the quality characteristics of choice and here are several S/N ratios available depending on the type of performance characteristics [9]. The S/N ratio can be characterized into three categories when the characteristics are continuous:Nominal is the best characteristic:

$$S/N = 10\log\frac{\bar{y}}{S_y^2}$$

Smaller the better characteristics:

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

Larger the better characteristics:

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

where '$\bar{y}$' is the average observed data, 'S_y^2' the variance of 'y', 'n' the number of observations, and 'y' the observed data. For each type of characteristics, higher or lower value of S/N ratio indicates the better result value [13].

Objective of study

In this study, the Taguchi parameter design phase is the most important design phase and served the objective of determining the optimal end-milling parameters to achieve the lowest surface roughness and cutting force values for HNT-Al/epoxy hybrid composite under varying end-milling parameter conditions. The following are the questions considered in this study:

- The relationship between the control factors (depth of cut, spindle speed and feed rate) and output response factors (surface roughness and cutting force).
- The optimal conditions of the end-milling parameters for surface roughness and cutting force.

Experimental design

Orthogonal array and experimental factors

In the parameter design stage of the Taguchi method in Fig. 1, the first step is to set up and select a proper orthogonal array (OA). To accommodate three control factors into the experimental study, a standardized Taguchi-based experiment design, $L_{27}(3^3)$ was chosen to be used in this study and is shown in Table 1. This basic design makes use of three control factors with three levels each and the design has capability to check the interaction between the factors. From the standard design (Table 1), there are 27 experimental runs that need to be conducted with the combination of levels for each control factor (A–C). As the incorporation of the noise factors into the OA is optional, the noise factor is omitted from this experimental study. The selected parameters are displayed in Table 2 together with their codes and values for the application in Taguchi parameter design study. In this study, the control factors (Depth of cut, Spindle speed, and Feed rate) are the independent variables while the response factors (Surface roughness, Cutting force) are the dependent variables.

In Table 3, a modified OA has been created by using basic Taguchi OA (Table 1) and the selected parameters from Table 2. In this modified OA, the basic arrays of control factors are combined with the arrays of response factors along with the S/N ratio (η) values and it brings to the total number of 27 experimental runs.

Materials and methods

By following the selected OA from the previous step, experimental runs need to be conducted to collect the desirable data.

Materials

The sample material chosen for this experiment is the halloysite nanotube (HNT) reinforced with aluminium-epoxy hybrid

Table 1 The basic Taguchi $L_{27}(3^3)$ orthogonal array.

Run	Control factors and levels		
	A	B	C
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3
19	3	1	1
20	3	1	2
21	3	1	3
22	3	2	1
23	3	2	2
24	3	2	3
25	3	3	1
26	3	3	2
27	3	3	3

Table 2 Parameters, codes, and level values used for orthogonal array.

Parameter	Code	Level 1	Level 2	Level 3
Control factors				
Depth of cut, *d* (mm)	A	0.4	0.6	0.8
Spindle speed, *S* (rpm)	B	500	1000	1500
Feed rate, *f* (mmpm)	C	20	40	60
Response variable				
Surface roughness, Ra (μm)	–	–	–	–
Cutting force, Fr (N)	–	–	–	–

Table 3 Orthogonal array.

Run	Inner control factor array			R_a	η_{Ra}	F_r	η_{Fr}
	A	B	C				
1	1	1	1	1.15	−1.21	94.31	−39.49
2	1	1	2	1.94	−5.74	41.54	−32.37
3	1	1	3	1.18	−1.47	38.87	−31.79
4	1	2	1	0.96	0.34	16.44	−24.32
5	1	2	2	0.62	4.15	5.45	−14.73
6	1	2	3	0.77	2.25	35.85	−31.09
7	1	3	1	1.06	−0.48	43.78	−32.83
8	1	3	2	0.36	8.95	35.46	−30.99
9	1	3	3	0.29	10.84	83.02	−38.38
10	2	1	1	1.43	−3.12	60.28	−35.60
11	2	1	2	0.89	1.01	1.63	−4.23
12	2	1	3	1.28	−2.14	45.85	-33.23
13	2	2	1	1.10	−0.82	12.76	−22.12
14	2	2	2	0.86	1.36	7.57	−17.58
15	2	2	3	0.77	2.23	23.60	−27.46
16	2	3	1	0.37	8.71	9.46	−19.52
17	2	3	2	0.63	3.97	4.81	−13.64
18	2	3	3	0.84	1.55	47.63	−33.56
19	3	1	1	1.14	−1.12	3.13	−9.92
20	3	1	2	1.80	−5.08	62.40	−35.90
21	3	1	3	1.81	−5.16	93.45	−39.41
22	3	2	1	1.15	−1.22	41.94	−32.45
23	3	2	2	1.43	−3.08	2.27	−7.11
24	3	2	3	2.11	−6.47	42.31	−32.53
25	3	3	1	0.95	0.47	8.41	−18.50
26	3	3	2	1.25	−1.94	23.51	−27.42
27	3	3	3	0.47	6.54	14.23	−23.06
	A	B	C				
R_a Effects							
Level 1	0.93	1.40	2.92				
Level 2	0.91	1.08	1.08				
Level 3	1.34	0.69	1.06				
η_{Ra} Effects							
Level 1	1.96	−2.67	0.17				
Level 2	1.42	−0.14	0.40				
Level 3	−1.89	4.29	0.91				
F_r Effects							
Level 1	43.86	49.05	32.28				
Level 2	23.73	20.91	20.52				
Level 3	32.41	30.03	47.20				
η_{Fr} Effects							
Level 1	−30.67	−29.10	-26.08				
Level 2	−22.99	−23.27	−20.44				
Level 3	−25.14	−26.43	−32.28				

composite. This hybrid composite consists of 0.5% wt HNT, 10% wt aluminium, 62.65% wt epoxy resin and 26.85%wt hardener. The Casting method was performed under the constant temperature of 70 °C kept for 5 h in an oven to prepare this composite in an aluminium mould with the sample block dimension of 120 × 70 × 15 mm.

Experimental details

In this experimental process, 27 different combinations of milled lines with 6 mm width were made by performing an end-milling operation (dry condition) on the hybrid composite sample as shown in Fig. 2. The milling operation processes were performed in a 3-axis OKUMA CNC milling centre. Meanwhile, the cutting tool used is the NKO end-milling tool with four flutes (dia, 6 mm). The surface roughness measurement was done by using a portable surface roughness tester TR200 (measures R_a in μm; stylus travel 1.5 mm cut-off). Besides that, the cutting forces were also measured online during end-milling operation with a sensitive three component Kistler 5070A type piezoelectric dynamometer with a charge amplifier. The data acquisition was made through the charge amplifier and a computer using the appropriate software (Dynoware). The microsurface morphology study was carried out using the Scanning Electron Microscope Hitachi S-3400N.

Results and analysis

From Fig. 1, data analysing on the optimal levels for all control factors is the first step after completing the experimental stage. The main aim for this experiment is to optimize the milling parameters to obtain lower surface roughness and optimum resultant cutting force values so the smaller the better characteristic was chosen in this analysis. The results from the experimental stage which are the surface roughness, R_a and cutting force, F_r values are recorded in Table 3. Conceptual S/N approach is recommended by Taguchi for the means and S/N ratio analysis which involves graphing the effects and visually identifying the factors which appear to be significant without using ANOVA analysis. Thus, these made the approach to become more simple and effective.

Determination of the optimum machining parameters

Surface roughness

The-smaller-the-better characteristic was used to determine the smallest surface roughness (R_a) that would be the ideal situation for this study. Meanwhile, the larger S/N ratio would be projected as the best response given in the machine set-up system which would be the ideal situation. The graphs in Fig. 3 are used to determine the optimal set of parameters from this experimental design. From the graphs, the control factor of depth of cut (A) at level 1 (0.4 mm) shows the best result. On the other hand, the cutting speed control factor (B) provides the best result at the level 3 (1500 rpm). Meanwhile, the feed rate control factor (C) gives the best results at the level 3 (60 mmpm). There are no conflicts in determining the optimal depth of cut, spindle speed and feed rate and the criteria of the lowest response and highest S/N ratio were followed. Thus, the optimized combination of levels for all the three control factors from the analysis which provides the best surface finish was found to be A1–B3–C3.

Cutting force

In the other response factors, the resultant cutting force (F_r), the-smaller-the-better characteristic was used and the smallest resultant cutting force value would be the ideal situation. The graphs in Fig. 4 are used to determine the optimal set of parameters from this experimental design. From the graphs (Fig. 4), the control factor of depth of cut (A) at level 2 (0.6 mm) showed the best result. Besides that, the cutting speed control factor (B) provided the best result at the level 2 (1000 rpm). On the other hand, the feed rate control factor (C) showed the best results at the level 2 (40 mmpm). There were also no conflicts happening in determining the optimal depth of cut, spindle speed and feed rate while the criteria of the lowest response and highest S/N ratio were followed.

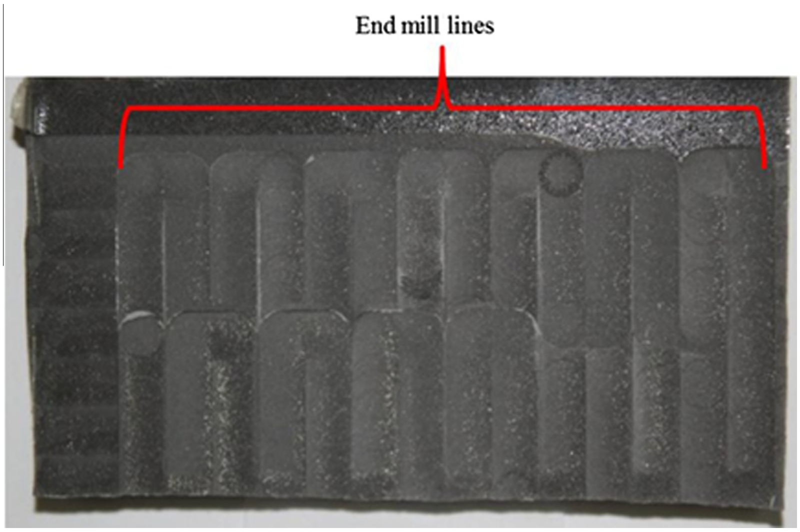

Fig. 2 27 End-mill lines with 6 mm width on HNT/Al/Epoxy hybrid composite.

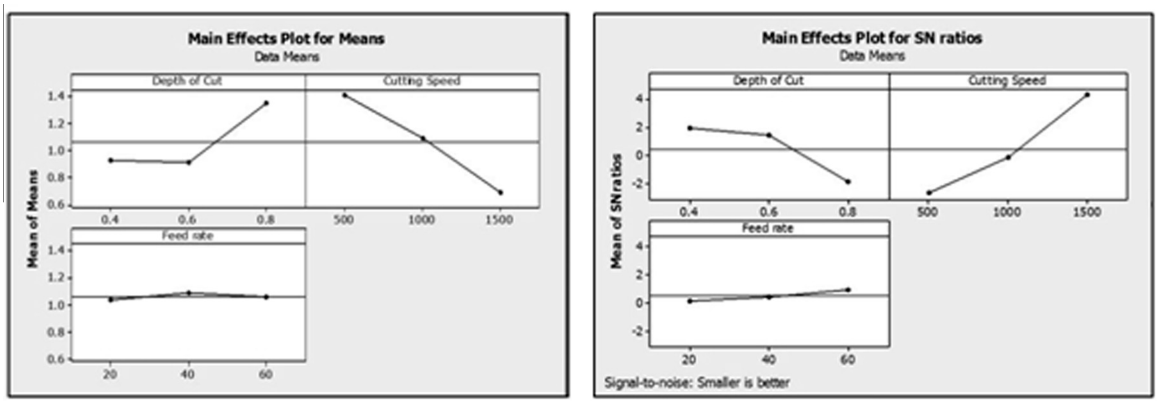

Fig. 3 R_a means and S/N ratio effects for each control factors.

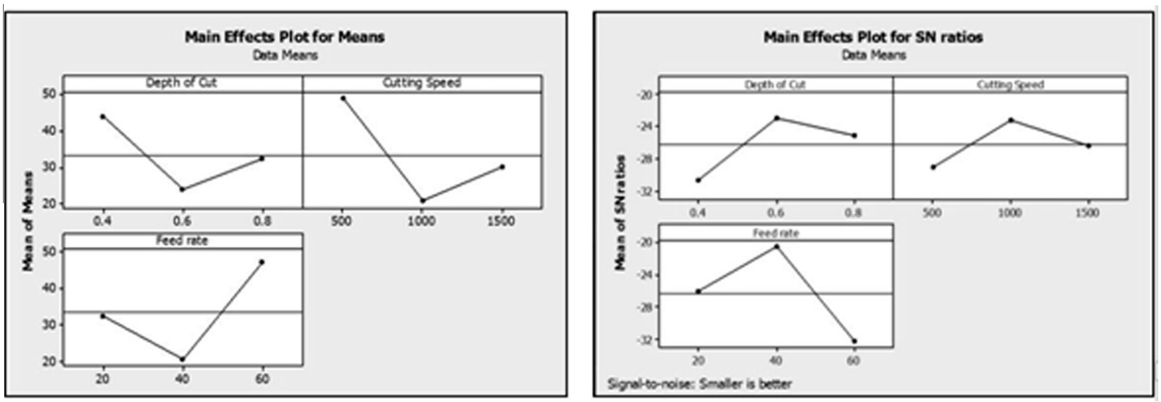

Fig. 4 Fr means and S/N ratio effects for each control factors.

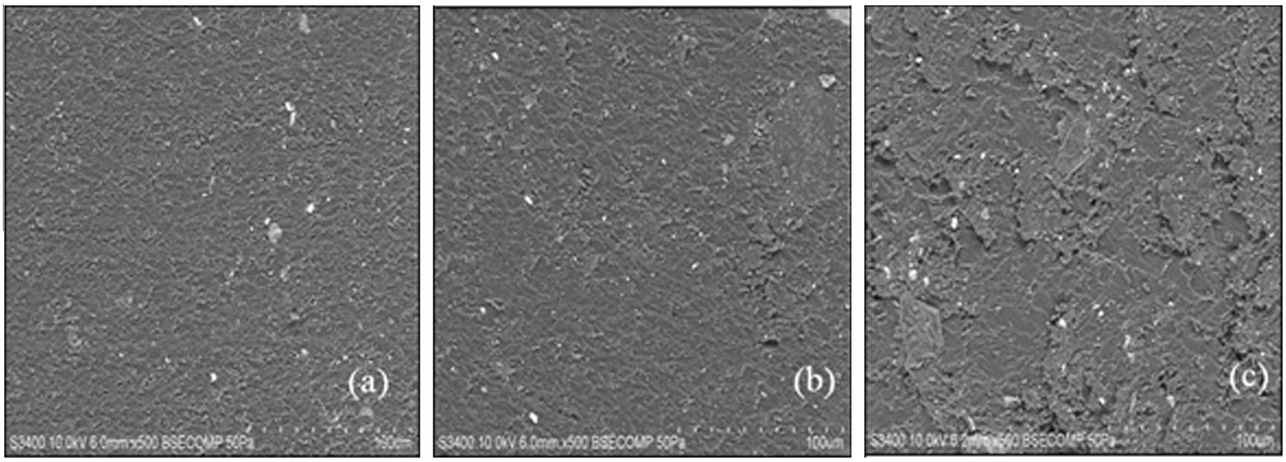

Fig. 5 SEM Surface morphology study. (a) Lowest R_a (b) medium R_a and (c) highest Ra.

Thus, the optimized combination of levels for all the three control factors from the analysis which provides the lowest cutting force was found to be A2–B2–C2.

Morphology study

From the analysis of surface roughness, in Fig. 3, there are three optimal combinations of control factors which give three different responses in surface roughness value that can be identified. The first control factor combination which gives lowest surface roughness value is A1–B3–C3. Meanwhile, the second control factor combination of A2–B2–C2 gave a medium surface roughness value (R_a). For the third combination of the control factors, A3–B1–C1 gives the highest surface roughness value (R_a). In Fig. 5, the surface morphology studies were done on all three optimum surfaces. From the study, the surface morphology images in terms of roughness for all three machining lines can be seen to be varied following the variation of surface roughness value.

Conclusions

In this study, the Taguchi method was performed to select the optimal cutting parameters from varying combinations of cutting parameters for end-milling operations on the HNT-Al/epoxy hybrid composite material. A basic $L_{27}(3^3)$ orthogonal array was selected with 27 experimental runs which included the three main factors each at three levels and this proved that the Taguchi parameter design is an efficient way to determine the optimal combination of cutting parameters for lowest surface finish and cutting force. Additionally, the micro-structure surface morphology study was presented on the visual variation of machined surface roughness which seems to be identical to the variation of surface roughness value.

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