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INFLUENCE OF FIBRE VOLUME REINFORCEMENT IN DRILLING GFRP LAMINATES

D. ABDUL BUDAN[1], S. BASAVARAJAPPA[1,*], M. PRASANNA KUMAR[2]
AJITH G. JOSHI[3]

[1]Department of Mechanical Engineering, University B.D.T. College of Engineering, Davangere – 577004, India
[2]Department of Mechanical Engineering, Bapuji College of Engineering & Technology, Davangere – 577004, India
[3] Department of Mechanical Engineering, Canara Engineering College, Benjanapadavu, Mangalore-574219, Karnataka, India
*Corresponding Author: basavarajappas@yahoo.com

Abstract

This paper presents an investigation on the influence of fiber volume reinforcement on various aspects of machining. Drilling experiments were conducted to study the tool wear, surface finish, delamination factor and hole quality on GFRP composites. The work reports the variation of tool wear, surface roughness, hole quality, chip characteristics, delamination factor with the variation of fibre volume reinforcement. Results revealed that the increase in fiber percentage increased the tool wear, delamination factor, surface roughness value and decreased hole quality. Minimum surface roughness, tool wear and better hole quality was obtained for 30% fibre content composites. 70% Fibre content composites produced hazardous surface roughness. Pull out of fibres and fibril formation are significant in decreasing the hole quality and increased surface roughness. Increased tool – fibre interaction and thermal softening of the tool causes increased tool wear. In higher fibre content composites, extensive plasticity was absent consequently brittle ceramic fibres were fractured easily. Hence small segment type chips were obtained. The fibre pull out and fibrils present near the hole exit forms the remainder of the laminate causes increased damage zone near the hole exit. Hence high delamination factor was obtained.

Keywords: GFRP, Composites, Drilling, Fibre volume fraction, Delamination.

1. Introduction

Fiber Reinforced Polymeric (FRP) composites are becoming most popular materials in aerospace and other industries where high strength to weight ratio is the requirement. Their application have shown a promising future in such areas where fatigue and stress corrosive cracking are considered the dominant mode of failure. Extensive investigations have taken place in the past decade in research and development area to manufacture composite components economically [1]. Among FRP's, Glass fibre reinforced plastic surfaced the industrial market because of their low cost and excellent properties they enhance. GFRP components are usually manufactured by near-net shape fabrication. However for fastening and assembling purposes, secondary machining processes such as drilling, turning, trimming, sawing and slitting and so on are essential [2]. Unlike most of the engineering materials, polymeric composites are characterized by marked anisotropy, structural inhomogeneity and lack of plastic deformation behavior. These properties render them peculiar in machining operations. Excessive tool wear, poor surface quality, fibre pullout, fuzzy holes, poor dimensional accuracy and delamination are some of the problems observed during drilling [3, 4].

Among the defects caused by drilling, delamination appears to be of most critical. Delamination can result in lowering of bearing strength and can be detrimental to the material durability by reducing the in-service life under fatigue loads. Delamination during drilling is due to compressive thrust force acting on the uncut portion and peeling force acting on the cut portion [5]. Though the thrust force that cause delamination is higher near the exit and entry where the uncut portion is minimum, the mechanical property of a composite which is based on fiber resin proportion, play a vital role in drilling [6].

Much of the literature reporting on the drilling of FRP material by conventional tools has shown that the quality of cut surface is strongly dependent on drilling parameters. An improper selection of these parameters can lead to unacceptable material degradation, such as fibre pullout, matrix cratering, thermal damage and wide spread delamination [7-8].

Lee and Jang [9] reported that the failure processes such as de-bonding fibre pullout and local plastic deformation increases with the increase in fibre percentage. In addition the modulus of the composites increases linearly with the increment of glass fibre volume fraction. The phenomenon of delamination during drilling was identified and analyzed. Hocheng and Dharan [5] and Jain and Yang [10] reported that plate bending theory and Linear Elastic Fracture Mechanics were adopted to develop the model which can be used to predict the critical thrust and cutting forces which are important in optimizing drilling parameters. Bhattacharyya and Horigon [11] performed drilling on Kevlar composite by normal and modified tool bit under ambient and cryogenic conditions. They reported that modified drill bits under cryogenic condition undergo much lower wear rate. However the thrust force generated are higher than that produced under ambient condition with normal bit.

Wen [12] performed experimental investigations on the drilling of CFRP composite laminates. The concept of delamination factor is used to analyze the degree of delamination. The effect of drilling parameters and tool wear on delamination factor was discussed. Cutting temperature has been recognized as an important factor that influences the wear rate and tool life. It is reported that delamination free drilling may be possible by proper selection of tool geometry and drilling parameters. Lin and

Shen [13] and Lin and Chen [14] studied drilling of fibre reinforced composite materials and concluded that tool wear is the major problem at high speeds. The advanced designs of tools are four facets, eight facets, jo-point, inverted cone, candle stick drills and Zhirov. Many research studies focused on these types of tools and compared their characteristics with the conventional twist drill [15 - 18].

Davim et al. [19] investigated the correlation between cutting velocity and feed rate with a specific cutting force, feed force, damage factor and surface roughness in GRFP composite material. A plan of experiments based on the techniques of Taguchi was established considering drilling with pre-fixed drilling parameters. In these studies the special geometry of the drill “brad & spur” presents good performance. Jawali et al. [6] reported that increase in fiber content increases the tensile strength, wear resistance and resistance movement of drill bit. Gaitonde et al. [20] stated that point angle followed by feed and speed are the major contributing factors for delamination during drilling of CFRP. Iliescu et al. [21] have presented a model to predict the thrust during drilling of CFRP. Işık and Ekici [22] have presented a new approach to select cutting parameters for damage factor in drilling of GFRP. Tsao and Chiu [23] studied influence of drilling parameters on thrust force during drilling of CFRP using compound core-special drill, which is one of the promising drill. Rubio et al. [24] have reported that interaction between feed speed, speed and drill point angle influences significantly on the surface roughness during drilling of glass-whiskers reinforced polyamide composites.

Based on the literature review it can be conclude that many researchers paid attention towards the study on influence of fibre orientation only as design parameter, on machining characteristics. As the machining characteristic is mainly based upon the mechanical properties of the material that vary with respect to fibre percentage, the influence of fibre percentage play an important role on the machining characteristics. Thus an attempt has been made to study the influence of fibre volume fraction on the drilling GFRP composites.

2. Experimental Details

Drilling experiments on 8 mm thick flat specimen made of cross woven E-Glass fibre roving reinforced with epoxy resin were performed using DR23 DONAU type drilling machine. Five HSS twist drills of 8 mm diameter with 300 helix angle and 1180 point angle were used. Five specimens with fibre content viz. 30, 40, 50, 60 and 70 percent by weight were prepared by hand lay-up technique. Specimens were cured at ambient temperature and macroscopic tests were performed for the occurrence of voids. By controlling the number of layers of cross woven fibres in the composite laminate fibre percentage was controlled. 55 holes were drilled on each specimen using a separate drill tool. Drill speed of 470 rpm and feed rate of 0.076 mm/rev were applied for all the experiments. Readings were recorded on each stage after drilling 10, 20, 40 and 55 holes.

Since the major concern is over the effect of fibre percentage on machining performance, the surface roughness values on wall surface of the hole drilled at the end of each stage were recorded using the Taylor Hobson Surftronic stylus instrument. Cutting edge of the drill tool was focused at 10× magnification in toolmakers microscope for tool wear measurements. Kyoritsu & Co. made tool pre-setter was used to observe minute decrease in height of drill due to wear. The damage zone was observed at 10× magnification in toolmakers microscope for maximum diameter evaluation.

3. Experimental Results

3.1. Effect of fibre percentage on surface finish

Since the specimen with 70% fibre percentage produced a fuzzy hole with heavy fibre pullout, the hole wall surfaces were giving hazardous Surface Roughness values, hence only four specimens with fibre percentage 30, 40, 50, 60% by weight were considered for this analysis. Figure 1 illustrates the variation of surface roughness values with respect to fibre percentage on each stage. Maximum variation was observed on specimen with 60% fibre content. Minimum Ra (3.06 µm), Rt (22.6 µm) and Rz (17.8 µm) values were observed on specimen with 30% fibre content in the first stage. These values were increased with the increase of fibre percentage and reaching to maximum on specimen with 60% fibre content at final stage. The values of peak to valley height on specimen with 50% fibre content and above were observed to be very high after drilling 50 holes. This increase in surface roughness values is due to increase in tool wear with the increase of fibre percentage. The wornout tool produces holes with poor surface quality.

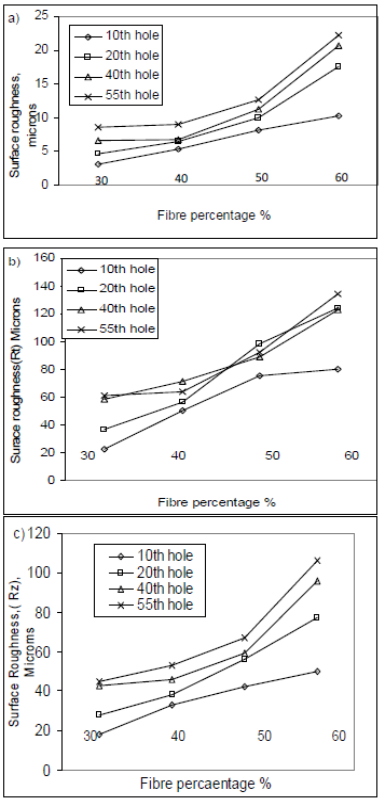

Fig. 1. Variation of Surface Roughness with Fibre Percentage (a) Ra, (b) Rt, (c) Rz.

In Fibre Reinforced Polymer Matrix Composites, as the drill bit proceeds extensive pull out of fibres occurs which increases with the increase in the fibre volume fraction. Each individual pulled out fibres tends to form fibrils during drilling. The fibrils formation was also explained by Won and Dharan [25] in case of the drilling of aramid/epoxy composites. Thus the increase in pull out of fibres produces the lower surface finish. The temperature reached during drilling, the polymer matrix deforms easily and the fibre ends are mostly covered by such an action of the polymers similar to recast [26]. Thus low fibre content exhibited better surface finish. However in higher fibre content composites, lower volume fraction of matrix prevents the action of covering the fibre ends, thus fuzzy and fibre pull out occurs easily.

3.2. Effect of fibre content on tool wear

Figure 2 illustrates the influence of fibre percentage and the number of holes drilled, on tool wear progress. The cutting edge of the drill was focused at 10x magnification on toolmakers microscope to measure the wear progress. Readings were recorded at each stage of drilling 10, 20, 40 and 55 holes. Very minute tool wear was observed on drills used on specimens possessing less than 40% fibre content, however high increase in tool wear was observed on drills used on specimens above 50% fibre concentration. High exposed fibre tool contact area in the specimens with higher fibre content is the reason for higher wear rate in these specimens.

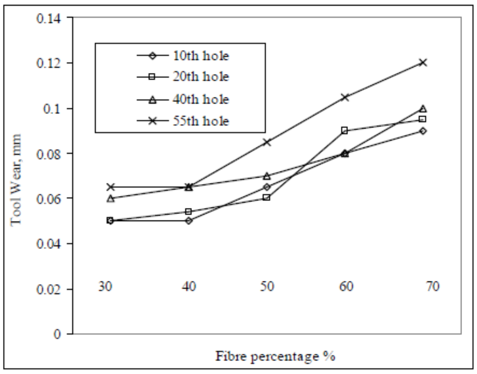

Fig. 2. Influence of Fibre Percentage and Number of Holes Drilled on Tool Wear.

A regression equation was developed to check the extent of the individual effect on tool wear as shown in Eq. (1). The equation can give the magnitude of the effect due to number of holes drilled and due to fibre volume reinforcement. It is observed that fibre percentage has shown high effect on wear progress than the number of holes in the present situation.

$$Y = 0.005 + 0.05N + 0.12V \qquad (R^2 = 92.3\%) \qquad (1)$$

where Y is the tool wear, N and V are the coded variables of number of holes drilled on specimen and fibre percentage by weight. Minimum wear of 0.05 mm was observed after drilling 10 holes on specimen with 30% fibre content, where as the maximum wear of 0.12 mm was observed after drilling 55 holes on specimen with 70% fibre percentage.

As Krishnaraj [14] explained there was chipping at edges of the drill bit while drilling. As drill encounters hard glass fibre reinforcement. Similarly in the present study there was tool wear during drilling and it increases with the increase in the fibre content of the composites. Increase in tool-fibre interaction generates greater amount of heat. The temperature also increases due to rubbing action of fibre and tool against the soft matrix. The low thermal conductivity of the glass fibre composites prevents chips from heat absorption, thus major amount heat generated is absorbed by tool causing thermal softening of tool and enhances the flank wear. The increase in flank wear was also reported by Rawat and Attia [27]. Besides increase in fibre concentration increases the tool - fibre interaction and subsequently increased tool fibre interaction results in abrading phenomenon causing abrasive wear of tool. Hence there was an increase in the tool wear. The results of the present study also agree with the study of Jawali et al. [6], which they observed in the case of glass fibre reinforced Nylon 6 composites.

3.3. Hole quality

In order to judge the hole quality, the delamination factor, macroscopic observation of hole appearance, surface roughness values and chip characteristic were adopted. Figure 3 illustrates the photograph showing the appearance of holes drilled on specimens with varied fibre percentage. The visible change in hole appearance can be attributed to a change in cutting mechanism due to the variation in fibre percentage. The most visible effect of fibre percentage is witnessed at the exit faces of drilled holes on the specimens with higher fibre content, which tends to show an excessive delamination, an increasing number of loose and pulled out fibres, giving the surface a fuzzy texture. A clean hole with minimum fibre pullout was observed on specimen with 40% fibre content. Figure 3(e) reveals the fuzzy and rough cuts obtained for higher fibre content composites due to the fact that low coefficient of thermal conduction and accumulated heat stagnated around tool edge, causes excessive material flow behind tool edge.

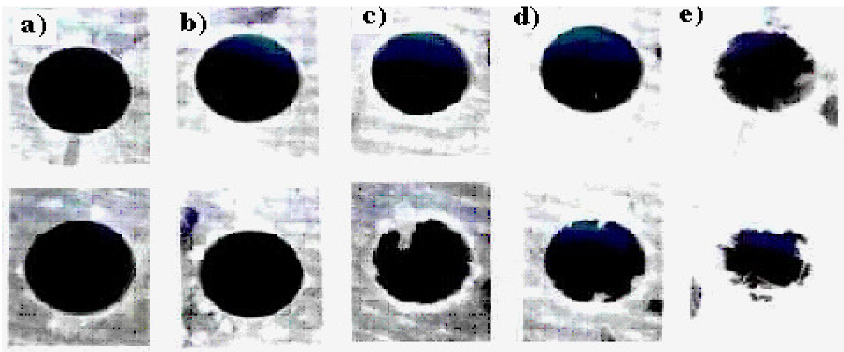

Fig. 3. Influence of Fibre Volume Fraction on Hole Quality at the Entry (Top) and Exit (Bottom) Sides of the Specimen (a) 30%, (b) 40%, (c) 50%, (d) 60%, (e) 70%.

3.4. Chip characteristic

Figure 4 illustrates the appearance of chips produced while drilling specimens with varied fibre percentage. Long, continuous and curly chips were produced when drilled on specimens with lower fibre content. Specimens with lower fibre percentage gave good surface finish since they deformed easily. Short chips were produced when drilled on specimens with 50% fibre content. The chips were so delicate that they became powder like while handling. Small segment like chips were produced on specimens with 60% fibre content, probably because of increase in fibre percentage. At 70% fibre percentage the chips were almost like powders. Specimens with minimum fibre content that produced long and curly chips showed good surface quality and hence the chip length may be considered as a measure of surface quality. The tests conducted have revealed that higher fibre content result in poor surface finish and lower fibre content result in good surface finishes. However it is not advisable to maintain lower fibre content as it will lower the mechanical properties. On comparing the results of all the above methods of machinability evaluation, the specimen with 40% fibre content has shown better and acceptable quality.

In the machining of FRP's, material mechanism is by rupture, debonding or deformation and shearing and fiber ends crushed and fractured sharply [12]. The study of Jawali et al. [6] reveals that better bonding is possible at 40% reinforcement compared with other reinforcement percentage and also specific tensile strength is maximum. Thus better surface finish with acceptable quality hole and chip characteristic was observed for 40% glass fiber reinforced composites.

When the fiber content is low, viscoelasticity of thermoplastics governs the chip characteristics during machining. At tool tip, heat accumulates and large increase of temperature in workpiece promotes plasticity by extensive chain sliding. Hence long chips were obtained. Whereas in higher fibre content composites, extensive plasticity was absent and fracture brittle ceramic fibres was broken easily. Hence small segment type chips were obtained. Similar discussion was found in previous literature [28].

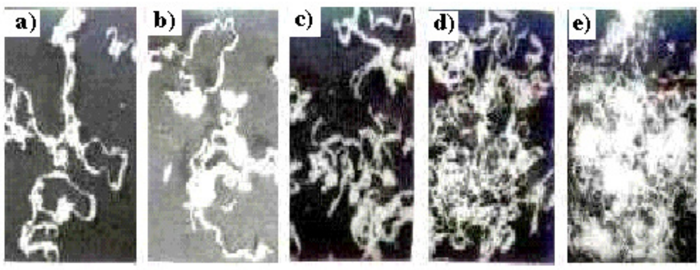

Fig. 4. Influence of Fibre Percentage on Chip Characteristic (a) 30%, (b) 40%, (c) 50%, (d) 60%, (e) 70%.

3.5. Delamination factor

Among the defects caused by drilling, delamination appears to be of most critical. Delamination can result in a lowering of bearing strength and can be detrimental to the material durability by reducing the in-service life under fatigue loads. The degree of delamination could be determined by delamination factor, which is defined as the ratio of maximum diameter, D of the damage zone around the hole to the hole diameter, d [29]. The delamination factor is proposed in order to analyse and compare the extent of delamination with the variation of fibre volume reinforcement in the composite. The delamination factor (P_d) is given by

Delamination factor $$P_d = D / d \quad (2)$$

The maximum diameter of the delamination zone on the holes produced on specimens with varied fibre percentage was measured as shown in Figs. 5 and 6. Distance between the arrows as illustrated in Fig. 5 gives the value of maximum diameter D. White patches around the hole are the damage zones. Tool maker's microscope was used to observe and measure the maximum diameter D near the damage zone.

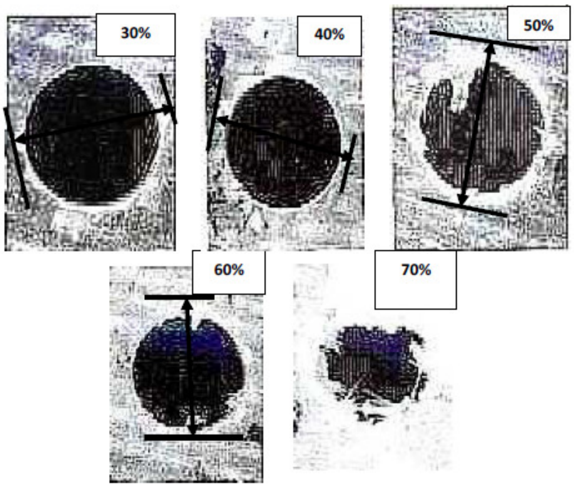

Fig. 5. Photograph (Distance between Arrows) Showing Maximum Diameter (*D*) in Damage Zone.

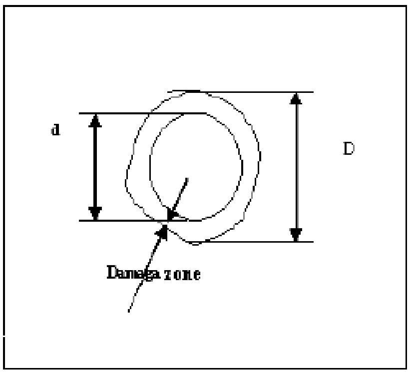

Fig. 6. Delamination Factor.

Increase in the fibre volume fraction increases the thrust forces [30] and causes the increased delamination [31]. Delamination near the exit side is introduced as the tool acts like a punch separating the thin uncut layer from the remainder of the laminate. Fiber pull out was higher for higher fibre content. The fibre pull out and fibrils present near the hole exit forms the remainder of the laminate. Thus forms increased damage zone near the hole exit. Hence high delamination factor was obtained for the higher fibre concentration as shown in Fig. 7. The obtained result agrees with the results obtained by Kim et al. [32].

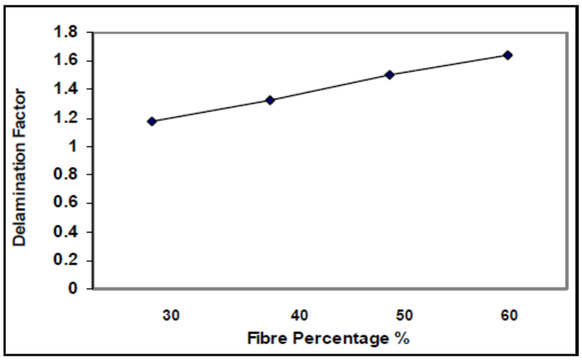

Fig. 7. Correlation between Delamination Factor and Fibre Content.

4. Delamination Mechanism

From the experimental results it is observed that the delamination occurs at the entry and exit side of the hole. Delamination by drill tool on either side follows different mechanism. The drill tool acts as a power screw. The delamination occurs due to the peeling effect of the drill tool as it pears in to the surface of the laminate during drilling. This mechanism is called as Peeling-up mechanism. Similarly as the tool approaches the exit side, the last ply called sub-laminate which is under the pressure of drill tool get delaminated. This way of delamination is called as Push-out mechanism. The delamination due to this peel up and push out action can be reduced to a maximum extent by providing pad support at the entry and exit side of the hole while drilling.

5. Conclusions

The Experimental study of the machining characteristic of GFRP composite material to detect the influence of fibre concentration on , surface finish, tool wear, hole quality, chip characteristic, delamination factor in drilling permit to draw the following conclusions.

- Fibre percentage in composite plays a vital role on drillability of GFRP. Drilling of 70% fibre percentage content composites produced hazardous surface roughness. Hence it is not considered for the study.

- Better surface finish was obtained for the composite with 30% fibre volume content composites. Increase in fibre percentage has increased the surface roughness of the composites. As the drill bit proceeds during drilling, extensive pull out of fibres occurs which increases with the increase in the fibre volume fraction. Each individual pulled out fibres tends to form fibrils during drilling.
- The increase in fibre percentage has resulted in increased tool wear. This is attributed due to the fact that increase in the fibre percentage increases tool – fibre interaction. The increased interaction of high modulus fibre with tool results in thermal softening of material and wear of the tool.
- Increase in fibre percentage lead to decrease of hole quality. The increase in the fibre percentage increased the probability of pulling out of fibres during drilling. It can also be explained on the fact that low coefficient of thermal conduction and accumulated heat stagnated around tool edge, causes excessive material flow behind tool edge.
- When the fiber content is low, at tool tip heat accumulates and large increase of temperature in workpiece promotes plasticity by extensive chain sliding. Hence long chips were obtained. Whereas in higher fibre content composites, extensive plasticity was absent consequently brittle ceramic fibres were fractured easily. Hence small segment type chips were obtained.
- The fibre pull out and fibrils present near the hole exit forms the remainder of the laminate. Thus forms increased damage zone near the hole exit. Hence high delamination factor was obtained for the higher fibre concentration.

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