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DELAMINATION IN DRILLING GFR-THERMOSET COMPOSITES

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ABSTRACT

Delamination is a major problem associated with drilling fiber-reinforced composite materials that, in addition to reducing the structural integrity of the material, also results in poor assembly tolerance and has the potential for long-term performance deterioration. Delamination-free in drilling different fiber reinforced thermoset composites are the main objective of the present paper. Therefore the influence of drilling and material variables on thrust force, torque and delamination of GFRP composites was investigated experimentally. Drilling variables are cutting speed and feed. Material variable include matrix type, filler and fiber shape. Drilling process was carried out on cross-winding/polyester, continuous-winding with filler/polyester, chopped/polyester, woven/ polyester and woven/epoxy composites. A simple inexpensive accurate technique was developed to measure delamination size.

The results show that the presence of sand filler in continuous-winding composites not only raised the values of cutting forces and push-out delamination but also increased their values with increasing cutting speed. In contrast, increasing the cutting speed in drilling cross-winding, woven and chopped composites reduces the push-out delamination as a result of decreasing the thrust force. The thrust forces in drilling continuous-winding composite are more than three orders of magnitude higher than those in the cross-winding composites. Chopped composites have lower push-out delamination than that made from woven fibers. For the same fiber shape, the peel-up and push-out delaminations of woven/epoxy composite are lower than that for woven/polyester composites. Delamination, chipping and spalling damage mechanisms were observed in drilling chopped and continuous-winding composites. In drilling woven composites the delamination was observed at different edge position angles due to the presence of the braids that made by the interlacing of two orthogonal directions of fibers tows (warp and fill). Delamination-free in drilling cross-winding composites was achieved using variable feed technique.

KEY WORDS

Composites, filler, chopped fiber, woven fiber, polyester, epoxy, thrust, torque, drilling, feed, speed, peel-up delamination, push-out delamination.

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1. INTRODUCTION

Drilling is often a final operation during assembly; any defects leads to rejection the part represent an expensive loss. In the aircraft industry, for example, drilling-associated delamination accounts for 60% of all part rejections during final assembly of an aircraft [1]. The economic impact of this is significant considering the value associated with the part when it reaches the assembly stage. The quality of the drilled holes such as waviness/roughness of its wall surface, axial straightness and roundness of the hole cross-section can cause high stresses on the rivet, leading to its failure. Stress concentration, delamination and microcracking associated with machined holes significantly reduce the composites performance [2-4].

In machining composite parts, a finish comparable to metals cannot be achieved because of inhomogeneity and anisotropy of materials [4,5]. FRP composites consist of a load-carrying fiber component, whose geometrical orientation depends on force directions is enveloped in the matrix, which mainly provides the fixation of the fibers and the distribution of forces. The physical properties of fiber and matrix are quite different and together with the fiber orientation they determine, by their combination, the performance as well as the machinability of the composite [6]. The resulted chip from machining the metals were classified into continuous, sectional (discontinuous) and broken chip. Thermoset composites are brittle and possess less capability for plastic deformation than metals and thus their chips tend to fracture earlier to give discontinuous chips in powder and scrap form [7].

Drilling in fiber reinforced thermoset composites results in a series of mini-fiber fractures, fiber pullouts, and matrix cracking. Cutting variables in drilling process (feed and speed) have great influence on the thrust force and torque and hence on the quality of the machined holes. Low feeds in some cases improve the surface roughness due to the reduction of thrust force. In other cases drilling at lower feeds and high speed leads to increase the generated temperature that assisted by low coefficient of thermal conduction and low transition temperature of plastics. The accumulated heat around the tool edge destroys the matrix stability and produces fuzzy and rough cuts [7,8].

Delamination can often be the limiting factor in the use of composite materials for structural applications. In drilling polymeric composite materials the thrust force has been cited as the cause of delamination by several investigators [1,2,8-16] and some [1,8,15-17] have been predicted the critical thrust at the onset of delamination using linear elastic fracture mechanics and classic plate bending theory. One application of this theory is to control feed respect to the depth of drilling [18].

Delamination has been measured using different techniques [1,4,5,14,19,20]. Chen [14] measured the damaged zone using X-ray as a non-destructive technique. This method demand coating the hole edge with tetrabromoethane. He used the delamination factor (the ratio of the maximum diameter in the damage zone to the hole diameter) in order to analyze and compare the delamination degree in the drilling of carbon FRP composite laminates. Enemuoh et al. [5] and Reis el al [20] measured the delamination in AS4/PEEK and CFRP composite materials using a tool marker's microscopes at 5X and 30X magnification respectively. Caprino et al. [19] measure the extent on the damaged area of drilled GFRP composites using visual inspection at 10X magnification, with the help of a strong light source located on the back. Visual measurement of hole delamination diameter for graphite-epoxy composites was achieved by Stone et al. [1] using CCD camera with the aid of visual digitizer that used to capture a frame from the camera to produce the images. Tagliaferri et al. [4] used the diffusion phenomena of the liquid into the material through the cut surface to measure the damaged area around the hole with optical microscope at 10X magnification. It was noted that the actual value was strongly affected by the immersed time. Therefore they carry out all the measurements after 24 h after immersion the specimens in the liquid, in order to reliably compare the results from different tests. The latter technique is not applicable when comparing the damaged zone for different composites where each composite material has different diffusion coefficient [21]. Also the specimen can't be used for farther mechanical measurements such as notched strength and pin bearing strength where the absorption of the liquids significantly reduces the mechanical properties of FRP composites [22].

The main objective of the present work is to study the influence of drilling and material variables on thrust force, torque and delamination of GFRP composites. Drilling variables are cutting speed and feed. Material variable include matrix type, filler and fiber shape. Drilling process will carry out on cross-winding/polyester, continuous-winding with filler/polyester, chopped/polyester, woven/ polyester and woven/epoxy composites. Based on strain-gage sensor, the thrust force and torque will be measured using two-component dynamometer. While the delamination size will be measured using a simple and inexpensive technique.

2. EXPERIMENTAL WORK

2.1 Materials

Drilling processes were conducted on five different types of E-glass fiber reinforced thermosetting composites. The constituent materials and fiber volume fractions (V_f) for each composite type were illustrated in Table 1. Two thermoset resins were used in this study: polyester and epoxy. The different types of thermoset composites are: continuous-winding with filler/polyester, cross-winding/polyester, chopped/polyester, woven/polyester and woven/epoxy. The former two types were supplied from Lokma Group Inc. while the author has been manufactured the latter three types using hand lay-up technique. Details about this technique were illustrated by Khashaba [23].

Table 1. Constituent materials of the polymeric composites

Composite type	Composition	Thickness (mm)	V_f%
Continues-winding	Chopped E-glass fiber Continues E-glass hoop fiber Filler (sand) Matrix: Orthophthalic Polyester resin	12.32	9.56 12.47 21.05
Cross-winding	Chopped E-glass fiber Continues hoop fiber Matrix: Orthophthalic Polyester resin	8.06	7.76 30.59
Woven/Polyester	Woven E-glass fiber Orthophthalic Polyester resin	7.15	33.27
Woven/Epoxy	Woven E-glass fiber Matrix: Araldite, LY 138-1	3.52	32.73
Chopped/Polyester	Chopped E-glass mat Matrix: Orthophthalic Polyester resin	4.14	27.6

2.2 Measurements of Thrust Force and Torque

Drilling tests were performed without backing plate and cutting fluid on convention radial drilling machine. While the variable feed technique was implemented on CNC milling/drilling machine. To neglect the effect of drill wear each hole was drilled using a new standard HSS drills with 8 mm diameter. Thrust force and torque were measured using two-component dynamometer, based on strain-gage sensor, Fig.1. The details about the design and manufacturing of this dynamometer were illustrated elsewhere [24]. The dynamometer was connected by a data acquisition system that assembled in PC to monitor and acquire the test data. The data was stored as an ASCII data file in the PC. These data represent the relationship between the machining time and the electrical output signals from the strain gages that forming the Wheatstone-bridges. The electrical output signals (volt) for thrust force and torque were calibrated using known thrust and torque. The variation of thrust force and torque with machining time were plotted as wave forms, while the average value of the maximum five peaks in these wave diagrams were used to investigate the influence of cutting variables on thrust force and torque. At least two testes were implemented for each cutting variables. The drilling variables are: feeds, $f = 0.03$, 0.08, 0.15, 0.23 and 0.3 mm/rev. and cutting speeds, n = 455, 875 and 1850 rpm.

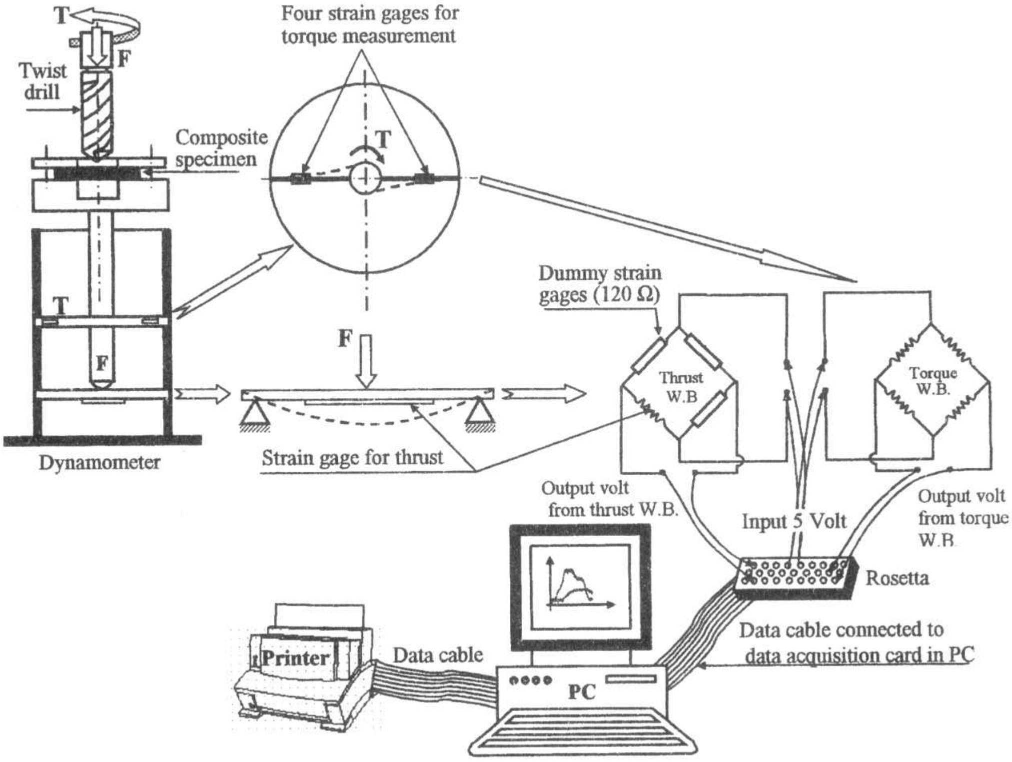


Fig.1 Set-up for measurements the thrust force and torque.

2.3 Delamination Size Measurements

In the present paper an accurate inexpensive technique for measurement the delamination size within 10^{-3} mm resolution has been developed. The equipments required for this technique are: PC, color flatbed scanner and image software (CorelDraw). The specimen was placed directly on the glass plate of the scanner (it is recommended to put a transparence on the glass plate of the scanner to protect it from the abrasive nature of the polymeric composite materials). The scanner used in the present paper is "ScanPrisa 640P, Acer". The Photo of the drilled specimen was acquired, with 400 DPI, using the software supplied with the scanner or using the CorelDraw software directly. Shadow zone (delamination) was clearly observed around the drilled hole due to the transmitted light through it. Using the contrast, brightness and focusing utilities the shadow zone can easily distinguish from the other undamaged area. The file was saved in BMP format. This file was imparted to the CorelDraw program and the photo was magnified up to 30X. A circular was drawn to the delamination (shadow) zone. The CorelDraw program gives the diameter of the circular within 10^{-3} mm. The delamination size is defined as the difference between the maximum damage radius and the drilled hole radius (4 mm), Fig.2. This technique was calibrated by measuring several dimensions on standard steel ruler. The error lies in the range from 0.3 to 0.8%. This error range was accepted compared with the measurements that carried out using CCD sensor [25].

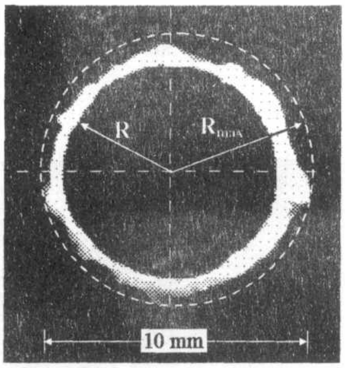


Fig.2. Photograph illustrates the push-out delamination in drilling cross-winding composites, n =1850 rpm and f = 0.08 mm/rev.), Delamination size = R_{max}– R = (10.584-8)/2 =1.292 mm.

3. RESULTS AND DISCUSSIONS FOR THRUST AND TORQUE

3.1 Behavior of Thrust Force and Torque During Drilling Different Composites

Figs.3 to 7 illustrate a complete drilling cycles for continuous-winding, cross-winding, chopped, woven/polyester and woven/epoxy composites respectively. The thrust force and torque in these figures were measured at the lowest cutting conditions, n = 455 rpm and f = 0.03 mm/rev. The wave diagram of continuous-winding composites, Fig.3, shows a gradual increase of the thrust force, up to 25 N (point 1 to 2), was due to the cutting in polyester resin at the outer surface of the cylinder. As the chiseling edge progress in cutting it met the first layer of chopped FRP (point 2 to 3) followed by chopped FRP filled by sand (point 3 to 4).

From points 4 to 10 the weave curve has some peaks due to the cutting of alternating layers of sand RP and hoop FRP which have different cutting characteristics. After the thrust force reached to its maximum value it suddenly dropped as the chiseling edge exit the specimen, point 11.

The wave diagrams of cross-winding, chopped, woven/polyester and woven/epoxy composites, Figs.4 to 7, show a drastically increases in the thrust force up to the maximum value followed by gradual drop for cross-winding and woven/polyester, Figs. 4 and 6 respectively. On the other hand a sudden drop was observed in drilling chopped and woven/epoxy composites, Figs.5 and 7. The gradual drop in thrust force at the end of drilling cycle of cross-winding and woven/polyester perhaps due to the softening of the matrix [26] by the heat generated during drilling process which is higher than that generated in drilling chopped and woven/epoxy composites. Where the former composites have double thickness, Table 1, and hence double machining time than the latter composites. Nagao et al. [27] show that the temperature at the drill point rises in proportion to the square root of machining time.

The wave diagrams of the machined composite materials, Figs.3 to7, indicate that the start point of the torque cycles is delayed by few seconds (depending on the value of feed) than the thrust force cycles. This time is consumed to penetrate the specimen by chiseling edge [24]. For all the machined composites the torque was gradually increased up to the maximum value then behave approximately a constant value over the drilling cycle followed by a gradually drop up to a value equals the friction torque between the drill margin and the hole. The friction torque depends on the constituent materials of the composite specimens, specimen thickness and on the cutting conditions.

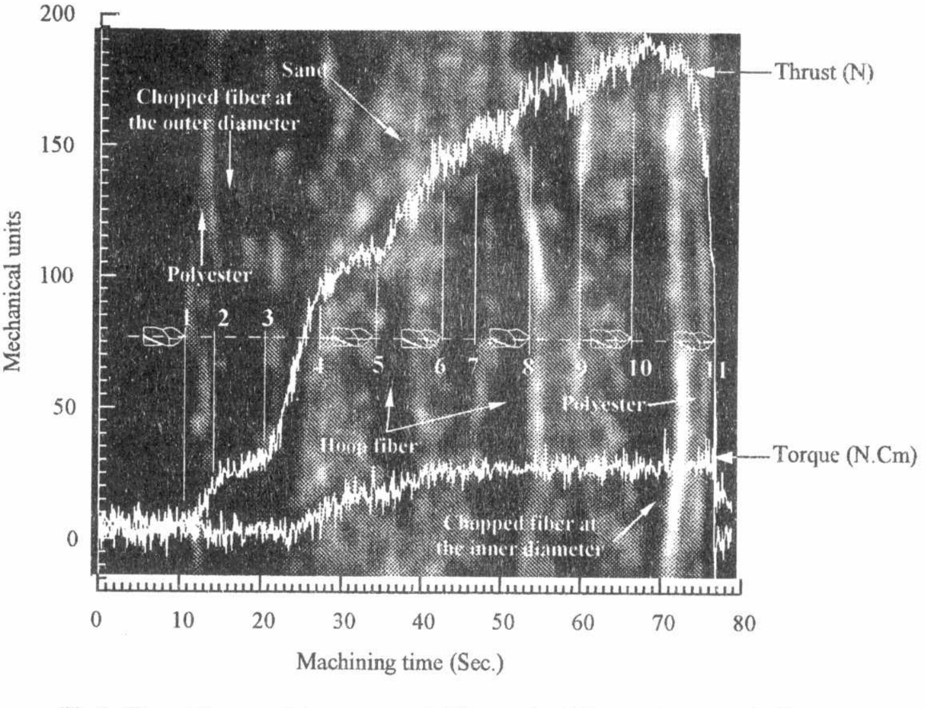


Fig.3. Thrust force and torque over drilling cycle of the continuous-winding composites, n = 455 RPM and *f* = 0.03 mm/rev.

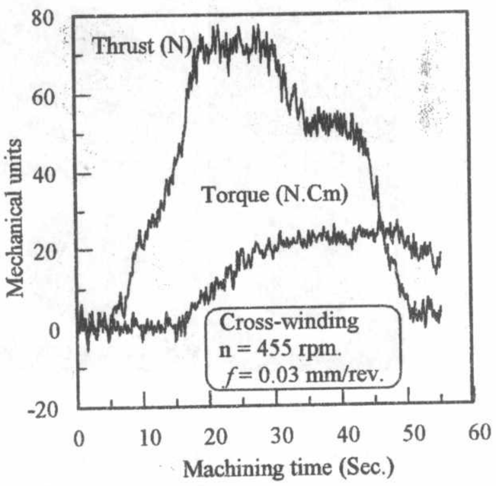


Fig.4. Thrust force and torque over drilling cycle of the cross-winding composites.

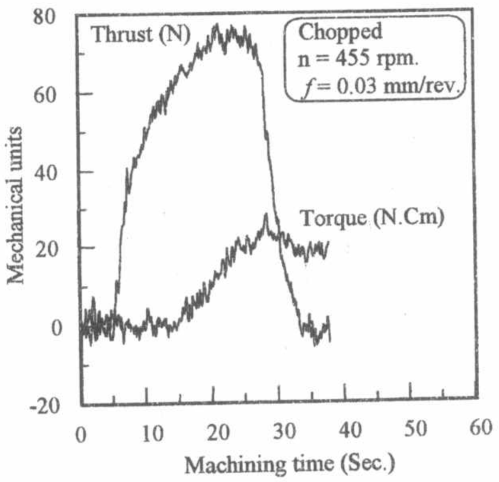


Fig.5. Thrust force and torque over drilling cycle for chopped composites.

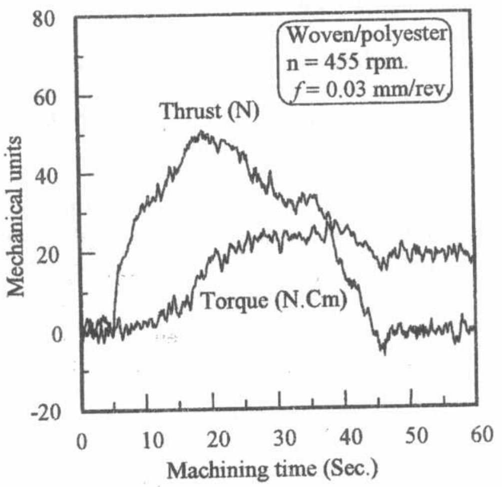


Fig.6. Thrust force and torque over drilling cycle of the woven/polyester composites.

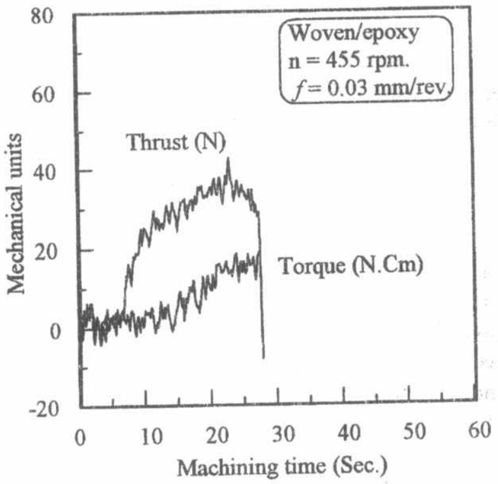


Fig.7. Thrust force and torque over drilling cycle of the woven/epoxy composites.

For the same composite material, e.g. cross-winding, the sudden drop in the thrust force at exit side can be changed to gradual decreases by reducing the feed, Fig.8. The gradual drop of the thrust force just before the drill exit, as a result of decreasing feed, is very significant for reducing the delamination size, Fig. 9.

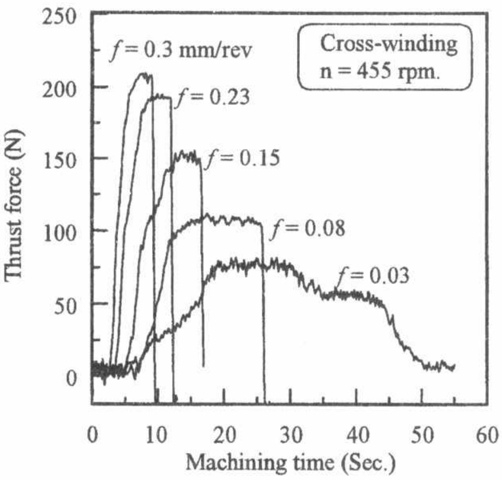


Fig.8. Effect of feed on thrust force over drilling cycles of cross-winding composites.

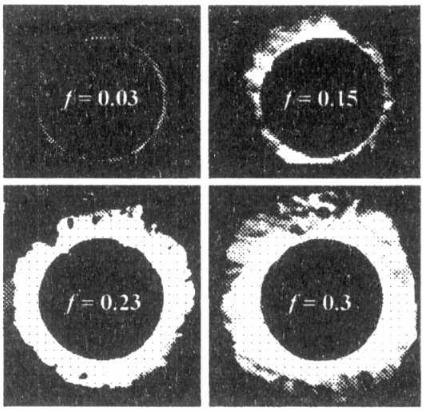


Fig.9. Photographs illustrate effect of feed on push-out delamination of cross-winding composites, n = 455 rpm.

3.2 Effect of Drilling Variables on Thrust Force and Torque

Figs. 10 and 11 shows the influence of drilling variables on peak thrust force and torque, respectively, for continuous-winding and cross-winding composites. The results in these figures indicate that, the thrust force and torque were increased with increasing feed. This fact was due to the increasing the cross-sectional area of the undeformed chip.

The presence of sand filler with abrasive nature in continuous-winding composite that, in addition to increasing the hardness and cutting resistance of the material, also result in wears the cutting edges of the drill. Therefore the thrust force and torque were increased with increasing cutting speed, Figs.10 and 11. This behavior was contrary to the results of many investigators [2,24,28] and also to the experimental results of cross-winding, woven/polyester, woven/epoxy and chopped composites, Figs.10 to 17 respectively. The results in Fig.10 also indicate that the thrust forces of continuous-winding composite are more than three orders of magnitude higher than those in the cross-winding, woven and chopped composites.

The decreasing of drilling peak thrust and torque for cross-winding, woven/polyester, woven/epoxy, and chopped composites, Figs.10 to 17 respectively, with increasing cutting speed was due to the increases of the generated heat that assisted by the low coefficient of thermal conduction and low transition temperature of plastics. The thermal conductivity (K) of the E-glass, polyester and epoxy are 1.3, 0.21 and 0.21 W/m°C respectively [29]. The thermal conductivity of the composite materials (K_c) can be calculated using the rule of mixtures equation, $K_c = K_f.V_f + K_m.(1-V_f)$. Where K_f and K_m are the thermal conductivity of fiber and matrix respectively. Therefore the thermal conductivity of the composite materials are very low compared with metals, K(steel) = 53 W/m°C and K(Aluminum) = 210 W/m°C. The accumulated heat around tool edge leads to softening the polymer matrix, where the glass-rubber transition temperature (T_g) of polyester and epoxy are 130 and 150 °C respectively [21]. The experimental results of Nagao et al. [27] indicate that the temperature of HSS drill tip was reached more than 200 °C during drilling epoxy resin. The softener materials make as a lubricant material, which reduces the friction forces, moment of friction force on the margins and moment of the forces of friction of the chip on the drill and on the machined surface.

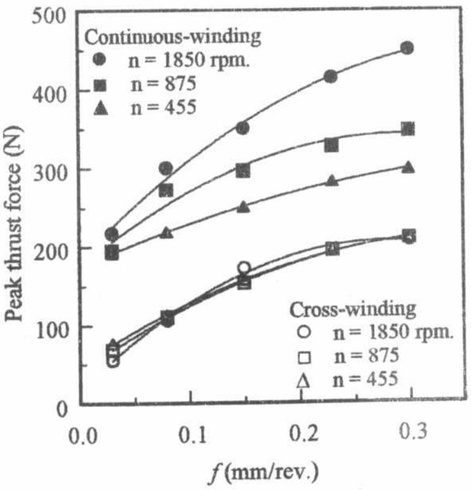


Fig. 10. Peak thrust vs. feed for winding composites at different speeds.

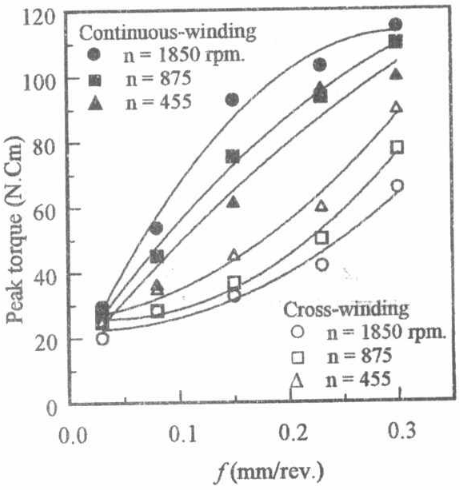


Fig. 11. Peak torque vs. feed for winding composites at different speeds.

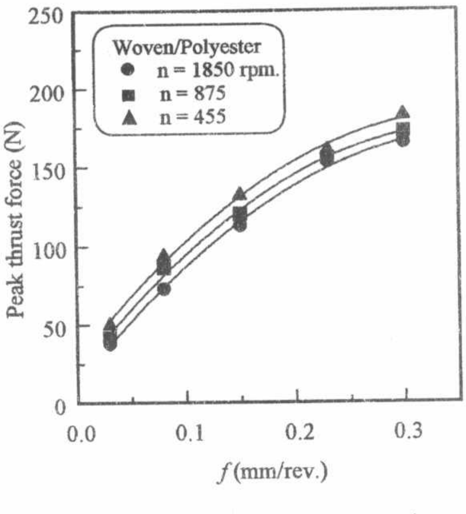


Fig. 12. Peak thrust vs. feed for woven/ polyester composites at different speeds.

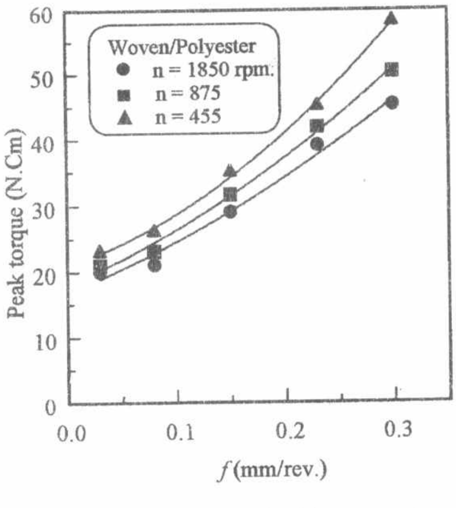


Fig. 13. Peak torque vs. feed for woven/ polyester composites at different speeds.

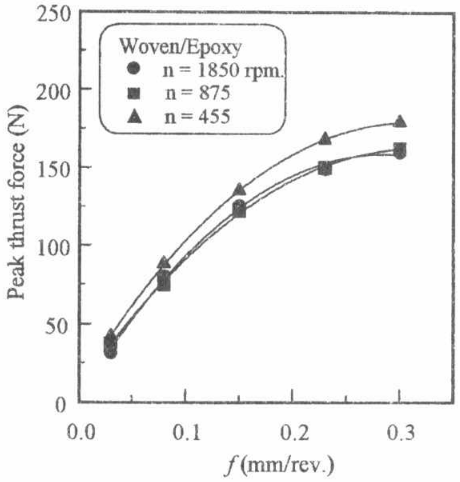


Fig. 14. Peak thrust vs. feed for woven/ epoxy composites at different speeds.

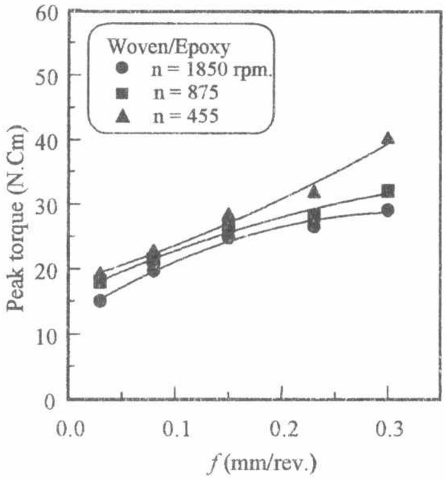


Fig. 15. Peak torque vs. feed for woven/epoxy epoxy composites at different speeds.

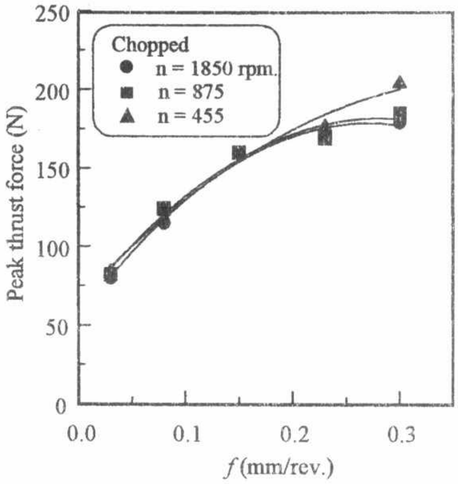


Fig. 16. Peak thrust vs. feed for chopped composites at different speeds.

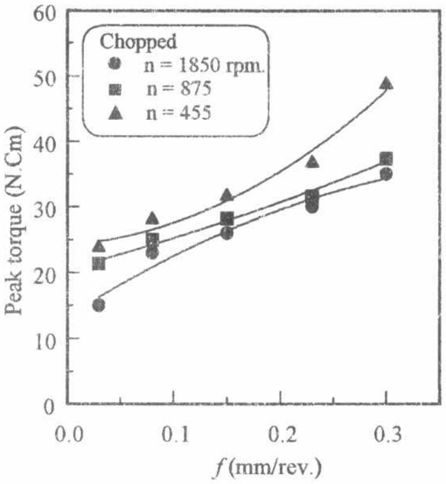


Fig. 17. Peak torque vs. feed for chopped composites at different speeds.

3.3 Effect of Matrix and Fiber Types on the Thrust Force and Torque.

Figs.18 to 23 illustrate the effect of matrix type (polyester or epoxy) and fiber shape (chopped or woven) on the cutting forces (thrust and torque) at different cutting variables (feed and speed). These figures were constructed from the experimental results in Figs. 12 to 17 of woven/polyester, woven/epoxy and chopped composites. The results in Figs.18, 20 and 22 show that for woven composites (Woven/polyester and woven/epoxy) the matrix type has insignificant effect on the thrust force. In contrast fiber shape clearly affect on thrust force where chopped composites has higher thrust force despite it has lower V_f (27.6%) than woven composites ($V_f \approx 33\%$).

Figs. 19, 21 and 23 show that, for the same matrix type, the woven/polyester composites have higher torque than chopped/polyester composites. This result was due to the woven fibers are made from two orthogonal directions of fibers (warp and fill), Figs.24-a, b & c. König et al. [6,30] show that the torque value is always a function of the fiber orientation in the cutting area. For unidirectional composites they found that the maximum torque occurs when the fiber is loaded compressively. For woven laminates the warp and fill fibers tows are perpendicular to each other. Each fiber direction will met at least the cutting edge twice per revolution i.e. each cutting edge will met at least four tangential fiber directions per one revolution. Two for the warp fibers at edge position angle equal 0 and 180°, Fig.24-b, and two for the fill fibers at edge position angle equal 90 and 270°, Fig.24-c. These fibers are loaded compressively resulting in higher tangential force (F_t) and torque than that for the chopped composites where the fibers are randomly oriented to give quasi-isotropic materials, Fig.24-d. The results in Figs. 19, 21 and 23 also indicates that, for the same fiber shape, the torque values for woven/polyester composites were higher than that for woven/epoxy composites.

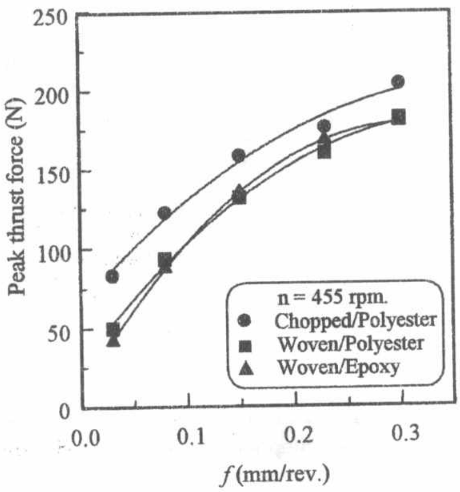


Fig. 18. Peak thrust vs. feed for woven and chopped composites, n = 455 rpm.

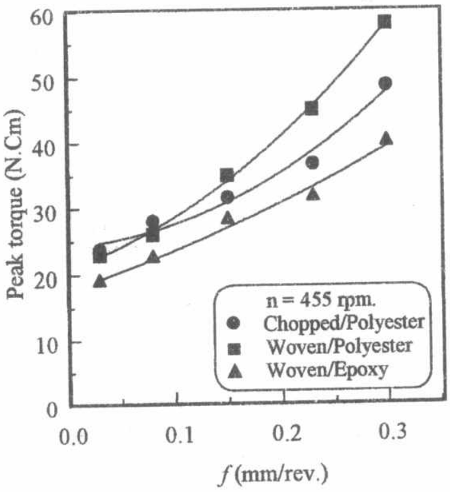


Fig. 19. Peak torque vs. feed for woven and chopped composite, n = 455 rpm.

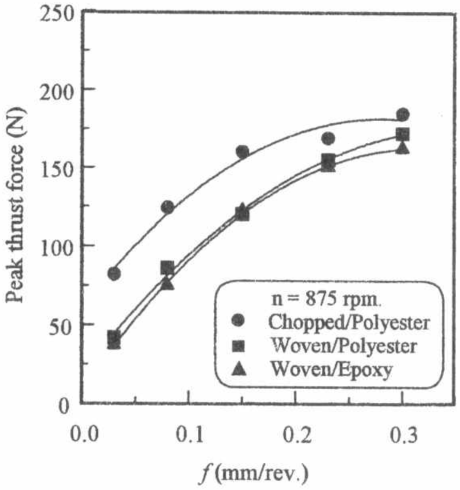


Fig. 20. Peak thrust vs. feed for woven and chopped composites, n = 875 rpm.

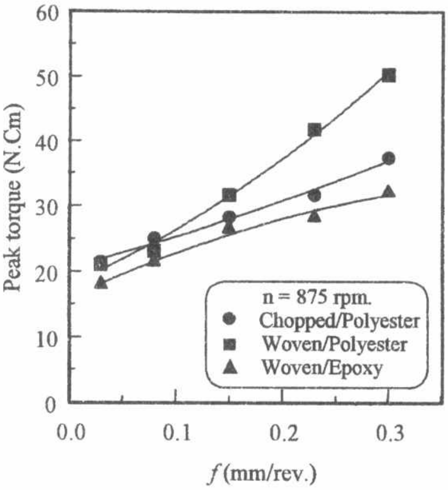


Fig. 21. Peak torque vs. feed for woven and chopped composite, n = 875 rpm.

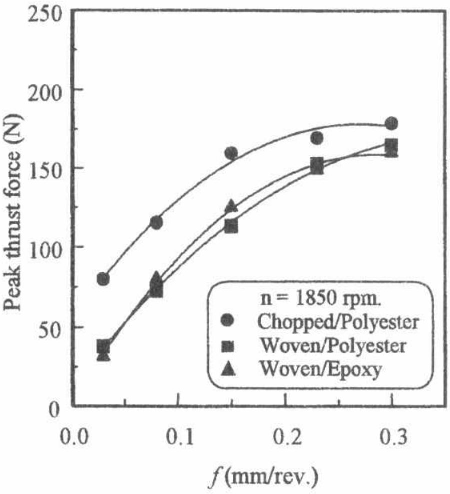


Fig. 22. Peak thrust vs. feed for woven and chopped composites, n = 1850 rpm.

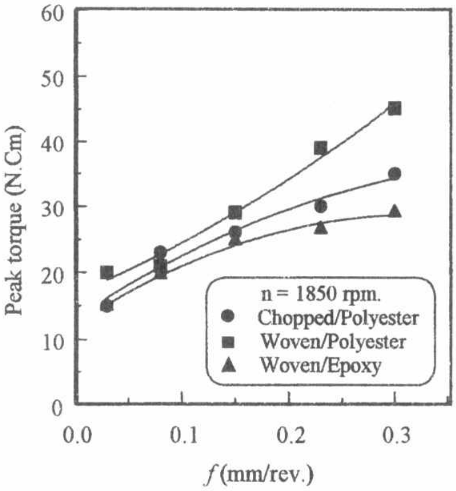
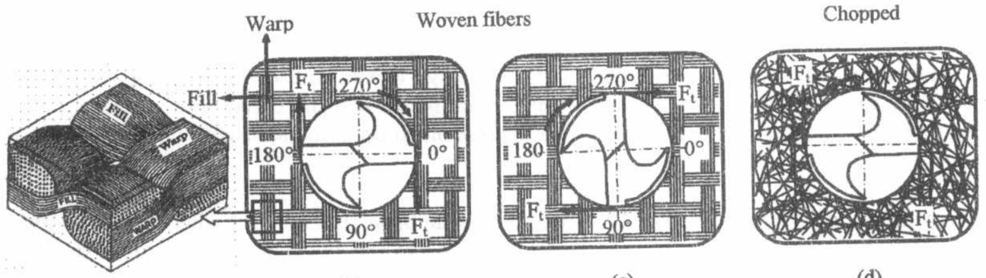


Fig. 23. Peak torque vs. feed for woven and chopped composite, n = 1850 rpm.



(a) (b) (c) (d)

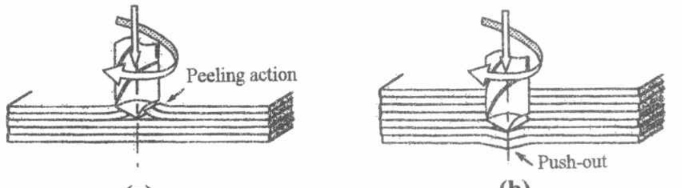
Fig. 24. Schematic diagrams illustrates: (a) a woven braid that made by the interlacing of warp and fill fibers, (b) the tangential force (F_t) perpendicular to warp fibers at edge position angles equal 0° and 180°, (c) F_t perpendicular to fill fibers at edge position angles equal 90° and 270° and (d) F_t engaged the chopped composites with random angles between the edge position and the fiber directions.

4. RESULTS AND DISCUSSIONS ON DELAMINATION

4.1 Delamination Mechanisms

Two mechanisms of delamination associated with drilling FRP composites were observed in the present study. They are known as peel-up at entrance and push-out at exit [7,8,10,20,31,32]. Peel-up occurs as the drill enters the laminate and is shown schematically in Fig. 25-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 delamination. It generates a peeling force in the axial direction through the slope of the drill flute results in separating the laminas from each other forming a delamination zone at the top surface of the laminate.

Push-out is the delamination mechanism occurring as the drill reaches the exit side of the material and is shown schematically in Fig. 25-b. As the drill approaches the end, the uncut thickness smaller and the resistance to deformation decrease. At some point the loading exceeds the interlaminar bond strength and delamination occurs. This happens before the laminate is completely penetrated by the drill as shown in Fig.25-b.



(a) **(b)**

Fig.25. Mechanisms of delamination; (a) Peel-up delamination at entrance and (b) Push-out delamination at exit [1].

4.2 Effect of Cutting Speed and Feed on Delamination Size.

Figs.26 to 30 show the influence of cutting speed and feed on the peel-up and push-out delaminations of continuous-winding, cross-winding, woven and chopped composites. The results in these figures indicate that the delamination size was increased with increasing feed as a result of increasing thrust force. Also the delamination associated with push-out is more severe than that of peel-up.

Push-out delamination for continuous-winding composite, Fig.26, is higher than the other composites, Figs.27 to 30. This result not only due to the low interlaminar shear strength between the sand filler and chopped layer at the exit side but also due to the highest thrust force of continuous-winding composite compared to the other composite materials. The presence of sand filler in continuous-winding composites not only raised the values of push-out delamination but also increased their values with increasing cutting speed. In contrast, increasing the cutting speed in drilling cross-winding, woven and chopped composites reduces the push-out delamination as a result of decreasing the thrust force. These results clearly indicate the dependability of delamination size on thrust force.

The effect of cutting speed on peel-up delamination is contrary to push-out delamination for polyester-base composites (continuous-winding, cross-winding, and woven/polyester composites). On the other hand the peel-up and push-out delaminations of woven/epoxy composites was decreased with increasing cutting speed, Fig.29.

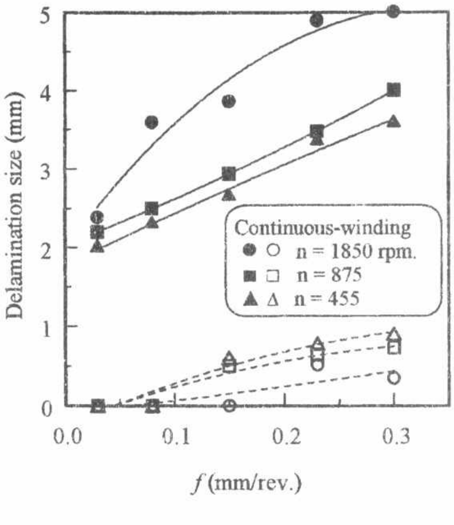


Fig. 26. Peel-up (white symbols) and Push-out (dark symbols) delaminations vs. feed for continuous-winding composites.

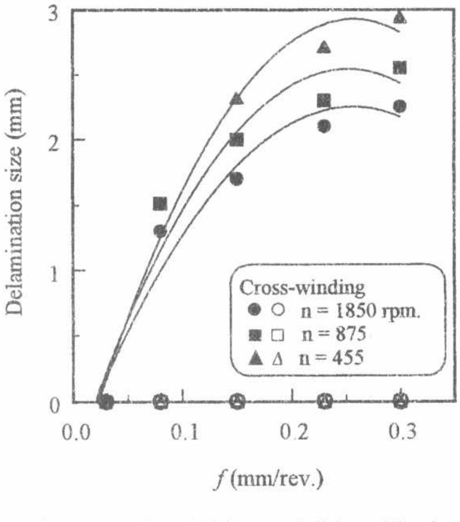


Fig. 27. Peel-up (white symbols) and Push-out (dark symbols) delaminations vs. feed for cross-winding composites.

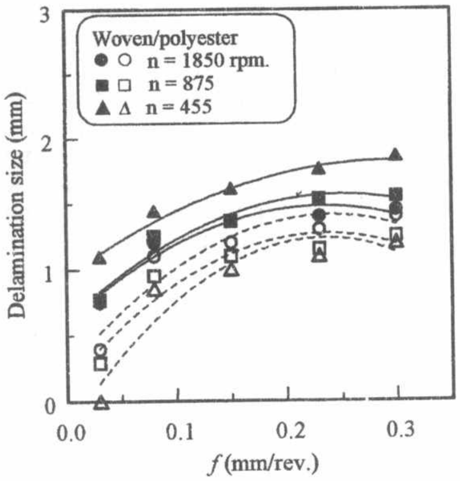


Fig. 28. Peel-up (white symbols) and Push-out (dark symbols) delaminations vs. feed for woven/polyester composites.

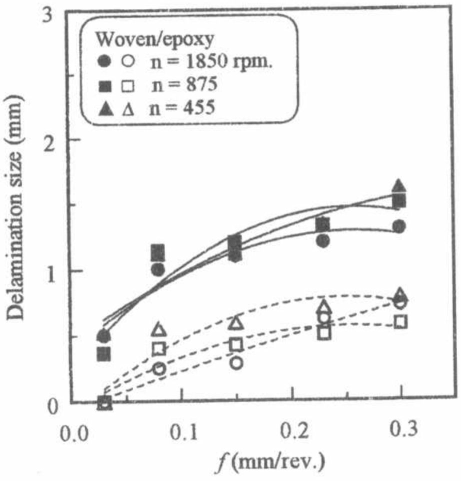


Fig. 29. Peel-up (white symbols) and Push-out (dark symbols) delaminations vs. feed for woven/epoxy composites.

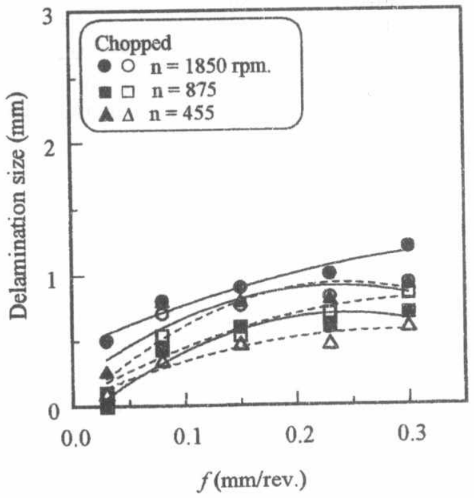


Fig. 30. Peel-up (white symbols) and Push-out (dark symbols) delaminations vs. feed for chopped composites.

4.3 Effect of Matrix and Fiber Types on Delamination

Figs.31 to 33 illustrate the influence of matrix and fiber types on the delamination size of woven/polyester, woven/epoxy and chopped composites. These figures have been constructed from the experimental results in Figs.28 to 30. The results in Figs. 31 to 33 indicate that although chopped composites has higher thrust force than woven composites, Figs., 18, 20 & 22, it has lower push-out delamination than woven composites. This result was due to the presence of the braids that made by the interlacing of two orthogonal directions of fibers tows (warp and fill) these braids implying weak in-plane shear resistance [33]. The peel-up and push-out delaminations of woven/epoxy composite are lower than that for woven/polyester composites despite the two composites have a proximately equal thrust forces, Figs. 18, 20 & 22. This result referred to the higher fiber/matrix interface bond strength of woven/epoxy than woven/polyester and successfully the interlaminar shear strength.

4.4 Damage Mechanisms

Damage in the surface layers is essential quality criterion in drilling polymeric composite materials [6]. In the present work different damage mechanisms were observed in drilling GFR-thermoset composites especially at drill exit, Fig.34. Delaminations at different edge position angles were observed in drilling woven/polyester and woven/epoxy composites, Fig.34-a &b respectively, $f = 0.3$ mm/rev. and n = 455 rpm. Similar delamination was found in drilling plain-woven cloth composites, Nobe et al. [11]. Their results show that the thrust force and the damage width have four peaks in one revolution of the drill. These peaks occur at the edge position angle about 45, 235, 225 and 315°. Delamination, spalling and chipping damages was observed in drilling chopped and continuous-winding composites at high feeds. These damage mechanisms are illustrated in Fig.34-c for chopped composites drilled at $f = 0.3$ mm/rev. and n = 455 rpm. A massive delamination associated with chipped fibers was observed in drilling continuous-winding composites, $f = 0.3$ mm/rev. and n = 1850 rpm, Fig.34-d. Where the first and last layers are chopped fibers. The reason for the different characteristics damaged zones lied in the different in interlaminar fracture resistance of the GFRP composites with different constituent materials.

4.5 Delamination-Free in Drilling GFRP Composites

the experimental results in Figs.26 to 30 show that the minumum peel-up and push-out delaminations occured at minimum feed. Drilling polymeric composite materials at very low feed will be inefficient and may cause thermal damage to the drilled composites [7,18] that, in addition reducing the productivity as a result of increasing the machining time and cost. Jain et al. [15,18] recommended using variable feed technique for delamination preventation in drilling polymeric composite materials. This technique involved drilling the composite specimen in the beginning by the recommended feed that prevent peel-up delamination for certain depth from the top surface then gradually increases the feed as fast as practicall permissible and then progressively decrease the feed at the drill approaches exit. In the present work this technique was applied on cross-winding comosites using CNC milling/drilling machine.

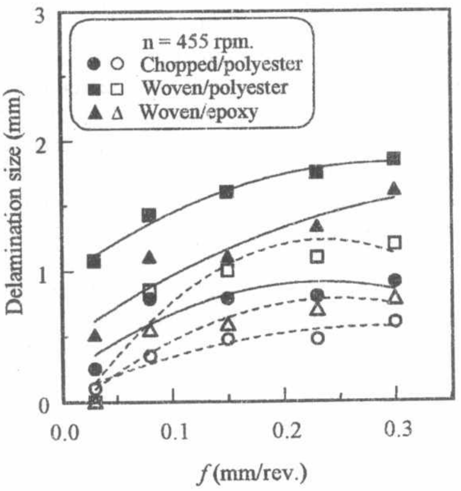


Fig. 31. Peel-up (white symbols) and Push-out (dark symbols) delaminations vs. feed for different composites, 455 rpm.

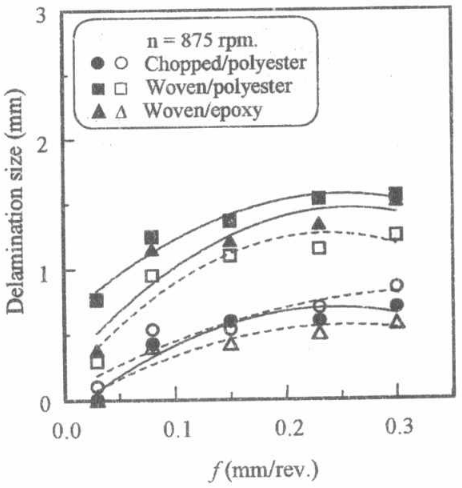


Fig. 32. Peel-up (white symbols) and Push-out (dark symbols) delaminations vs. feed for different composites, 875 rpm.

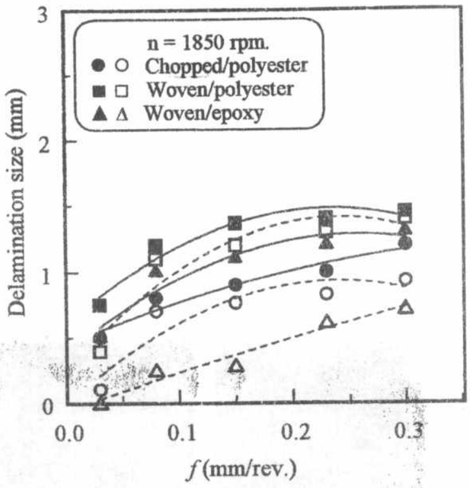


Fig. 33. Peel-up (white symbols) and Push-out (dark symbols) delaminations vs. feed for different composites, n = 1850 rpm.

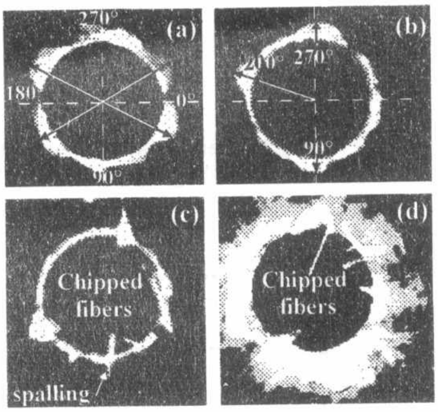


Fig. 34. Photographs show the delamination for various composites (a & b) woven/epoxy (c) chopped & (d) Continuous Winding.

The drill entrance the specimen by the maximum cutting cutting variables (f = 0.3 mm/rev. and n = 1850 rpm), Fig.35. At these cutting variables the peel-up delamination equal zero and push-out delamination equal 2.251 mm, Fig.27. Then the feed was progressively decreased up to it reaches 0.03 mm/rev., at distance X from the exit side, where push-out delamination equal zero, Fig.27. The distance X from the exit side, at which the optimum cutting variables was applied without delamination, was determined experimentally as illustrated in Fig.36. The results in this figure indicate that delamination preventation in drilling cross-winding composites was achieved using variable feed technique by applying the minimum feed (0.03 mm/rev.) at 0.75 mm from the exit side. Fig.37 shows that the top and bottom sides of the drilled holes using variable feed technique are free from the delamination. Similary the variable feed technique can be applied to the other composite materials after selecting the optimum cutting variables, from the experimental results, that prevent the delamination around the drilled holes.

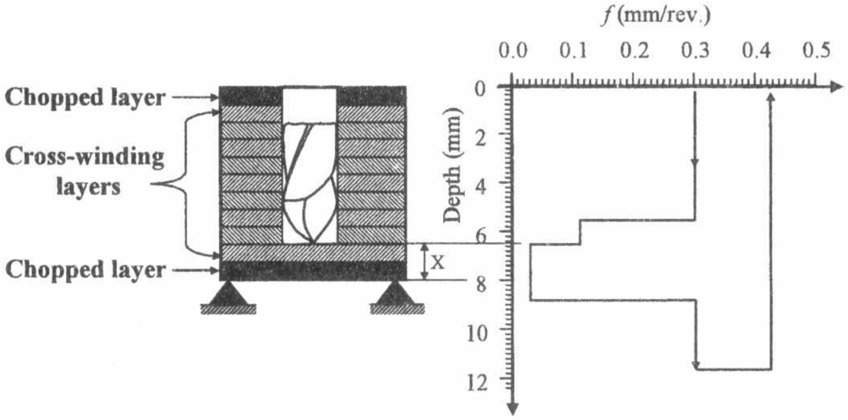


Fig.35 Feed variation along the hole depth for delamination-free in drilling cross-winding composite, n = 1850 rpm.

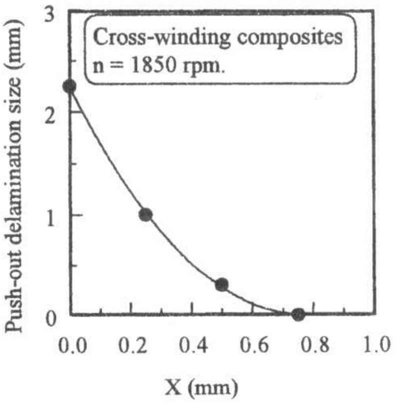


Fig.36. Distance X vs. Push-out delamination in drilling cross-winding composites.

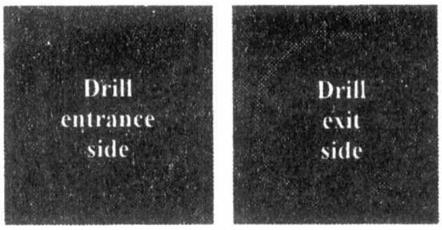


Fig.37. Delamination-free in drilling cross-winding composites.

5. CONCLUSIONS

1. Accurate inexpensive technique for measurement the delamination size within 10^{-3} mm resolution has been developed.

2. The constituent materials of the composite specimens, specimen thickness and machining time have a significant effect on the behavior of thrust force and torque over the machining time. At minimum cutting variables the thrust force of continuous-winding, woven/epoxy and chopped composites were suddenly dropped from the maximum value to zero at the drill exit with significant push-out delamination. On the other hand gradual decreases in thrust force was observed for cross-winding composites resulting in delamination-free at drill exit.

3. The presence of sand filler in continuous-winding composites not only raised the values of cutting forces and push-out delamination but also increased their values with increasing cutting speed. In contrast, increasing the cutting speed in drilling cross-winding, woven and chopped composites reduces the push-out delamination as a result of decreasing the thrust force. The thrust forces of continuous-winding composite are more than three orders of magnitude higher than those in the cross-winding composites.

4. The perpendicularity of weft and fill fibers in woven composites makes each cutting edge met at least four tangential fiber directions per one revolution. Two for the warp fibers at edge position angle equal 0° and 180° and two for the fill fibers at edge position angle equal 90° and 270°. These fibers are loaded compressively resulting in higher torque than chopped composites, which made from the same matrix. For the same fiber shape (woven) the matrix has insignificant effect on thrust force. In contrast the torque of woven/polyester composites is higher than that for woven/epoxy composites.

5. The effect of cutting speed on peel-up delamination is contrary to push-out delamination for polyester-base composites (continuous-winding, cross-winding, and woven/polyester composites). While the peel-up and push-out delaminations of woven/epoxy composite were decreased with increasing cutting speed. The delamination size was increased with increasing feed as a result of increasing thrust force. The delamination associated with push-out is more severe than that of peel-up.

6. For the same fiber shape, the peel-up and push-out delaminations of woven/epoxy composite are lower than that for woven/polyester composites despite the two composites have a proximately equal thrust forces. Although chopped composites has higher thrust force than woven composites it has lower push-out delamination than woven composites.

7. Delamination, chipping and spalling damage mechanisms were observed in drilling chopped and continuous-winding composites. In drilling woven composites the delamination was observed at different edge position angles.

8. Delamination-free in drilling cross-winding composites was achieved using variable feed technique. This technique can be applied to the other composite materials after selecting the optimum cutting variables, from the experimental results, that prevent the delamination around the drilled holes.

REFERENCES

[1] Stone, R. and Krishnamurthy, K., "A Neural Network Thrust Force Controller to Minimize Delamination During Drilling of Graphite-Epoxy Laminates", J. Mach. Tools & Manufact., Vol.36, No.9, PP.985-1003, (1996).

[2] Park, K.Y., Choi, J.H. and Lee, D.G., "Delamination-Free and High Efficiency Drilling of Carbon Fiber Reinforced Plastics", J. Composite Materials, Vol.29, No.15, PP.1988-2002, (1995).

[3] Andrews, S.D., Ochoa, O.O. and Owens, S.D., "The Effect of Fastener Hole Defects", J. Composite Materials, Vol.27, No.1, PP.3-20, (1993).

[4] Tagliaferri, V., Caprino, G. and Diterlizzi, A., "Effect of Drilling Parameters on the Finish and Mechanical Properties of GFRP Composites", J. Mach. Tools & Manufact., Vol.30, No.1, PP.77-84, (1990).

[5] König, W., Cronjäger, L., Spur, G., Tönshoff, H.K., Vigneau, M. and Zdeblick, W.J., "Machininh of New Materials", CIRP, Vol.39/2, PP.673-681, (1990).

[6] König, W.and Graβ, P., "Qua;ity Definition and Assessment in Drilling of Fiber Reinforced Thermosets", CIRP, Vol.38/1, PP.119-124, (1989).

[7] Ho-Cheng, H., Pwu, H.Y. and Yao, K.C., "Machinability of Some Fiber-Reinforced Thermoset and Thermoplastics in Drilling", Materials & Manufacturing Processes, 8(6), PP.653-682, (1993).

[8] Ho-Cheng, H., Dharan, C.K.H., "Delamination During Drilling in Composite Laminates", J. of Engineering for Industry, ASME, Vol.112, PP.236-239, (1990).

[9] Zhang, L.B., Wang, L.J., Liu, H.W., Zhao, H.W., Wang, X. and Luo, H.Y., "Mechanical Model for Predicting Thrust and Torque in Vibration Drilling Fiber-Reinforced Composite Materials", J. Mach. Tools & Manufact., Vol.41, PP.641-657, (2001).

[10] Piquet, R., Ferret, B., Lachaud, F. and Swider, P., "Experimental Analysis of Drilling Damage in Thin Carbon/Epoxy Plate Using Special Drills", Composites, Part A, Vol.31, PP.1107-1115, (2000).

[11] Nobe, H., Aoyama, E., Inoue, H., Hirogaki, T., Kitahara, Y., Katayama, T., Gunjima, M., Ogawa, K. and Okuno, Y., "Study on Cause of Internal Damage of Drilled GFRP", Key Engineering Materials, Vol.137, PP.123-130, (1998).

[12] Capello, E. and Tagliaferri, V., "Drilling Damage of GFRP and Residual Mechanical Behavior--Part II: Static and Cyclic Bearing Loads", J. Composites Technology and Research, Vol.23, No.2, PP. 131-137, (2001).

[13] Jain, S. and Yang, D.C.H., "Effects of Feedrate and Chisel Edge on Delamination in Composite Drilling", J. of Engineering for Industry, ASME, Vol.115, PP.398-405, (1993).

[14] Chen, W.C., "Some xperimental Investigations in the Drilling of Carbon Fiber-Reinforced Plastic (CFRP) Composite Laminates", J. Mach. Tools & Manufact., Vol.37, No.8, PP.1097-1108, (1997).

[15] Jain, S. and Yang, D.C.H., "Delamination-Free Drilling of Composite Laminates", J. of Engineering for Industry, ASME, Vol.116, PP.475-481, (1994).

[16] Sadat, A.B., "Prediction of Delamination Load in Drilling of Graphite/ Epoxy Composites", PD-Vol.75, Engineering System Design and Analysis, Volume 3 ASME, PP.21-27, (1996).

[17] Chandrasekharan, V, Kapoor, S.G. and Devor, R.E., "A Mechanistic Approach to Predicting the Cutting Force in Drilling: with Application to Fiber-Reinforced Composite Materials" J. of Engineering for Industry, ASME, Vol.117, PP.559-570, (1995).

[18] Jain, S. and Yang, D.C.H., "Effects of Feedrate and Chisel Edge on Delamination in Composite Drilling", J. of Engineering for Industry, ASME, Vol.115, PP.398-405, (1993).

[19] Caprino, G. and Tagliaferri, V., "Damage Development in Drilling Glass Fiber Reinforced Plastics", J. Mach. Tools & Manufact., Vol.35, No.6, PP.817-829, (1995).

[20] Davim, J.P. and Reis, P., "Study of Delamination in Drilling Carbon Fiber Reinforced Plastics (CFRP) using Design Experiments", J. Composite Structures, Vol.59, PP.481-487, (2003).

[21] Khashaba, U.A., " Effect of Water and Temperature Environments on the Impact Behavior of Woven GFR Thermoset Composites", Proc. of the Fifth Int. Conf. On Prod. Eng. and Design for Development, Ain Shams University, Egypt, PP.359-371, (1998).

[22] Khashaba, U.A. and EL-ASSAL,A.M., "Structural and Environmental Effect on Compressive Strength of Chopped GFRP Composites", Proc. of the Fifth Int. Conf. On Prod. Eng. and Design for Development, Ain Shams University, Egypt, PP.389-402, (1998).

[23] Khashaba, U.A., "Fracture Behavior of Woven Composites Containing Various Cracks Geometry" J. Composite Materials, Vol. 37, No.1, PP.5-21, (2003).

[24] El-Sonbaty, I., Khashaba, U.A. and Machaly, T., "Factors affecting the machinability of GFR/Epoxy composites", Proc. of Third Int. Conf. on Mech. Eng. Adv. Tech. for Indus. Prod., Assiut University, Egypt, Vol.1, PP.203-215, (2002).

[25] Fischer, J. Haasz, V. and Radil, T., "Simple Device For Small Dimension Measurement Using CCD Sensor", Proceedings of the 12th IMEKO TC4 International Symposium, Electrical Measurements and Instrumentation, Zagreb, Croatia, PP. 433-437, September 25-27,(2002).
http://measure.feld.cvut.cz/groups/videometry/Other/IMEKO_TC4_2002_Haasz_abstrakt_ex.pdf

[26] Dipaolo, G., Kappor, S.G. and Devor, R.E., "An Experimental Investigation of the Crack Growth Phenomenon for Drilling of Fiber-Reinforced Composite Materials", J. of Engineering for Industry, ASME, Vol.118, PP.104-110, (1996).

[27] Nagao, T. and Hatamura, Y., "Investigation into Drilling Laminated Printed Circuit Bord Using a Torque-Thrust-Temperature Sensor", CIRP, Vol.37/1, PP.79-82, (1988).

[28] Radhakrishnan, T. and Wu, S.M., "On-Line Hole Quality Evaluation for Drilling Composite Material Using Dynamic Data", J. of Engineering for Industry, ASME, Vol.103, PP.119-125, (1981).

[29] Gibson, R.F., "Principles of Composite Material Mechanics", McGraw-Hill, Inc., (1994).

[30] König, W., Wulf, C., Graβ, P. and Willerscheid, H., "Machining of Fiber Reinforced Plastics", CIRP, Vol.34/2, PP.537-547, (1985).

[31] Ozaki, M., "Supervisory Control of Drilling of Composite Materials", Ph.D. Thesis, Engineering-Mechanical Engineering, University of California, Berkeley, (2000).

[32] Capello, E. and Tagliaferri, V., "Drilling Damage of GFRP and Residual Mechanical Behavior--Part I: Drilling Damage Generation", J. Composites Technology and Research, Vol.23, No.2, PP.122-130, (2001).

[33] Cox,B.N. and Flanagan, G., "Handbook of Analytical Methods for Textile Composites", NASA Contractor Report 4750, Langley Research Center, pp. 169, (1997).
http://techreports.larc.nasa.gov/ltrs/cit.html