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Influence of Machining Parameters on Tool Wear in Drilling of GFRP Composites – Taguchi Analysis and ANOVA Methodology

Sathish Rao U[1]. and Dr. Lewlyn .L.R. Rodrigues[2]

Abstract

Nowadays, the Fiber Reinforced Polymer (FRP) has replaced many of the mechanical components and this composite industry is experiencing significant growth. FRP's also have replaced several traditional materials used in building, sporting equipment/appliances, automotive/aircraft parts, boat and canoe hulls, and bodies for recreational vehicles. The composites in general, offer many advantages over traditional materials: important among these are high strength to weight ratio, light weight, flexible design, parts consolidation, dimensional stability, corrosion resistance and low tooling costs. Since the composites are anisotropic in nature, machining them is a complex process especially with reference to drilling and milling. Therefore, during the dry drilling operation on composites, drilling induced damage drastically affects the performance of the drill tool. So, the present investigation is an attempt to study the effect of the drill process parameters like the spindle speed (1000, 1200 and 1500 rpm), the feed rate (0.1, 0.2 and 0.3 mm/rev), the drill diameter (6, 8 and 10mm) and fiber orientation (Random, Random+Stitched and Random+Rowings) on the tool wear of the HSS drill bits in dry drilling of glass fiber reinforced polyester composites. The experimental runs of the set process parameters were determined using Taguchi's experimental design technique. Orthogonal arrays of Taguchi, the Signal-to-Noise (S/N) ratio, and the Analysis Of VAriance (ANOVA) are employed to find the optimal process parameter levels to minimize the tool wear and to analyze the contribution of each of these process parameters on tool wear.

Keywords: polymer composites, design of experiments, tool wear, analysis of variance.

Introduction

Composite Materials are used extensively because of their higher strength to weight ratios and modulus to weight ratios, when compared to metals, which make them to offer new opportunities for design. Conventional machining methods such as drilling, turning, sawing, routing and grinding, can be applied to composite materials using appropriate tool design and operating conditions.

Amongst all conventional machining processes in industries, drilling is one of the most important metal-cutting operations, comprising approximately 33% of all machining operations [3, 4]. In this process, HSS twist drills are used commonly for metals, non-metals and composites. Drilling processes are widely used in the aerospace, aircraft, and automobile industries especially in assembly lines and in fastening operations. Drilling is the most common machining operation, since many holes must be drilled in order to install mechanical fasteners. Poor quality of the hole accounts for an estimated 60% of part rejections, and since the holes are drilled on finished products, part rejections due to poor quality of the hole prove very costly.

Tool wear is defined as the unwanted removal of tool material from the cutting edge leading to undesirable changes in the cutting edge geometry. Thrust and torque depend upon drill wear, which in turn depends on drill size, feed rate and spindle speed. Research results shows that tool breakage, tool wear and work piece deflection are strongly related to cutting force. Once the initial cutting geometry is altered, the cutting tool becomes less effective in material removal and generating good quality machined surface [5]. Tool wear leads to undesirable consequences such as reduction in cutting edge strength, increased tool forces and power consumption, increased cutting temperatures, reduction in surface finish, loss of dimensional accuracy, and loss of productivity [6]. In fact, it has been predicted that an accurate and reliable tool can increase cutting speeds from 10-50%, compared to worn out tools and a proper conditioned tool reduces the machine downtime by allowing to be scheduled in advance and an overall increase in savings between 10-40% (Adam, Dr. Jin Jiang and Dr. Peter, 2004)[14].

Tool wear in drilling is a progressive and comparatively slow phenomenon whereas tool failure and cutting edge breakage are usually catastrophic without any warning. Even though a drill tool begins to wear as soon as it is placed into operation, the wear occurs at an accelerated rate once a drill becomes dull. In general, the distribution of heat generated during cutting, gradients of pressure, friction, and the stress distribution at the tool–work piece interface influence wear patterns [7].

Many researchers have selected outer corner wear as the predominant type of wear in drilling. But in practice, the most important types of wear in drilling of metals are flank and crater wear [8]. Several investigations have shown that while machining on metals, the tool wear is mainly due to abrasion at lower speed conditions. When the cutting speed is increased, temperature further increases under dry machining conditions.. Consequently, diffusion is considered as the dominant wear mechanism for tools at higher cutting speeds. The atoms that are diffused from the tool to the chip are carried away by the flow of work material along the contact surface. This will consequently lead to significant reduction in tool life (Choudhury, Gangaraju, 2000)[15].

Being non-homogeneous, anisotropic, and reinforced with abrasive fibres, the composite materials are difficult to machine. Significant damage to the work piece may be introduced and high wear rates of the tools are experienced [9]. Highly alloyed tool steel is capable of maintaining hardness at

[1]Assistant Professor (Selection Grade), Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal, Karnataka, 576 104
[2]Professor and Head,, Department of Humanities and Management, Manipal Institute of Technology, Manipal, Karnataka, 576 104

elevated temperatures better than high carbon and low alloy steels. Due to this observation, the research is focused on HSS drilling on composite materials.

GFRP specimen preparation

The specimens used for experimentation were manufactured using the hand-layup technique. The S-glass fiber mat with

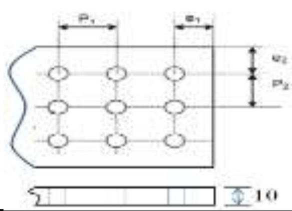
Figure 1. Polymer composites with Different fabrics

random, stitched and rowings fabric were used as the reinforcement. The raw glass fiber mats (random, stitched and rowings) were cut according to the size of the flat plate mold. Isopthalic polyester resin is used as the matrix along with Araldite as binder and hardener material. The laminate thickness was set to 10mm and the fiber- volume fraction of the specimen was set at 0.33 (Figure 1).

Experimentation

A schematic diagram of the dimensional specifications for hole spacing for the present work is shown in Figure 2.

The



d_0 Hole diameter.

Distances and spacing	Mandatory minimum
e_1	$1.2d_0$
e_2	$1.2d_0$
p_1	$2.2d_0$
p_2	$2.4d_0$

Figure 2. Hole specifications in drilling

holes were generated on the GFRP laminates accordingly. The machining operations were carried out on 3 - Axis CNC Vertical Machining Center (VMC) AMS Spark machine, shown in Figure 3.

For drilling holes, the chosen factors and their set levels are shown in Table 2.

Figure 3. 3-axis CNC Vertical Machining Center

Design of Taguchi orthogonal array layout

The Taguchi orthogonal array layout stipulates the way of conducting the minimal number of experiments which could give the full information of all the factors that affect the performance parameter. It consists of an inner array and an outer array. The inner array is made up of the orthogonal array (OA) selected from all the possible combinations of the controllable factors. The outer array contains the combinations of the uncontrollable factors. In the present case, in comparison to noise factors, the controllable factors have considerably high impact on the quality of drilled hole in the composite laminates and consequently their tensile strength. Therefore, only inner array has been considered [10]. While, there are many standard orthogonal arrays available, each array is meant for a specific number of independent design variables and levels. L9 orthogonal array is selected for the present investigation.

Table 2.Factors and their set levels

Symbols	Factors	No. of Levels		
		Level 1	Level2	Level 3
A	Spindle Speed (rpm)	1200	1500	1800
B	Feed (mm/rev)	0.1	0.2	0.3
C	Drill diameter (mm)	6	8	10
D	Fabric type	Random	Random+ Strand (R+S)	Random + Rowing (R+R)

The experimentation is conducted to understand the influence of four independent variables each at three levels. Table 3 shows L9 orthogonal array layout.

Signal-to-Noise ratio

To determine the effectiveness of a design, there must be some measure to evaluate the impact of the design parameters on the output quality characteristics. The term signal represents the

Table 3. Taguchi's L9 Orthogonal Array

Expt No	A	B	C	D
E1	1	1	1	1
E2	1	2	2	2
E3	1	3	3	3
E4	2	1	2	3
E5	2	2	3	1
E6	2	3	1	2
E7	3	1	3	2
E8	3	2	1	3
E9	3	3	2	1

desirable component of the output characteristics, which is close to its specific target value. The term noise represents the undesirable component and is measure of the variability of the output characteristics. The Taguchi method uses the Signal-to-Noise ratio (S/N) to express the scatter around a target value. A high value of S/N implies that the signal is much higher than the random effects of the noise factors. From the quality point of view, there are three possible categories of the quality characteristics. They are (1) smaller is better; (2) nominal is better; (3) larger is better. In the present investigation, the objective is to minimize the tool wear, so ''smaller is better'' quality characteristics is selected, whose logarithmic function given as $S/N = -10 \log_{10} (1/n \ \Sigma \ Y_i^2)$ where n is the number of measurements in a trial/row [11, 12]. In this research work, n=3 and y_i is the i^{th} response value or measured value in a run/row.

Plan of Experiment:

The experiments were conducted as per the standard Taguchi's orthogonal array. The selection of the orthogonal array is based on the condition that the degrees of freedom for the orthogonal array should be greater than or at least equals sum of those of wear parameters. In the present investigation an L9 orthogonal array was chosen as shown in Table 4, which has 9 rows corresponding to the number of tests.

Table 4. L9 orthogonal Array with experimental factors and levels

Expt No.	Spindle Speed (rpm)	Feed Rate (mm/rev)	Drill Diameter (mm)	Fabric Type
E1	1200	0.1	6	R
E2	1200	0.2	8	R+S
E3	1200	0.3	10	R+R
E4	1500	0.1	6	R+R
E5	1500	0.2	8	R
E6	1500	0.3	10	R+S
E7	1800	0.1	6	R+S
E8	1800	0.2	8	R+R
E9	1800	0.3	10	R

Experimental Procedure

- Preparing the Vertical CNC machining center ready for performing the machining operation.
- Preparing composite plates of size 300 mm × 25 mm × 10 mm for performing CNC drilling.
- Cleaning the drill bit using Acetone to remove impurities and atmospheric inclusions.
- Measuring weight of each drill by the high precision digital balance meter before machining.
- Creating CNC part programs for tool paths with specific commands using different levels of spindle speed and feed for performing drilling operation.
- Perform the drilling operation by drilling required number of holes (75 holes).
- Cleaning the drill bit using Acetone to remove deposited chip powders and other impurities.
- Measuring weight of each machined plate again by the digital balance meter.
- Determining tool wear by weight difference method / volume loss method (Table 5).

Experimental Results

Response (Tool Wear) Table for Means (Minitab)

Analysis of the S/N ratio

In the Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value (standard deviation, SD) for the output characteristic. Therefore, the S/N ratio is the ratio of the mean to the SD. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. In this experiment, Smaller is Better (LB) characteristic is used.

The smaller is better quality characteristic can be formulated

Table 5. Tool wear values with S/N number

Expt. No.	Average Tool wear (Weight diference)(gms) (T1+T2+T3)/3	S/N Ratio
E1	$2.67\text{x } 10^{-4}$	71.4698
E2	$3.73\text{x}10^{-3}$	48.5658
E3	$1.89 \text{ x}10^{-4}$	74.4708
E4	$2.97 \text{ x } 10^{-3}$	50.5449
E5	$7.07 \text{ x } 10^{-3}$	43.0116
E6	$4.33 \text{ x } 10^{-4}$	67.2702
E7	$6.8 \text{ x } 10^{-4}$	63.3498
E8	$2.57 \text{ x } 10^{-3}$	51.8013
E9	$5.5 \text{ x } 10^{-4}$	65.1927

as as $S/N = -10 \log_{10} (1/n \, \Sigma \, Y_i^2)$, where n is the number of measurements in a trial, in this research work, n=3 and y_i is the i^{th} measured value in a run/row. The S/N ratio values are calculated by taking the above equation as shown in Table 5.

Taguchi Analysis: Tool Wear versus A, B, C, D (Minitab)

Graphical Representation

The investigational results and calculated values were obtained based on the plan of experiment and then the results were analyzed with the help of commercial software MINITAB 16, a software for the design of experiment and statistical analysis of experimental data. The influence of controlled process parameters such as drill spindle speed, drill feed, drill diameter and composite fiber orientation has been analyzed. The tool wear for each factor and level is calculated. The rank of involved factors on the tool wear is found by calculating the difference between maximum and minimum S/N number as shown in Table 6 and Table 7.

Table 6. Response table for means (Minitab)

Levels	A	B	C	D
1	0.001395	0.001306	0.001090	0.002612
2	0.003491	0.004457	0.002400	0.001614
3	0.001250	0.000374	0.002646	0.001910
Δ = Max - Min	**0.002241**	**0.004083**	**0.001556**	**0.000998**
Rank	**II**	**I**	**III**	**IV**

It is evident from the above Table 6 and Table 7 that, among these parameters, drill feed is a dominant factor on the tool wear rate. The influence of controlled process parameters on tool wear is graphically shown in Figure 4.

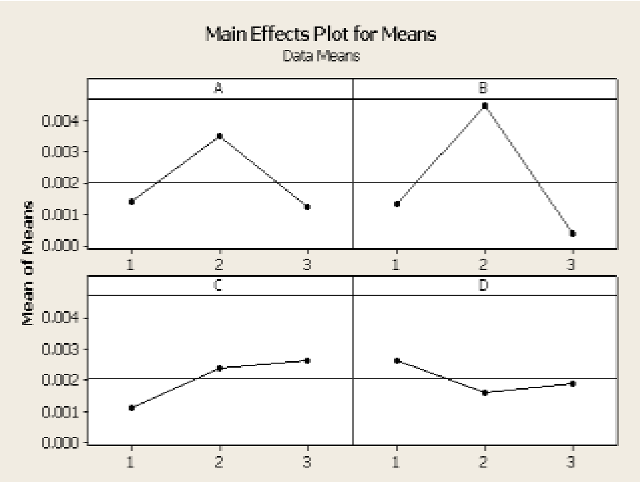


Figure 4. Graph of Main effect plot

Based on the analysis of S/N ratio, the optimum conditions resulting in minimum tool wear is shown in Figure 5.
The figures clearly indicate that the first level of speed (A1)

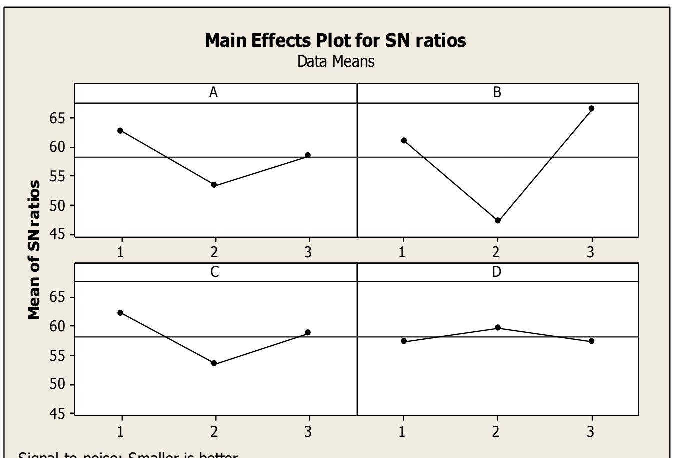


Figure 5. Graph of Main effect plot for S/N ratio

and third level of feed (B3) and first level of drill diameter (C1) and random+strand fiber orientation (D2) are the optimum factors and their levels for minimum tool wear.
It can be seen from Figure 5 that for the graph of feed rate, the slope is bigger. It means that the feed rate changes significantly affect tool wear, and the same trend can also be observed on the graph of drill spindle speed and drill diameter.

Results of Analysis of Variance (ANOVA)

ANOVA is a statistically based, objective decision-making tool for detecting any differences in the average performance of groups of items tested. ANOVA helps in formally testing the significance of all main factors and their interactions by

Table 7. Response Table for Signal to Noise Ratios: Smaller is better

Levels	A	B	C	D
1	64.84	61.79	63.51	60.17
2	53.61	47.79	55.04	59.73
3	60.39	69.25	60.28	58.94
Δ = Max - Min	**11.23**	**21.46**	**8.47**	**1.23**
Rank	**2**	**I**	**3**	**4**

comparing the mean square against an estimate of the experimental errors at specific confidence

Table 8 Analysis of Variance for Tool Wear

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr %
Speed	2	0.0000595	0.0000595	0.0000298	231.12	0.0000	33.75
Feed	2	0.0000768	0.0000768	0.0000384	298.02	0.0000	43.51
DD	2	0.0000251	0.0000251	0.0000125	97.43	0.0000	13.83
FT	2	0.0000138	0.0000138	0.0000069	53.63	0.0000	7.61
Error	18	0.0000023	0.0000023	0.0000001			1.30
Total	26	0.0001775					100.00
R-Sq = 98.69% R-Sq(adj) = 98.11%							

levels. The total sum of squares value is used to measure the relative influence of the factors. The large value of sum of squares, the more influential the factor is for controlling the responses.
Table 8. shows the results of the analysis of variance on the wear rate for glass fiber polyester matrix composite. This analysis is carried out at a level of 5% significance that is up to a confidence level of 95%. The last column of the table indicates the percentage of contribution (Pr) of each factor on the total variation indicating the degree of their influence on the results.
From Table 8, one can easily observe that the drill feed factor has greater influence on tool wear rate (Pr-F=43.51%). Hence applying feed rate is an important control process parameter to be taken into account while wear process. Feed rate is further followed by the influence of spindle speed (Pr-S=33.75%), drill diameter (Pr-DD=13.83%) and fiber orientation (Pr-FT=7.61%) on drill tool wear.

CONCLUSIONS:

This study has discussed an application of the Taguchi method for investigating the effects of cutting parameters on the tool wear of drills in the dry drilling of Polymer Matrix Composites. In the drilling process, the parameters were selected by taking requirements of manufacturer and industry into consideration.
By using the conceptual Signal-to-Noise (S/N) ratio approach and Taguchi's optimization method along with application of ANOVA, the following can be concluded from the analysis of the results of the drilling process of the present study:

1. Conceptual S/N ratio and ANOVA Software approaches for data analysis drew similar conclusions.
2. Statistical results show that the feed rate (B), cutting speed (A), and drill diameter (C) have significant effect on tool

wear in dry drilling of Polymer Matrix Composites and the impact is 43.51%, 33.75%, and 13.83% respectively.

3. The above result concludes that the factors affecting the tool wear in dry drilling of Polymer Matrix Composites are Drill Feed followed by Drill Spindle speed, Drill diameter and Fabric Type respectively.
4. The minimum tool wear value is calculated as 3.9093 x 10^{-4}gms using Taguchi's optimization method.
5. In this study, Taguchi's analysis of the experiments for drill tool wear has shown the optimum cutting parameters as A1B3C1D2, which are spindle speed = 1200 rpm (A1), feed rate = 0.3 mm/rev (B3), drill diameter = 8mm (C2) and fabric type = random+strand (D2).

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