A Review Paper on Effects of Drilling on Glass Fiber Reinforced Plastic

B.V.Kavada*, A.B.Pandeya, M.V.Tadavi, H.C.Jakharia

Abstract

Drilling is an important process for making and assembling components made from Glass Fiber Reinforced Plastic (GFRP). Various processes like conventional drilling, vibration assisted drilling and ultrasonic assisted drilling have been attempted in order to maintain the integrity of the material and obtain the necessary accuracy in drilling of GFRP. This paper attempts to review the influence of machining parameter on the delamination damage of GFRP during drilling. In conventional machining feed rate, tool material and cutting speed are the most influential factor on the delamination hence machining at higher speed, harder tool material and lower feed rate have lesser delamination of the GFRP. Vibration assisted drilling and Ultrasonic assisted drilling have lesser thrust and hence lesser delamination compared to conventional drilling, which indicates that both vibration assisted drilling and Ultrasonic assisted drilling are more appropriate for drilling of GFRP.

Keywords: GFRP; Drilling; Feed Rate; Thrust Force; Cutting Speed; Tool Material; Delamination;

1. Introduction

Glass fiber reinforced plastic (GFRP) composites have been widely used in engineering application such as automotive, aircraft and manufacture of spaceships and sea vehicles’ industries due to their significant advantages
over other materials. They provide high specific strength/stiffness, superior corrosion resistance, light weight construction, low thermal conductivity, high fatigue strength, ability to char and resistance to chemical and microbiological attacks. As a consequence of the widening range of applications of GFRP, the machining of these materials has become a very important subject for research [1, 2]. Machining composite materials is a rather complex task owing to their heterogeneity, anisotropy, and high abrasiveness of fibers, and it exhibits considerable problems in drilling process such as delamination, fiber pull-out, hole shrinkage, spalling, fuzzing and thermal degradation [3]. Several non-traditional machining processes such as laser cutting, water-jet cutting, ultrasonic cutting, electro discharge machining, etc., have been developed for application on FRPs for machining holes. Due to the anisotropic and inhomogeneous structure of FRPs, drilling FRPs causes some problems, which do not occur in other materials. Among the defects caused by drilling, delamination around the drill hole site appears to be the most critical, which can result in a lowering of bearing strength and can be detrimental to durability by reducing the in-service life under fatigue loads [4]. Delamination can often become a limiting factor in the use of FRPs for structural applications [4–7]. Therefore, addressing how to improve the quality of holes in drilling of FRPs is imperative.

Thrust force has been considered as the cause of delamination by several researchers and it is believed that there is a ‘critical thrust force’ below which no damage occurs. Vibration drilling is a branch of vibration cutting, which is fundamentally different from conventional drilling. The vibration drilling technique has attracted extensive interest in recent years. Both the theoretical investigations and experimental results have indicated that the machining quality of the drilled holes can be improved, as well as the thrust force being reduced by means of vibration drilling metals [8–11]. Some researchers, on the other hand, have conducted experiments to recognize the effect of vibration-assisted drilling on thrust force and delamination [12-14]. These studies showed that applying vibration may reduce the amount of thrust force, delamination and wear of tool. As well as applying ultrasonic assisted drilling reduces the thrust force and therefore the drilling induced delamination dramatically [15]. This review paper shows effect of different machining process on delamination of GFRP and this will help to choose better machining process to reduce delamination while drilling of GFRP.

2. Conventional Drilling

Drilling is an essential operation in the assembly of the structural frames of automobiles and aircrafts. The life of the joint can be critically affected by the quality of the drilled holes [16].

2.1 Delamination mechanisms

Damages associated with drilling FRP composites were observed, both at the entrance as well as at the exit of the drilled hole, in the form of peel-up and push-out delamination, respectively [17].

2.1.1 Peel-up at entrance

Peel-up delamination occurs as the drill enters the laminate and is shown schematically in Figure 1(a). After the cutting edge of the drill makes contact with the laminate, the cutting force acting in the peripheral direction is the driving force for peel-up delamination. It generates a peeling force in the axial direction through the slope of the drill flute. The flute tends to pull away the upper laminas and the material spirals up before it is machined completely. This action results in separating the upper laminas from the uncut portion held by the downward acting thrust force and forming a peel-up delamination zone at the top surface of the laminate. The peeling force is a function of tool geometry and friction between the tool and work piece [18].

2.1.2 Push-out at exit

Push-out delamination occurs as the drill reaches the exit side of the material and is shown schematically in Figure 1(b). As the drill approaches the end, the uncut thickness gets smaller and the resistance to deformation decreases. At some point, the thrust force exceeds the interlaminar bond strength causing an exit delamination zone as the tool
Figure 1. Mechanisms of delamination: (a) peel-up at entrance and (b) push-out at exit.

pierces through the exit side. This happens before the laminate is completely penetrated by the drill. Different drill geometry and cutting conditions can reduce the push-out delamination by lowering the thrust force. In practice, it has been found that the push-out delamination is more severe than that of peel-up (Figure 2)[19].

2.1.3 Parametric Studies

Khashaba et al. [20] reviewed a number of research work on drilling of polymer matrix composites and concluded that new drill types and geometries and new efficient and practical drilling methods are able to distribute the thrust force toward the drill periphery rather than concentrate it at hole center are still required for making delamination-free holes in laminated composites. The contribution of chisel edge to the thrust force is often up to 40–60% of the total thrust. Using pre-machining techniques such as step drill and pilot hole play an important role in reducing the thrust force and successively the machining delamination free holes. Using backup plate on the exit side of drilling, if possible, will provide a support for the uncut plies of a laminate and preventing the delamination owing to the downward bending deflection of the laminate caused by the drilling thrust force. The variable feed rate strategy in which feed rate is decreased toward the exit of the hole has been addressed for drilling composites with delamination-free holes. Drilling polymeric composite materials leads to increase the generated temperature,
assisted by a low coefficient of thermal conduction and a low transition temperature of plastics. The accumulated heat around the tool edge destroys the matrix stability, produces thermal damages associated with fuzzy and rough cuts, and increases tool wear owing to cutting at high temperature.

The ways in which the temperature can be observed, the form in which the thermal and mechanical damages occurs, and the correlations between them have not yet been fully reported and problems remain to be solved. The stress concentration owing to the softening and resolidification of the matrix material that has different thermal properties than the fiber is another problem that leads to reduction in the residual mechanical properties of the drilled holes.

Sonbaty et al. [16] studied the factors affecting the machinability of GFR/epoxy composites with an objective to investigate the influence of some parameters on the thrust force, torque and surface roughness in drilling processes of fiber-reinforced composite materials. These parameters include cutting speed, feed, drill size and fiber volume fraction. The results indicate that the start point of torque cycle was delayed by few seconds (depending on the value of feed) than the thrust force. This time was consumed to penetrate the specimen by chiseling edge. After the thrust force reached its maximum value it is gradually decreased during the full engagement of the drill and goes to zero when both the chisel edge and the cutting lips have exit of the laminate. In contrast the torque was gradually increased up to the end of the cycle and sudden jump to a value about 10 times the peak value. Cutting speed has insignificant effect on the thrust force and surface roughness of epoxy resin. For glass fiber reinforced epoxy composites (GFREC) with (volume fractions) \( V_f = 9.8\text{--}23.7\% \) the thrust force and torque were decreased with increasing cutting speed. On contrast increasing feed, drill size and fiber volume fractions lead to increase the thrust force and torque. The drilled holes of GFREC with lower \( V_f \) ratio at lower feed have greater roughness than that drilled at higher feed. Specimens with high \( V_f \) ratio have a contrary behavior. Drill diameter combined with feed has a significant effect on surface roughness. bữa & Ekeri [21] presented a new comprehensive approach to select cutting parameters for damage factor in drilling of glass fiber-reinforced polymer (GFRP) composite material. The influence of drilling on surface quality of woven GFRP plastic composite material was investigated experimentally. Drilling tests were carried out using carbide drills of 8 mm in diameter at 50, 70, and 90 m/min cutting speeds and at 0.06, 0.12, and 0.18 mm/rev feed rates. Damage factor was investigated based on hole entrance and exit. Analysis of variance (ANOVA) test was applied to the experimental results. The result indicated that increasing of cutting speed decreases DF at both hole entrance and exit. Increasing of feed and flute number increases DF at hole exit and decrease DF at hole entrance. Increasing of point angle increases DF at both hole entrance and exit. Khashaba et al. [22] investigated the effect of machining parameters (feed, speed and drill diameter) on the thrust force and machinability of woven glass fiber-reinforced epoxy (GFRE) composites. The selected machinability parameters were delamination size, surface roughness, and bearing strength. The results show that, delamination-free in drilling GFRE composites is not observed, in the range of the investigated cutting parameters. Surface roughness increases with increasing the cutting feed, while no clear effect of the cutting speed is observed. The increases of feed results in higher thrust force which in turn increases the resulting delamination damage and subsequently low bearing strength.

E. Kilickap [23] investigated the influence of the cutting parameters, such as cutting speed and feed rate, and point angle on delamination produced when drilling a GFRP composite. The damage generated associated with drilling GFRP composites were observed, both at the entrance and the exit during the drilling. The optimum drilling parameter combination was obtained by using the analysis of signal-to-noise ratio. The conclusion revealed that feed rate and cutting speed were the most influential factor on the delamination, respectively. The best results of the delamination were obtained at lower cutting speeds and feed rates.

At present, conventional drilling is used most commonly, but grinding drilling, vibration-assisted twist drilling, and high speed drilling provide better quality of drilled holes as well as high efficiency [24]. Considerable efforts have been focused on the better understanding of the phenomena associated to the mechanism of delamination induced by drilling. The applications of special drill bits, support plate, pre-drilled pilot hole, vibration-assisted twist drilling, and high speed drilling provide significant quality improvement of drilled holes. Feed rate is seen to make
the largest contribution to delamination, thrust force, and tool wear during drilling of composite laminate. The use of low feed rate and high cutting speed favors the minimum drilling-induced delamination and extend tool life [24]. Rajamurugan et al. [25] made an attempt to establish an empirical relationship between the thrust force and drilling parameters (tool rotational speed, tool feed rate, drill diameter and fiber orientation angle) in drilling of GFRP Composites. Experiments were conducted on a VMC on glass fiber reinforced plastic (GFRP) specimens with Brad and Spur tool material. Statistical tools such as design of experiments, analysis of variance, and regression analysis are used to develop the relationship. The developed empirical relationship can be effectively used to predict the thrust force of drilled holes at the 99 per cent confidence level. HUSSEIN M ALI, ASIF IQBAL and LI LIANG et al. [26] Drilling and milling processes are extensively used for producing riveted and bolted joints during the assembly operations of composite laminates with other components. The main purpose of the present study was to assess the influence of drilling and milling machining parameters on hole making process of woven laminated GFRP material. Analysis of variance (ANOVA) was performed to isolate the effects of the parameters affecting the hole making in the two types of cutting processes. The results showed that milling process is more suitable than drilling process at high level of cutting speed and low level of feed rate, when the cutting quality (minimum surface roughness, minimum difference between upper and lower diameter) is of critical importance in the manufacturing industry, especially for precision assembly operation.

Reddy et al [27] focused on performance comparison of Carbide and HSS drills when drilling a glass fiber reinforced general purpose resin composite. Delamination is a measure of the quality of a drilled hole, which in turn is primarily dependent on the thrust force. The comparison of thrust force and the corresponding delamination produced has been made with reference to drilling by HSS and Carbide tools with the independent variables being cutting tool geometry, drill diameter, material thickness, feed rate, and speed. Results shows that drill material has significant effect on the quality of drilled hole. It was also reported that under all experimental drilling condition, the thrust force and delamination in case of HSS drill is greater than that of Carbide drill. It can be concluded that Carbide drill produced higher quality of drilled hole in comparison with HSS. Khashaba et al [28] conducted experimental investigation to evaluate the effect of drilling parameters (feed, speed, and drill pre-wear) on the machinability parameters (thrust force, torque, peel-up and push-out delaminations, surface roughness, and bearing strength) in drilling GFRE composites. The results show that the behavior of thrust force during drilling process was greatly affected by the drill pre-wear. This effect becomes more significant at high-cutting speed and feed, which in turn increases peel-up and push-out delaminations. At high feeds (0.45 mm/revolution), the drill point acts as a punch that pierces the laminate, instead of cutting through it, with approximately constant push-out delamination size irrespective to the value of the thrust force. In addition, the increasing of thrust force as a result of increasing drill pre-wear leads to destruction of the fiber/matrix interfaces and successive deterioration of the surface finish. The partially sheared fibers due to the abrasion action of the pre-wearied drill point are another reason for the increasing of surface roughness. The failure of the bearing specimen was initiated with delaminations owing to the interlaminar shear failure between the composite layers, under the compressive bearing load. The final failure was due to the buckling of the delaminated layers, either momentarily (with catastrophic failure) or progressively (with gradual reduction in the bearing load).

Venkateshwaran and ElayaPerumal [29] focused on the analysis of delamination behaviour as a function of drilling process parameters at the entrance and exit of the composite plates. In this work, drilling was carried out by varying the feed (0.1, 0.2, 0.3 mm/rev) and speed (500, 1000, 1500 and 2000 r/min), respectively. The drill bit used is made of high-speed steel of a diameter of 10 mm. The quality of the hole drilled was assessed using the machine vision technique, and the extent of delamination was carried out using the ultrasonic C-scan imaging method. The experimentally observed delamination factor was compared with ANOVA technique and found that the feed rate affect the delamination than speed. Murthy and Rodrigues [30] conducted experiments on a TRIAC CNC vertical machining centre which enables high precision machining. The test specimen used was a GFRP composite material which was manufactured by hand layup method. The drill point angle, drill diameter, material thickness, spindle speed and the feed rate were considered as the input variables. Delamination was considered as the output variable. This study reveals that the most contributing parameter for delamination is the material thickness and the least contributing parameter is the spindle speed and delamination is directly proportional to the thrust force.
3. Vibration Assisted Drilling

Arul et al. [31] conceived a new drilling method that imparts a low-frequency, high amplitude vibration to the work piece in the feed direction during drilling. Using high-speed steel (HSS) drill, a series of vibratory drilling and conventional drilling experiments were conducted on glass fiber-reinforced plastics composites to assess thrust force, flank wear and delamination factor. The thrust in vibration drilling is smaller than that in the conventional drilling, which indicates that the vibration drilling method is suitable for defect constrained drilling of polymeric composites. The trend of variation of thrust, flank wear, delamination factor, AE power and AE rms with number of holes for conventional and vibration drilling are similar. Good correlation between thrust and delamination factor indicates that on-line monitoring of thrust can facilitate defect-constrained drilling. From the drilling experiments, it was found that vibratory drilling method is a promising machining technique that uses the regeneration effect to produce axial chatter, facilitating chip breaking and reduction in thrust force.

Ramkumara et al. [32] studied effect of work piece vibration on drilling of glass/epoxy (GFRP) laminates using three types of drill, e.g. tipped WC, 2-flute solid carbide and 3-flute solid carbide. A UD-GFRP laminate of 4mm thickness was prepared and drilling was carried out using a vertical drilling machine. The result indicate that (I) Giving small amplitude low frequency vibration to work piece results in much better drill performance in drilling of GFRP laminates. (II) The number of holes that can be drilled with vibrating work piece before drill performance deteriorates is much larger than for conventional drilling. (III) Hole quality is improved and delamination reduced when work piece is given a small amplitude low frequency vibration. (IV) Among the three types of drills used, e.g. tipped WC, 2-flute solid carbide and 3-flute solid carbide, 3-flute solid carbide drill performs the best. Wang et al. [33] investigated on thrust in vibration drilling of fiber-reinforced plastics using a carbide drill and a high-speed steel (HSS) drill, a series of vibration drilling and conventional drilling experiments are conducted on glass fiber-reinforced plastic composite (GFRP), carbon fiber-reinforced plastic composite (CFRP) and printed circuit board (PCB). The experimental results show that the thrust of vibration drilling is smaller than that of conventional drilling, which indicated that the vibration drilling method is appropriate for producing micro holes on FRPs. Sadek et al. [34] carried out characterization and optimization of vibration-assisted drilling of fiber reinforced epoxy laminates. Vibration-assisted drilling (VAD) can reduce thermal and mechanical defects associated with drilling of composites. Machinability maps are presented to establish the effect of the process parameters (speed, feed, frequency, and amplitude) in the low frequency–high amplitude regime (<200 Hz, <0.6 mm) on the hole quality attributes. The optimized VAD conditions can reduce the cutting temperature by 50% and the axial force by 40% and produce delamination-free holes, without affecting productivity.

4. High Speed Drilling

High speed machining (HSM) is an outstanding technology capable of improving productivity and lowering production costs in manufacturing companies. Rubio et al. [35] found the effect of high speed in the drilling of glass fibre reinforced plastic. The experimental results indicate that to obtain larger material removal rates associated with minimal delamination, higher spindle speeds should be used when drilling GFRP. At a spindle speed of 40 000 rpm, delamination is minimal, irrespectively of the feed speed employed. Within the cutting range tested, delamination decreases as the spindle speed is elevated, probably owing to the fact that cutting temperature is elevated with spindle speed, thus promoting the softening of the matrix and inducing less delamination. At high spindle speeds drill produced less delamination compared to the twist drills with 115° and 85° point angle, owing to the fact that drill acts similarly to a trepanning tool, promoting lower shear area and, consequently, lower thrust force values.

The effect of the material removal rate on the adjusted delamination factor for Three cemented carbide drills (ISO grade K20) with 5mm diameter and 25° helical angle coded DIN 6539 RN and DIN 8038 RN with 118° and 85° point angle, respectively, and one “Brad & Spur” special geometry drill [36] code WN R FK. The results suggest that the drill geometry WN R FK not only provides lowest delamination factor, but also is also capable of maintaining the delamination factor at stable values as the material removal rate is elevated. The use of HSM is suitable for drilling GFRP ensuring low damage levels.
5. Ultrasonic Drilling

Delamination is a major problem in drilling of fiber-reinforced composite materials. Thrust force is an important factor leading to propagation of delamination during drilling process. One of effective methods to reduce machining forces is application of ultrasonic vibrations. Mehbudi et al [37] applying ultrasonic vibration to decrease drilling-induced delamination in GFRP laminates. A setup for making holes in composite laminates was designed and fabricated which was capable of giving rotation and ultrasonic vibration to drill bits. It was concluded that increasing vibration amplitude may thrust force and delamination damage significantly. The results of ultrasonic-assisted drilling were compared with conventional drilling results. This comparison showed applying ultrasonic vibrations during drilling GFRP laminate may reduce the drilling thrust force and drilling-induced delamination up to 50 per cent. It was observed that using ultrasonic vibration is an effective method to improve hole quality in drilling of GFRP laminates.

6. Conclusion

The following conclusions can be drawn with regard to the drilling of GFRP:

- In conventional machining feed rate, tool material and cutting speed are the most influential factor on the delamination hence machining at higher speed, harder tool material and lower feed rate have lesser delamination of the GFRP.
- The use of High Speed Machining is suitable for drilling GFRP ensuring low damage levels and it is an outstanding technology capable of improving productivity and lowering production costs.
- Vibration assisted drilling and Ultrasonic assisted drilling have lesser thrust hence lesser delamination compared to conventional drilling, which indicate that both vibration assisted drilling and Ultrasonic assisted drilling are more appropriate for drilling of GFRP.
- HSM, Vibration assisted drilling and Ultrasonic assisted drilling are new machining technique for drilling of GFRP and have better result compared to conventional drilling of GFRP.
- HSM, Vibration assisted drilling and Ultrasonic assisted drilling have scope for future work on drilling of GFRP.
- Pure ultrasonic machining for drilling on GFRP can be investigated.

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