REDUCING DRILL WEAR BY OPTIMIZING THE PROCESS FACTORS IN THE MACHINING OF CFRP COMPOSITE LAMINATES USING DOE AND TAGUCHI ANALYSIS

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Abstract: Tool wear has been recognized as one of the most critical problems during the machining of composite materials. Minimization of tool wear during the drilling of CFRP composite laminates has been a research work for many years and a considerable amount of work has already been done to reduce it. In most of the research work related to tool wear of different machining operations on different types of composite materials, it was observed that the tool wear during machining could be optimized by controlling the respective process parameters. So, with respect to this, in this technical paper, drilling of CFRP composite material is considered for tool wear optimization and various drilling parameters such as spindle speed (N), feed rate (F), drill diameter (D) and tool point angle (θ) have been taken into consideration for the study. The drill land width difference has been taken as the parameter to measure the tool wear. From the experimental observations and taguchi analysis it was found that the tool wear is influenced by the drill diameter followed by spindle speed, feed and point angle. A regression equation was generated to predict the tool wear. The micrograph findings inferred that the adhesion and abrasion are the major mechanisms that cause the drill wear during the CFRP drilling.

Keywords - CFRP composites, ANOVA, tool wear, S/N ratio, orthogonal array

I. INTRODUCTION

Composite Materials are made by joining two or more physically distinct and mechanically separable materials with significantly different properties. The two major constituents of any composite material are the resin or the matrix material (which forms the bulk of the composite material) and the reinforcement or fiber material (which provides the required strength and stiffness to the composite). The two materials combine to give the composite unique properties which are better than those of the individual
constituents, when used alone [1]. In contrast to metallic alloys, each material retains its separate physical, chemical and mechanical properties. Composites are nowadays commonly used in industrial and domestic purposes as they are light in weight but stronger compared to metals. The Matrix material performs several critical functions like taking up the initial applied load and gradually transferring it to the fibers, maintaining the fibres in the proper orientation and protecting them from abrasive environment. By choosing an appropriate combination of the constituent materials (matrix+fiber), a new composite material can be made that can exactly meet the requirements of a particular application [2].

Carbon fiber reinforced plastic (CFRP) is one of the composite materials that are well recognized for their superior mechanical properties. Nowadays CFRP materials are being applied for various mechanical structures and components in aerospace, automobile and marine industries, where high rigidity with light weight is required.

Drilling is the most frequently employed operation in any of the conventional / composite materials, owing to the need for structure joining and assembly. The rapid tool wear of the drill bit has been recognized as one of the major problems during drilling operations. The consequences of tool wear while machining may change the dimension, tolerance, shape and surface finish of a drilled hole. Care must be taken in early stage before the tool breakage has damage on the product or process flow in order to reduce cost and time [3]. So, the process of drilling of composites is economically important since the extremely abrasive nature of the fibers limits the drill life [4]. The experimental results and theoretical analysis show that the degree of tool damage depends on drilling factors and on the composite material composition [5].

It was found that, with an optimized combination of the various factors of the materials, machine and the tool, the wear of the drill can be minimized [6]. A number of research works reveal that, in practical, the significant type of wear in drilling are flank and crater wear [7]. Many investigations say that the tool wear in drilling occurs due to abrasion of tool material at lower cutting speeds and through diffusion at higher speeds in machining on metals [8]. Thus composite materials are difficult to machine because of anisotropy nature, and of the abrasive nature of reinforcements. So, damage to the work piece is significant and tool will high wear at higher rate [9]. The alloyed tool steel material can withstand hardness at higher temperatures and are economical. Due to these findings, the present study is focused on HSS drilling on CFRP composites to minimize the drill wear by controlling the machining factors. The machining factors considered are Spindle speed, Feed, Drill diameter and Drill point angle.

II. METHODOLOGY

Composite laminate of constant thickness of 6mm was manufactured by vacuum bagging method (Figure 1). Carbon fibers of 15 micron diameter with bidirectional plain weave fabric type was used as reinforcement material and Hinpoxy C resin was used as matrix material.

material for fabricating the composite laminate. The fiber weight fraction was set to 50%. Alternate layers of fiber, resin and hardner mix are laid up until the required thickness of 6mm is reached.

**Process factors and levels:**

- **Drill Spindle speed:**
  - The spindle speed levels chosen are 4000, 5000 and 6000 rpm.

- **Drill feed:**
  - The drill feed process factor was set to 0.3mm/rev and 0.4mm/rev and 0.5mm/rev.

- **Drill diameter:**
  - HSS drills of diameters 6mm, 8mm and 10mm are opted for the experimental studies. A set of 9 drill bits were chosen for each run of the experimental design.

- **Drill point angle:**
  - The point angle of the drill bit was taken into account as the fourth process factor with three levels of 90°, 104° and 118°. The point angles were ground on a set of 9 drill bits each.

- Each experimental run was started with a new HSS drill and a new CFRP composite laminate.

**Sizing of the CFR laminates (using CREO):**

- Number of slabs required for each drill diameter: 9
- Number of holes to be drilled in each laminate: 60
- Maximum tool travel distance in x-y direction: 250 mm x 145mm.
- Cutting allowances to be given: 4 to 5 mm.

Out of the different patterns available for drilling 60 holes on CFRP composite, the hole pattern with 6 rows *10 columns was found to be optimum in terms of material consumption and hence the same pattern was selected for all the 3 drill diameters.

- The calculations for sizing of each type of laminate were done using the modelling software, CREO. After trying different combination of drilling 60 holes in each laminate, the most optimum way was chosen which would give us the required number of slabs needed for the experiments by minimum material consumption. The optimum calculations for each type of slab are shown below:

**Optimum laminate dimensions for a 6 mm drill (Figure 2):**

- Minimum requirement: 133.2 mm*86.4 mm.
- Dimensions after allowance: 150 mm*100mm.

**Optimum laminate dimensions for 8 mm drill (Figure 3):**

- Minimum requirement: 177.6 mm*115.2 mm.
- Dimensions after allowance: 190 mm*130 mm

**Optimum laminate dimensions for a 10 mm drill (Figure 4):**

- Minimum requirement: 222 mm*144 mm.
- Dimensions after giving allowance: 240 mm*160 mm

**Experimental Design:**

- For the experimental study, the tool factors have been used as the control factors whereas the CFRP material
factors were kept constant (CFRP material thickness=6mm and Fiber volume fraction=50%). The various tool factors and the Minimum requirement: 222 mm*144 mm.

- Dimensions after giving allowance: 240 mm *160 mm.

**Experimental Design:**

For the experimental study, the tool factors have been used as the control factors whereas the CFRP material factors were kept constant (CFRP material thickness=6mm and Fiber volume fraction=50%). The various tool factors and the different levels of each parameter used in the experiment are shown in Table 1.

For the present experimental study, four process factors and three levels of each factor has been taken into consideration and the optimum number of experiments per run are determined using Taguchi’s L₉ Orthogonal Array[9,10] and number of replications of each experiment was set to 3, thus leading to a total numbers of 27 experiments. The various experiments as per Taguchi’s L₉ experimental design are shown in Table 2.

**Experimental Setup:**

CNC Vertical Machining Centre (Figure 5) was used for drilling operation on the composite laminates. A fixture was position (Figure 5) during drilling. There were a total of 27 laminates and in each laminate 60 holes were drilled during the drilling operation.

**Drill wear measurement:**

From the previous research investigations, it was observed that the cutting edge or the land of the drill is subjected to maximum wear during the drilling operation. Therefore, the change in the land width before and after the drilling operation was taken as a
measure to show the amount of drill wear during the drilling of the CFR Composite. Tool room microscope was used for measuring the land width difference. The precision of the Tool room microscope was 0.005 mm (Figure 6).

The undeformed land width was measured accurately for each drill before the drilling operation corresponding to each experimental run. The land width was measured again using the same measuring set up after the drilling operation. The corresponding difference in the land width was considered for the tool wear of the drill for each experimental run. Two such trials were carried out and the average of difference of land width was considered for safeguarding the accuracy and reliability of measured data (Table 3).

III. Results and Discussions

Taguchi Analysis, ANOVA and Regression analysis

The Main effect plot for Mean (Figure 9) of drill wear shows that drill diameter has more influence on drill wear followed by spindle speed, drill feed and drill point angle. This is further supported by ranking of the process factors in Table 4.

The S/N ratio plot for drill wear was based on smaller the better criterion. Based on this, the value of S/N Ratio for different levels of factor is shown in Table 5.
The minimum drill wear occurs at a spindle speed of 6000 rpm, feed rate of 0.3 mm/rev, 6 mm drill diameter and 118° drill point angle (Figure 10).

From Table 4 and Table 5, the ranking of process factors in terms of their significance were found to be:
- Drill diameter, Spindle speed, Feed rate and Drill point angle

**Analysis of Variance (ANOVA) of drill wear**

From Table 6, the value of P-level for each process factor is limited to zero which is lesser than the level of confidence opted i.e. α=0.05. This again implies that each process factor has some significant effect on the drill wear. To find the level of significance of each process factor on the drill wear, the percentage contribution of each process factor towards the drill wear is determined [10]. The contribution of each process factor is as shown below (Table 6).

**IV. Regression equation for Drill wear**

The following Regression Equation was generated for the Drill wear by considering the effect of main factors only:

\[
\text{Drill wear} = 0.0995 - 0.000022\times\text{spindle speed} + 0.1375\times\text{feed rate} + 0.01188\times\text{drill diameter} - 0.000357\times\text{point angle}
\]

**V. Micrograph analysis**

To observe the wear pattern, the micrograph analysis of the drill land was observed under the focus of Trinacular Inverted Metallurgical Microscope at a magnification factor of 500X.

The Figure shows the micrograph image taken at a spindle speed of 4000 rpm and feed rate of 0.3 mm/rev and drill diameter 6mm (drill point angle =118°). The drill land was found to be spread with a patch of white layer with parallel ridges (Figure 10). This is due to the ploughing of the plastically deformed matrix material that is transferred on to the drill land. The parallel ridges are formed due to the abrasion of the drill land. The drill land is also observed with the black carbon particles. So adhesion and abrasion could be the wear mechanisms under this condition.

At a spindle speed of 5000 rpm, feed 0.4 mm/rev and for 8mm drill diameter (drill point angle =118°), wider and deeper ridges were observed. Apart from this,
small scratches were also detected at some locations (Figure 11) due to abrasion and higher speed and feed and more contact area of the drill diameter with respect to the work piece material while machining. So, it can be concluded that the abrasion is the major wear mechanisms under this machining conditions. Deeper grooves along with damaging of the ridges were observed at a spindle speed of 6000rpm, feed rate of 0.5mm/rev and drill of 10mm diameter. The land surface also displayed small lumps of matrix material spread all over the area of the land along with ridge damage (Figure 12). This could be due to the fatigue and overloading of the drill during machining of CFRP composite. Thus the wear mechanism here could be due to abrasion of harder carbon fiber with the drill and fatigue load applied on the drill.

V. CONCLUSIONS
1. From the experimental study, the following conclusions were derived
   - There was a decrease in the land width after the machining of CFRP composites.
   - Powdered metal chips were observed for all the experimental runs.
   - Delamination of the CFRP composite was observed during machining operation.
2. From the ANOVA study, drill diameter was found to be the most significant factor that effects the drill wear with 45.03% contribution, followed by spindle speed with 36.35% contribution, drill feed with 14.04% contribution and drill point angle with the least contribution of 4.37%.
3. Drill spindle speed of 6000 rpm, drill feed of 0.4mm/rev, 6 mm drill diameter and drill point angle of 118° were considered as the optimum process factors for drilling CFRP composites with HSS drills.
4. Micrograph analysis showed small matrix lumps, matrix adhesion on the drill land along with deeper and wider ridges, small cracks, scratches and damages on the ridges.
5. Micrograph analysis showed that adhesion, abrasion, and fatigue were the major wear mechanism responsible for drill wear while machining CFRP composites with HSS drills.

VI. REFERENCES


