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Effect of Heat Resistant Coating on the Drilled Hole Quality of Hybrid Fiber Reinforced Epoxy Composite

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Abstract: Drilling is considered an inevitable operation for joining components in automotive and aerospace industries. Hybrid fiber reinforced polymer (HFRP) composites have attained enormous attention due to their light weight and higher strength. In this study, HFRP composite was made of glass, carbon fibers and epoxy. The vacuum infusion molding technique is used to fabricate HFRP composites. Physical and mechanical properties of HFRP composites were analyzed according to ASTM standard. Heat resistant coating was made of conventional coating ingredients with fillers as a binder to enhance coating performance. This coating was applied on HFRP composite. Drilling performance was tested for HFRP and coated HFRP composites to examine the impact of coating of the composite in term of drilled hole quality. Results showed that density was reduced by 10% after applying the coating in HFRP composite. The tensile and flexural strength were found around 441.27 MPa and 409 MPa, respectively. The coating was effective in terms of improving drilled hole quality by minimizing delamination factor. It was found higher with the increment of spindle speed and feed rate for both coated and uncoated HFRP composite samples. Coated samples showed less DF at the entrance as well as exit compared to uncoated composites.

Keywords: Heat resistant coating; HFRP, VIM, delamination.

1. Introduction

Composites are cutting edge engineering materials used in modern high technology products. High performance fiber reinforced polymer (FRP) composite materials are getting attention because of their advantage in producing lightweight structures. FRP composites was found to have competitive edge despite of their initial cost and considered more efficient and durable when it comes to severely corrosive environments ¹. The ease of design flexibility, corrosion resistant and mechanical properties have made composite materials as primary choice for automotive industries ². In addition, possessing isotropic mechanical feature in three orthogonal direction, composite materials holds the attribute of low cost accessibility of reinforcement and ease of fabrication ³. The growing use of FRP composite materials in automotive and aircraft structural application requires drilling of holes makes it almost unavoidable operations for assembly/joining and repair purposes ⁴. Typically 100,000 holes are required in assembling of a small aircraft using mechanical fastener ⁵. But the problem associated with drilling of composite is

delamination which is basically defined as the fiber pull/push out occurring a damage at the entry and exit of the composite. This defect is highly responsible in influencing mechanical properties of the component as well as making the parts unacceptable ⁶. Flammability is one important parameter that limit the application of composite ⁷. The fire attack towards FRP is another safety concern in composite structure because in such fire environment, the FRP system cannot resist a regular load because of the reduced load-bearing capacity ⁸. Fire performance of polymer composites is not satisfactory since their organic matrix resin tends to soften when heated resulting loss of mechanical properties.

In recent years, most of the literatures showed that a lot of work has been done in investigating the influence of drilling parameters such as cutting speed, feed rate, tool diameters, drill point angle etc. on the thrust force, torque, delamination and surface roughness of either steel or CFRP or GFRP or their hybrid. Carbon and glass fibers are the most chosen materials in aerospace and automotive industries because of their high specific strength and stiffness ⁹. It was reported that drilling of glass fiber

reinforced polymer leads to a several problems mainly the delamination problem. If the material is hard, delamination will be more; when the tools thrust is high, damage will be equally high ¹⁰. *Daxi Geng et al.* ¹¹ reported in their research that delamination factor increased with the increased feed rate at any drilling parameters with various drill bits. The effects of cutting speed, feed rate, and point angle on delamination factor were analyzed using the models by generating response surface plots where researchers revealed that the delamination tendency decrease with increase in cutting speed and the study also suggested that low values of feed rate and point angle is better for reducing the damage in CFRP composite plate ¹². *N. feito et al.* ¹³ investigated and concluded that lowering the feed rate reduces delamination. *Maoinsar et al.* ¹⁴ concluded in his research that lowest spindle speed and feed rate resulted in lowest damage. *Higuchi et al.* ¹⁵ investigated the behavior of push out delamination while drilling composite laminates and concluded that the delamination is significantly affected by the thickness and materials of the bottom plies.

However, feed rate has been found the most influential parameters as it is generally responsible for resulting delamination on polymer composites. Moreover, due to the intricate application of drilling operation in various industries, it is important to look on the scopes of composite materials in fireproof application since no study on this has taken place. Heat resistant coating helps the underneath substrate by resisting heat penetration and ensuring quality surface finish of the parts.

In this study, we fabricated hybrid fiber reinforced polymer (HFRP) composites using vacuum infusion molding technique. The HFRP composite were coated with heat resistant coating of 2 mm. Physical and mechanical properties were measured. Drilling parameters such as spindle speed and feed rate were varied to investigate the delamination factor arisen at entry and exit side of HFRP composite.

2. Materials and methodology

Materials, fabrication technique, coating preparation method and characterization are described in this section.

2.1 Materials

Carbon and Glass fiber was purchased from RP Products Sdn Bhd, Bandar Baru Seri Alam, Malaysia. Epolam 2040/2042 resin hardener was bought from Advance Altimas Sdn Bhd, Petaling Jaya, Selangor, Malaysia. Table 1 shows the fibers properties. Conventional coating ingredients such as expandable graphite (EG), boric acid (BA), ammonium polyphosphate (APP), melamine and halloysite nanotube (HNT) were purchased from Sigma Aldrich (M) Sdn Bhd. Malaysia. Zirconium phosphate was purchased from Sichuan Hongchang Plastics Indus. Co. Ltd. China. BE-188 (BPA) resin and H-2310 polyamide amine

were used as a binder and brought from Mc-Growth Chemical Sdn Bhd. Malaysia.

Table 1: Physical and mechanical properties of woven carbon and glass fiber

Properties	Woven Carbon Fiber	Woven Glass Fiber
Type	T300	Biaxial LT 600
Areal weight	197 g/m ²	301 g/m ²
Areal density	1.8 g/m ³	2.54 g/m ³
Fiber diameter	13 µm	7 µm
Tensile Strength	512 KSI	360 KSI
Strain	1.5%	3.0%

2.2 Fabrication

The HFRP composite was designed based on the orientation of fiber, volume fraction of fiber and lamina stacking sequence. Orientation of fiber materials were maintained at 0/90° where fiber volume fraction was expected to achieve 45-55%. Lamina stacking sequence was taken as follows-[C-G-G-G-C-G-G-G-C]. Carbon fiber was taken as core and skin layers to achieve higher flexural modulus ¹⁶. Rising number of glass fiber layers in the outer skin significantly reduces the flexural strength ¹⁷. FVF was maintained around 30% (glass) and 15% (carbon).

A schematic diagram of vacuum infusion moulding is shown in Fig. 1. There are several steps involve in this fabrication process which are given below:

- Firstly, it is advised to clean the glass mold by using thinner and scraper. Wax was applied on the glass mold and kept 15 minutes for curing. Basically, it provides the easy removal of the composite model after solidification.
- The Sealant tape is applied around the glass mold with at least 50 mm bigger than the actual laminate size. After that, fiber clothes were laid over the wax inside the sealant tape area according to the stacking sequence.
- Then the polymer mesh and peel ply were placed over fiber clothes. The spiral tube was used to arrange the input and output flow of resin using the sealant tape. Inlet to resin and outlet to vacuum chamber- these two tubes are connected.
- Finally, the vacuum bag is placed on the mold tightly with the help of a sealant tape to avoid any leakage. Once the mold of composite is prepared, the vacuum pump was turn-on to achieve 80 KPa vacuum pressure on the attached pressure gauge. Then the pump is stopped, and the vacuum pressure is

monitored for 20 minutes to ensure if there is any leakage in the mold. If there is no change in gauge pressure which indicates there is no leakage in the mold, we can proceed to infuse of resin in the mold.

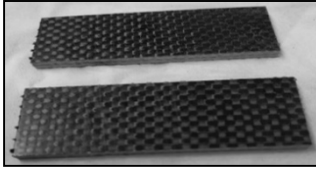


Fig. 1: Schematic diagram of VIM process and fabricated hybrid composites.

2.3 Coating Preparation

All the ingredients such as ammonium polyphosphate (APP), boric acid (BA), melamine (MEL), halloysite nanotube (HNT) and zirconium phosphate were mixed together manually according to our formulations given in Table 2 and grounded in a sheer mixer for about 90 seconds to make it homogenous. Expandable graphite (EG) was later added to the mixer and stirred a little with spoon. It is advisable not to grind expandable graphite because bigger the flakes, more the expansion. Then epoxy (BE-188) was added to the mixture and stirred at about 40 rpm for 15 mins using automatic shear mixer CAFRAMO (BDC 6015-220). Later, hardener (H-2310) was added and stirred for another 5 mins at 60 rpm. HFRP composite samples were coated using brush (Fig. 2). The samples were kept in the ambient temperature for 1 day for curing.

Table 2: Formulation of coating used in this study

Materials	Weight (%)
APP	11.36
BA	11
Melamine	5.5
EG	5.5
HNT	0.5
ZrP	0.5
Epoxy	41.94
Hardener	19.72
Total	100



Fig. 2: Coated HFRP composite samples

2.4 Characterization

The density was measured by Mettler Toledo AX-205 equipment according to ASTM D 0792 standard. Five samples of 2 cm × 2 cm were cut from the different section of the panel using diamond abrasive cutter. Average reading of these samples was taken for the accuracy of the test. Fiber volume fraction and void content was measured using burn-off test method according to ASTM D 3171 standards. Samples those were used in density measurement test were cleaned and placed in the carbolite furnace. The temperature of the furnace was set at 600°C for 30 minutes for the complete burning of the epoxy matrix. The samples were kept inside the furnace for 2 hours to cool to avoid thermal shocking. The hybrid fibers left inside (Fig. 3) the furnace was weighted in Mettler Toledo AX-205. Fiber volume fraction (V_f) and void content (V_v) was measured using the Equations ^{18, 19}.

$$V_f = \frac{n_{s1}e_{s1}tex_{s1}}{10t_c\rho_{s1}} + \frac{n_{s2}e_{s2}tex_{s2}}{10t_c\rho_{s2}} \quad (1)$$

$$V_v = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}} \quad (2)$$

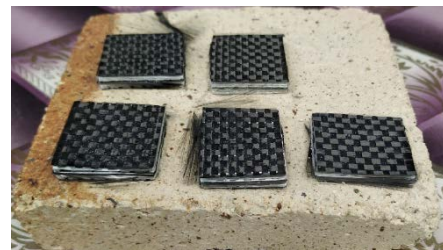


Fig. 3: HFRP composite sample used to measure FVF and void content

The tensile properties were examined using Zwick Roell Amsler HA50 universal testing machine (UTM) according to ASTM D 3039 (Fig. 4 a). A constant rate of 1.27 mm/min was applied and stress-strain data was recorded. Flexural test was done at Llyod UTM machine according to ASTM D 0790 standards (Fig. 4 b). The test speed was 1.60 mm/min.

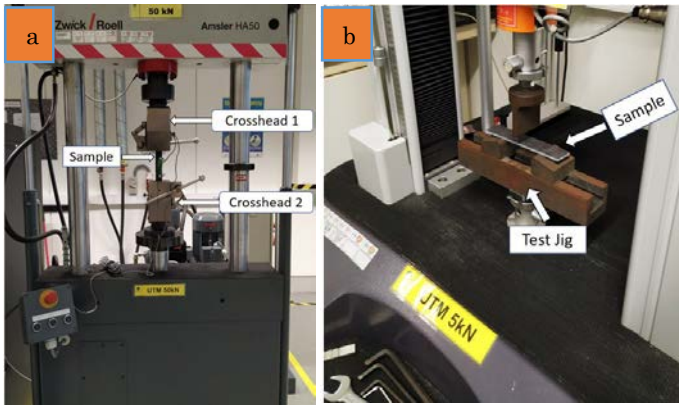


Fig. 4: a) Zwick Roell Amsler HA50 UTM, b) 5KN Lloyd UTM machine.

Mazak variaxis 630 CNC machine was used for drilling operation. The machine has maximum spindle speed of 25000 RPM and feed rate of 5000 mm/min (Fig. 5 a). HFRP and coated HFRP composites were cut in 70 mm x 25 mm size. HSS drill bit (5 mm diameter and 85° point angle) was selected in this study (Fig. 5 b). Main drilling parameters are given in Table 3. Delamination factor (DF) was used as drilling performance parameter and calculated as per Equation 3. Optical microscope was used to capture the drilled hole (entry and exit) images. The image processing was done in Solid-works 2013 software.

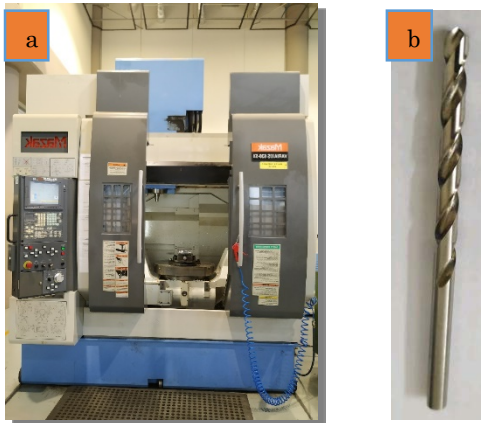


Fig. 5: a) Mazak Variaxis 630 CNC machine, b) HSS drill bit

Table 3: Drilling parameters.

Composite Type	Thickness (mm)	Feed rate (mm/rev)	Spindle speed (rpm)
HFRP	3.75	0.02	3000
Coated HFRP	5.75	0.08	6000

$$DF = D_{\max}/D_{\text{hole}} \quad (3)$$

3. Results and discussions

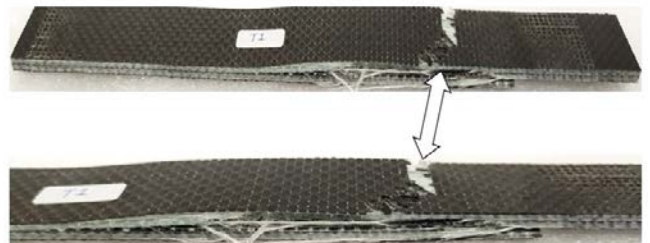
In section, properties of HFRP composite and coated HFRP composite are discussed.

3.1 Physical and mechanical properties

FVF and void content were found 46% and 0.391%, respectively. The analysis of the HFRP composite also shows that laminates have been successfully fabricated using the VIM process with less than 5% of void content²⁰⁾. The density of HFRP composite samples was measured by taking specimens from different sides of the panel, and the average density was found 1.68 g/cc. The average density is less than 1% of the theoretical density of 1.69 g/cc. The density of coated HFRP composite was also measured in a similar process and recorded as 1.516 g/cc, which means approximately 10% density gets reduced when we apply coating on the surface of the polymer composite.

The tensile strength recorded was compared with the previous literature. Damaged specimen after the tensile test is showing in Fig. 6 (a). Fig. 6 (b), shows the tensile stress vs. tensile strain graph. The average tensile strength and modulus achieved are 441.27 MPa and 23.25 GPa. The tensile properties of the composite are comparable with their theoretical value, and results are also in agreement with the composite made by *Pandya et al.*²¹⁾. The tensile strength of the HFRP composite has sufficiently increased compared to the composite strength reported by *Zhang et al.*²²⁾. Fiber percentage in the FRP composite directly affects the mechanical strength of the composite²³⁾. 433 MPa and 394 MPa tensile strength was reported for G-C and G-C-G-C hybrid composite made of land lay-up process by *Poyyathappan et al.*²⁴⁾. It also indicated that HFRP composite produced with the VIM process has more interlaminar strain energy than composite made with the hand-layup process^{25, 26)}. Mechanical and electrical properties of hybrid fiber composite was investigated by *El-Menshawey et al.*²⁷⁾ and results showed that placing carbon fiber at the core lowered the tensile strength as glass fiber is more sensitive to crack even in micron size.

(a)



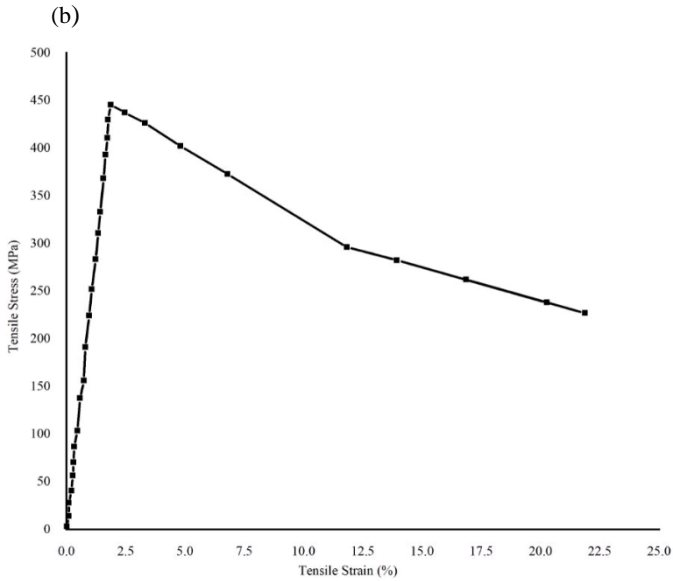


Fig. 6: a) HFRP composite damage during tensile testing b) Tensile properties of HFRP composite

Fig. 7 (a) shows the specimen after the flexural test. Fig. 7 (b) shows the flexural properties recorded in the test. Average flexural strength and modulus were recorded as 409 MPa and 20.72 GPa, respectively. The test results are comparable with what *Lazar et al.*²⁸⁾ reported. HFRP composite exhibits higher flexural strength than glass fiber reinforced polymer composite.

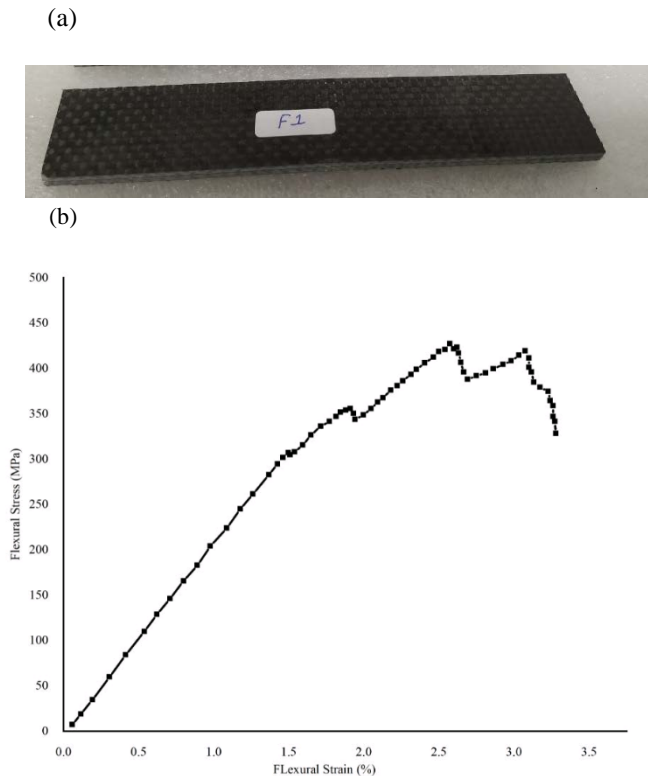


Fig. 7: a) HFRP composite damage during flexural testing b) Flexural properties of HFRP composite

3.2 Drilling Operation

Delamination factor (DF) at the entrance and exit for coated and uncoated specimens was calculated, which is shown in Table 4. Maximum DF (1.364) is reported in uncoated HFRP composite when drilling at a spindle speed of 6000 and a feed rate of 0.02 mm/rev. Minimum DF (1.03) for uncoated samples achieved for a spindle speed of 3000 and feed rate of 0.02 mm/rev. DF has been found to be increased as the spindle speed increases for uncoated HFRP composite. For entry, DF of uncoated HFRP composite was seen to have no significant effect of increasing feed rate at 3000 rpm. However, the exit DF was found declining for this drilling condition. At 6000 rpm, DF (entry) was found increasing with rise of feed rate for uncoated hybrid composite, but exit DF behaved different response. It has been observed that the coating has a substantial effect on the delamination of HFRP composite. For coated HFRP composites, DF at entrance and exit found increasing with rising the speed from 3000 rpm to 6000 rpm. Feed rate significantly influenced the entry DF for both cutting speeds and found increasing with increasing feed rate. On the other hand, the opposite response was seen at the exit. Maximum DF tested for coated samples is 1.22 (S-6000, F-0.08), which is approximately 10.5 % less than maximum delamination occurred in uncoated HFRP composites.

Table 4: Delamination factor (DF) calculated for various drilling parameters

Sl.	Composite type	S	F	DF Entry	DF Exit
1	Uncoated	3000	0.02	1.036	1.18
2	Uncoated	3000	0.08	1.03	1.072
3	Uncoated	6000	0.02	1.184	1.364
4	Uncoated	6000	0.08	1.204	1.286
5	Coated	3000	0.02	1.02	1.16
6	Coated	3000	0.08	1.038	1.08
7	Coated	6000	0.02	1.14	1.206
8	Coated	6000	0.08	1.178	1.22

Fig. 8 shows the microscopic images of the entrance and exit hole for uncoated hybrid composites at various drilling conditions. It can be seen that the quality of the drilled hole was better at inlet compared to the exit of the hole. Mainly delamination type was a form of fiber pull out, uncut fiber, and debonding of the matrix, which can be clearly seen at the exit of a drilled hole. There was crucial improvement found of coating at hybrid composite in terms of drilled hole quality (Fig. 9). The finishing quality was improved at the inlet hole compared to exit. The uncut fiber, fiber pull out, and matrix debonding were the primary reason for higher delamination at the exit for coated hybrid composites, which is clearly shown in Fig. 9.

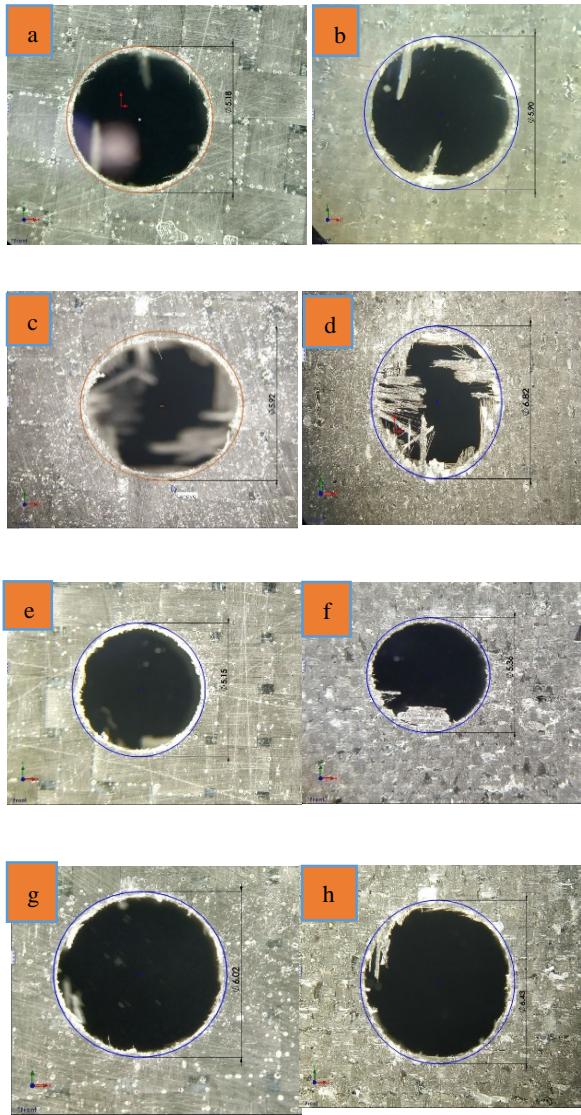


Fig.8: Delamination (a) uncoated S-3000, F-0.02 entry (b) uncoated S-3000, F-0.02 exit (c) uncoated S-3000, F-0.08 entry (d) uncoated S-3000, F-0.08 exit (e) uncoated S-6000, F-0.02 entry (f) uncoated S-6000, F-0.02 exit (g) uncoated S-6000, F-0.08 entry (h) uncoated S-6000, F-0.08 exit

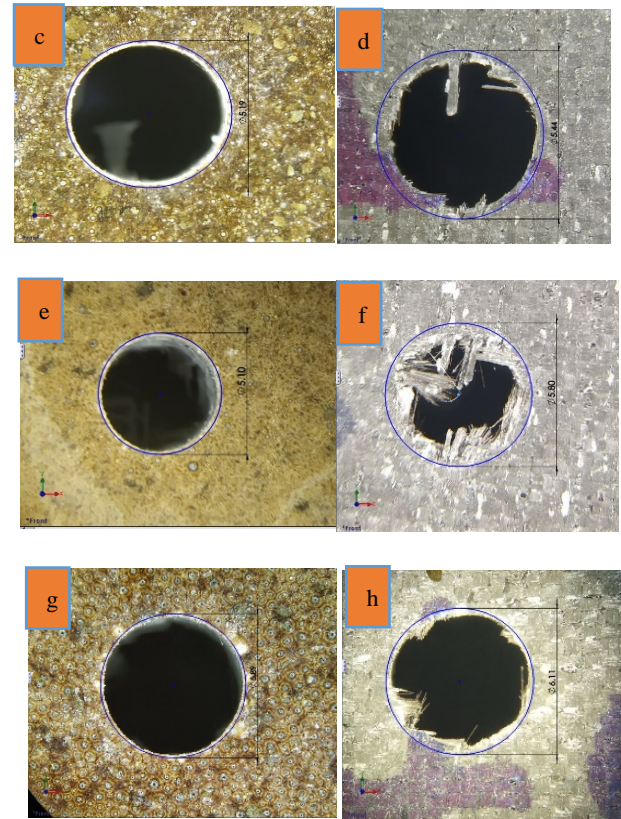
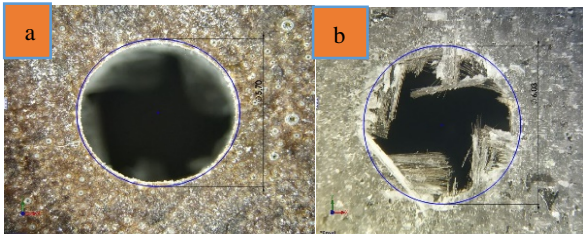


Fig. 9: Delamination (a) coated S-3000, F-0.02 entry (b) coated S-3000, F-0.02 exit (c) coated S-3000, F-0.08 entry (d) coated S-3000, F-0.08 exit (e) coated S-6000, F-0.02 entry (f) coated S-6000, F-0.02 exit (g) coated S-6000, F-0.08 entry (h) coated S-6000, F-0.08 exit

4. Conclusions

The primary objective of this research was the investigation of the effects of heat resistant coating on the drilling performance of carbon/glass fibers reinforced epoxy hybrid composite. The hybrid composites were prepared using VIM. The coating was made of APP, BA, EG, and MEL then applied to the hybrid composites. The physical and mechanical properties of the hybrid composite were tested. Results revealed that VIM is efficient in fabricating the composites with less than 5% void contents, which are a standard requirement for aerospace and automobile industries. FVF was maintained around 46-54% for the hybrid composites. The tensile and flexural strength of the composite part was tested and found as 441.27 MPa and 409 MPa. The elastic modulus for the tensile and flexural test is 23.25 GPa and 20.72 GPa, respectively. There was a significant effect seen on density for coated hybrid composite, which showed approximately 10% reduction compared to the uncoated HFRP composite. For the drilling point of view, the delamination factor was found higher with increasing spindle speed and feed rate. The exit side of the drilled hole showed more delamination than the entry. Coated specimens were better in terms of producing

less delamination than the uncoated specimens. Lowest delamination was observed for S-3000 RPM and F- 0.02 mm/rev at the entry side of the coated HFRP composite. Whilst highest delamination is observed for S- 6000 RPM and F- 0.02 mm/rev at the exit side of uncoated HFRP composite. There was significant improvement was found at the entry of the hole in terms of surface finishing due to coating. However, exit hole quality was not good for both types of hybrid composites. Mainly delamination was found in the form of fiber pull out, uncut fibers, and matrix debonding. Thus, the coating was not able to enhance the quality of the drilled hole for tested hybrid composites. However, the impact of other drilling parameters such as thrust force and drilling temperature can be examined in the future for coated hybrid composites.

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Nomenclatures

FRP- Fiber Reinforced Polymer
 HFRP- Hybrid Fiber Reinforced Polymer
 CFRP- Carbon Fiber Reinforced Polymer Composite
 GFRP- Glass Fiber Reinforced Polymer Composite
 EG- Expandable Graphite
 APP- Ammonium Polyphosphate
 BA- Boric Acid
 MEL- Melamine
 VIM- Vacuum Infusion Molding
 FVF- Fiber Volume Fraction
 n_s = number of plies
 e_s = number of yarns
 ρ = density of fiber
 tex_s = linear density in g/km
 t_c = final composite thickness in mm
 ρ_{ct} = theoretical density of the composite
 ρ_{ce} = experimental density of the composite
 DF = Delamination factor
 S = Spindle speed
 F = Feed rate

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