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마섬유(Jute Fiber) 보강 그래핀 충전 에폭시 나노복합체의 천공 특성에 관한 실험적 연구

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Experimental Investigation of Drilling Characteristics of Jute Fiber Reinforced Graphene Filled Epoxy Nanocomposites

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Abstract: Natural fiber reinforced composite has been the topic of recent studies and is preferred in various fields of engineering for the specific properties and bio-friendly nature. Surface modification of the natural fibers has been recommended to achieve good bonding. The performance of fiber reinforced polymer composites has been enhanced by the addition of nanofillers. The present work investigates the effect of surface modification of fibers by alkali treatment and the surface roughness and drilling forces in jute fiber reinforced nano-phased epoxy composite are also studied by changing the content of graphene. Graphene has enhanced the quality of hole in nanocomposites.

Keywords: jute fibre, graphene, drilling, thrust, torque, surface roughness.

Introduction

Natural fibre reinforced composite materials are being employed in consumer products, automotive and structural industries. Natural fibres such as jute, hemp, agave, bamboo, coir etc. are found to be suitable alternative to synthetic fibres.[1-3] These fibres are bio-degradable, renewable and available in abundance. They require less energy during manufacture and possess high specific strength.[4] Hemi-cellulose, cellulose, pectin, lignin, and water-soluble wax are present in natural fibres.[5] Natural fibres have found to be hydrophilic in nature, which result in poor bonding capability with the matrix. Treatment of these natural fibres by different methods such as alkali treatment, bleaching etc., to modify their surface has been reported to be effective in enhancing bonding.[6]

Nanofillers can help achieve improvement in mechanical, thermal and other properties of a composite. The nanofillers can be of metals, carbon, oxides etc. Carbon-based nanofillers such as carbon nanotubes (CNT), nanofibres and graphene are widely used in composites. Graphene is cheaper and graphene-based composites have better mechanical and thermal properties than CNT.[7] Level of dispersion of nanofillers in matrix highly influences these properties. The better dispersion can be achieved by methods like grafting, use of ultra sonic waves, rollers, *in-situ* polymerisation.[7,8] Sonication assisted by a solvent provides homogenous dispersion and increases the strength and toughness.[9] The addition of multi-walled carbon nanotubes as filler improved the mechanical properties such as tensile strength, modulus, flexural strength, and glass transition temperature.[10]

Composite materials processed in the form of a laminate or frame or channel is drilled to be employed in applications. Many types of researches have been done to analyse the drilling of synthetic fibre reinforced composites. Study of drilling characteristics of natural fibre reinforced composites is still at the early stage. Kishore *et al*. studied the effect of process parameters on thrust, torque and surface finish of holes drilled in sisal fibre reinforced composites.[11] The surface roughness of the drilled hole has drawn much attention as it has significant effect on the life of the material. Nanofiller has improved the

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surface roughness quality of the drilled hole.[12]

Torque should be minimized to avoid damage and ensure the roundness of the hole drilled.[13] Output characteristics like thrust force, torque, surface roughness, cylindricity, circularity, and perpendicularity have been studied to investigate the hole quality after drilling.[14] In this study, the effect of alkali treatment and graphene on quality characteristics such as thrust force, torque, and surface roughness have been investigated and reported.

Experimental

Untreated and alkali treated bidirectional woven jute fibre mat (0° and 90°) was used as reinforcement. Sodium hydroxide was used to modify the surface of the fibre. Epoxy resin (LY556) was modified with the addition of graphene as filler and used as the matrix. The dispersion of filler was achieved using the ultrasonic vibrator with solvent assistance. Graphene was first dispersed in ethanol by sonication for 1 h. To this neat epoxy resin was added and the contents were sonicated for 2 h followed by stirring. Resin and hardener were mixed well in a pot to achieve a homogenous mixture. Alternate layers of resin and fiber were placed inside an aluminium mould sprayed with silicone. The layers were rolled to remove any air bubbles and kept under compression moulding machine at 2.5 MPa for 24 h.[15] Five composite laminates were prepared by hand lay-up technique and machined. They were

UJFRP - Untreated Jute Fibre Reinforced Polymer

TJFRP - Treated Jute Fibre Reinforced Polymer

LJFRP - Low graphene Jute Fibre Reinforced Polymer (0.3 wt%)

MJFRP - Medium graphene Jute Fibre Reinforced Polymer (1.0 wt%)

HJFRP - High graphene Jute Fibre Reinforced Polymer (3.0 wt%).

High speed steel drill of 6 mm diameter with twist geometry and 118° point angle was used for drilling, which was carried on a vertical machining centre under dry conditions. The process parameters and levels are given in Table 1. KISTLER type dynamometer was used to measure thrust (F_z) and torque (M_z) during drilling. The surface roughness (R_a) was measured using Mitutoyo Surface Roughness Tester SJ-301.

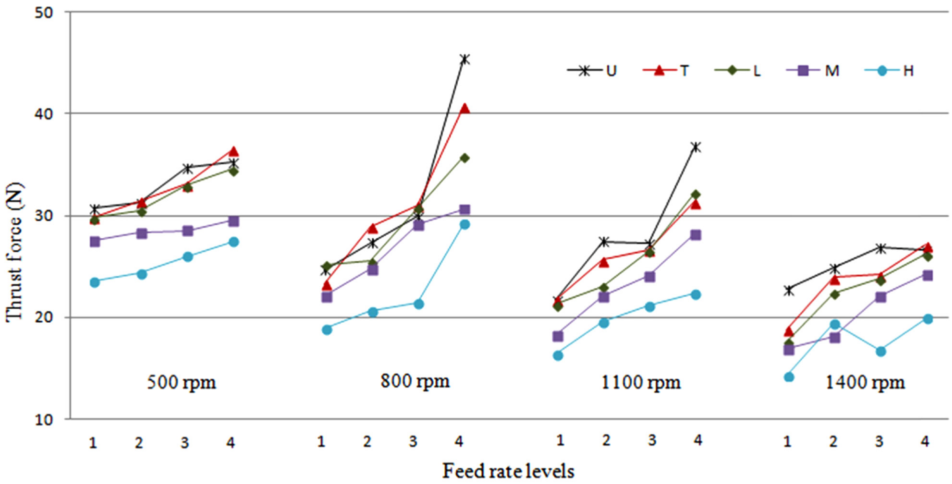
Table 1. Factors and Levels of Drilling Parameters

Symbol	Factors	Level			
		1	2	3	4
A	Speed (rpm)	500	800	1100	1400
B	Feed rate (mm/rev)	0.03	0.06	0.09	0.12

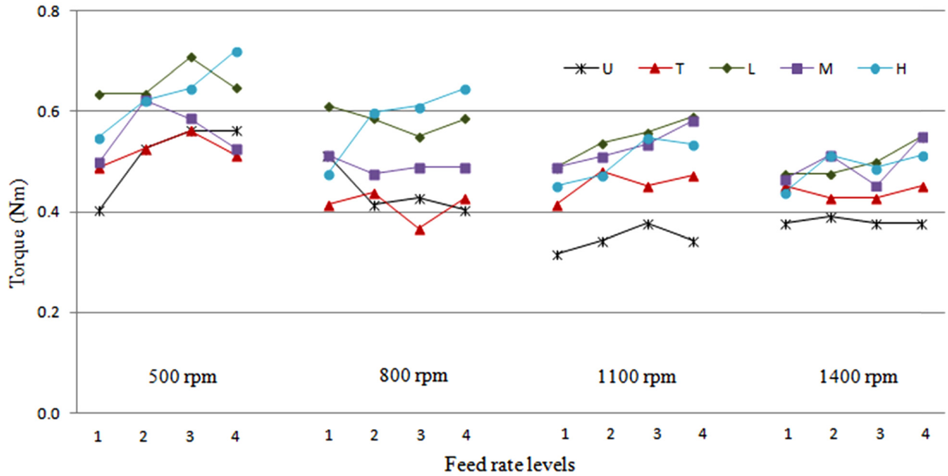
Results and Discussion

Thrust Force and Torque. In the drilling of composites, the induced delamination is mainly associated with the forces developed during drilling. These forces majorly contribute to delamination by both peel-up and push-down mechanism. These forces directly affect the quality of the holes drilled and hence their analysis becomes important. The thrust force and torque recorded during drilling are presented in Figure 1(a) & 1(b). The trend of thrust force was found to be similar at all experiments conducted. From the Figure 1(a), it can be seen that thrust force was higher during drilling UJFRP than TJFRP. A significant variation in thrust force was observed in UJFRP at low spindle speed (800 rpm) and high feed rate (0.12 mm/rev.). The thrust force increased with increase in feed rate. It is known that the thickness of undeformed chip increases with increase in feed rate. This results in higher resistance being offered to the advancing tool and hence higher values of thrust force. It was observed that thrust force decreased with increase in speed in both UJFRP and TJFRP. As speed increases, the amount of heat developed in the drilling zone also increases. But due to the poor thermal conductivity of the natural fibres and chips formed, the heat developed got accumulated in the drilling zone, which results in rise in temperature. It is known that polymer is sensitive to a rise in temperature and this could have caused plastic deformation and thermal softening of the polymer matrix. The variation in thrust force with respect to feed rate was observed to be lesser, in both the composites, at highest speed (1400 pm) considered than at lower speeds (800 and 1100 rpm). The maximum thrust force of 45.4 N and 40.68 N was recorded for U and TJFRP respectively for experiment number 8 corresponding to the speed of 800 rpm and feed rate of 0.12 mm/rev.

The torque developed during drilling of UJFRP and TJFRP can be compared from trend shown in Figure 1(b). It can be seen that at the lowest speed considered the variation in torque developed by both the neat epoxy composites were close to each other. The torque decreased with increase in spindle speed, which can be due to the heat accumulated in the drilling zone. It is known that amount of heat generated increases with increase in speed. As the polymer matrix is sensitive to rise in temperature, this causes plastic deformation of the matrix. The



(a)



(b)

Figure 1. (a) Thrust force (N); (b) torque (Nm) of composites.

accumulated heat also softens the matrix, which minimizes the resistance offered by the matrix to the rotating tool. The softened matrix can also act as a lubricant at the interface of tool and material thereby reducing the friction at the drilling zone. The effect of spindle speed was evident at higher speeds considered, where the difference in torque values of UJFRP and TJFRP was significantly higher. The difference in torque with respect to feed rates at these speeds showed negligible variation indicating the extent of thermal softening of matrix.

Thrust force was found to increase with an increase in feed rate and decrease with increase in speed in all the nanocomposites laminates investigated. Thrust force decreased with increase in wt% of nanofiller. This is indicative of the fact that increase in graphene has enhanced the ease of machining of nanocomposites. The increase in wt% of filler enhances the stiffness of composites, which resulted in lower thrust force recorded for all nanocomposites. From these values, it can be concluded that the drilling has been smoother and steadier in nanocomposites than neat epoxy composites. Paul *et al.* reported a similar trend in thrust force while drilling carbon nanofiber filled epoxy composites.[16] The reduction in thrust force value in nanocomposites indicates that the quality of hole produced has been better than in neat epoxy composites. The torque generated during drilling of nanocomposites was higher than that of neat epoxy composites at all the speeds considered. This is indicative of the fact that the nanocomposites were less affected by the heat developed during drilling. This could have been possible due to a significant contribution by graphene in enhancing the thermal stability of the nanocomposite laminates. Graphene has been reported to possess good thermal

Table 2. Glass Transition Temperature of Composites Observed During DMA

Composites	UJFRP	TJFRP	LJFRP	MJFRP	HJFRP
Glass transition temperature (°C)	98.6	99.2	101.6	103.2	103.7

conductivity.[17] As nanofiller it has been able to efficiently conduct the heat away from the drilling zone thereby reducing the effect of heat accumulation in the drilling zone. The torque showed a decrease with increase in spindle speed, which could be due to the solid lubricant property of graphene present in nanocomposites.

The highest thrust force recorded in UJFRP was 45.4 N and in HJFRP was 29.19 N, both at speed of 800 rpm and feed rate of 0.12 mm/rev. The addition of graphene has reduced the thrust force by 35.7 % indicating the improvement in the hole quality. The highest torque recorded in UJFRP was 0.562 Nm and HJFRP was 0.720 Nm, both at lowest speed of 500 rpm and feed rate of 0.12 mm/rev., showing an increase by 28.1%. Dynamic mechanical analysis (DMA) was conducted according to ASTM D5418 to understand this behaviour of composites. The glass transition temperature was determined from the tan δ plot and the same is presented in Table 2. An increase in the glass transition temperature indicates the increase in thermal stability. This increase shall be interpreted as due to the enhanced bonding due to treatment and presence of graphene which resulted in a steadier machining.

Surface Roughness. The surface roughness (R_a) was measured on the hole wall at diametrically opposite points and the average value has been used for discussions. The corresponding graphs are given in Figure 2. On comparing the R_a values of UJFRP and TJFRP, it can be seen that UJFRP showed more roughness on the drilled hole wall than TJFRP. This could be explained as majorly due to the heat developed due to drilling and strength of the composites to resist the tool. Both U and TJFRP have been severely affected due to the heat developed. The neat epoxy matrix in both the composites had softened, enabling the tool to push it along the direction of rotation during drilling. This caused smearing of polymer and redeposition of the same at different locations on the wall of the hole as shown in Figure 3(a) & 3(b).

With increased strength and thermal stability, TJFRP must have resisted the tool more than UJFRP and stood more stable during drilling. The high roughness in UJFRP indicates that after drilling, there might have been uneven cooling of the hole wall leading to more defects on it than on TJFRP. Matrix debonding, fibre protrusion and bending could be seen on the surface of hole drilled in UJFRP. Hence the wall of the hole did not show uniformity after drilling. Surface roughness of both the composites have shown increase with an increase in feed rate and showed the slight increase with speed. At the highest speed considered (1400 rpm), the increase in surface roughness with respect to feed rate was small when compared with other speeds.

From Figure 2, it can be observed that the composites made with graphene filled epoxy have produced smoother holes when compared with neat epoxy composites. This means that these composites have been less affected due to the heat developed during drilling. Graphene possesses good thermal conductivity. It could be because of this property that the heat

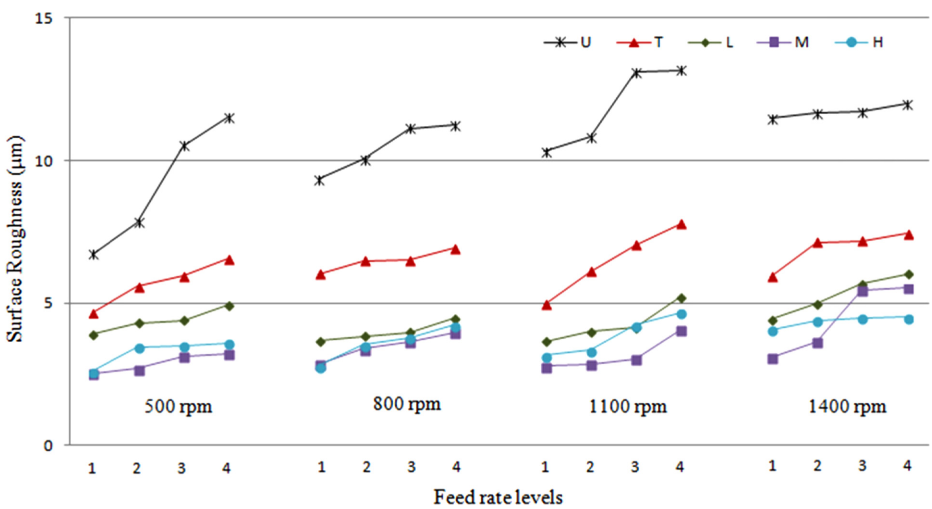
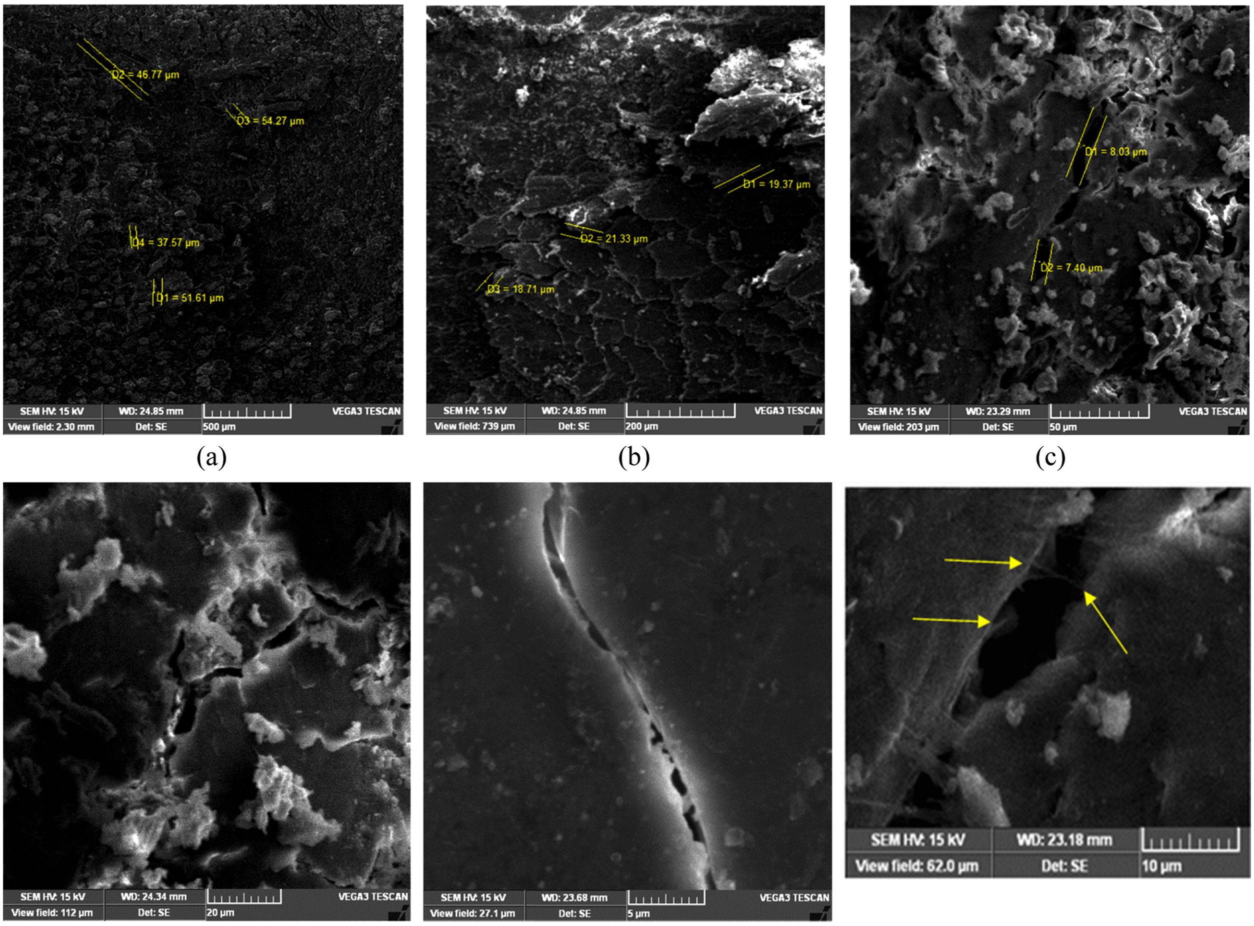


Figure 2. Surface roughness plot of the nanocomposites.



(a) (b) (c)

(d) (e) (f)

Figure 3. Morphology of drilled holes of (a) UJFRP; (b) TJFRP; (c) LJFRP; (d) MJFRP; (e) HJFRP. (f) Mechanism of crack bridging.

from the drilling zone would have been effectively conducted away from the hole resulting in a reduction of heat build-up. This could have lessened the extent of matrix softening, offering a steadier response to the advancing tool. The graphene filled nanocomposites have exhibited better thermal stability than neat epoxy composites. The increase in torque generated by nanocomposites, reported earlier, validates this discussion.

LJFRP produced roughly surfaced holes than MJFRP and HJFRP. But surface roughness of LJFRP was lower than TJFRP, indicating the role of graphene in producing quality holes even at low loading. It can be noted from Figure 3 that the surface roughness characteristic was better in graphene filled epoxy composites than neat epoxy composites. This indicates the effect of graphene loading on surface roughness. Ponnuvel *et al*.[12] also reported improvement in surface roughness quality of drilled hole with carbon nanotubes as filler in glass fibre reinforced epoxy laminate. Of the nanocomposites, MJFRP has produced smoother holes in most of the experiments conducted. At the highest speed feed combination (1400 rpm and 0.12 mm/rev.), HJFRP produced better quality hole than MJFRP. The highest surface roughness measured in UJFRP was 13.17 micron and HJFRP was 4.65 micron, both at a speed of 1100 rpm and feed rate of 0.12 mm/rev. Surface roughness has improved by 64.7% due to the addition of graphene.

To investigate the quality of the hole achieved and damage mechanisms, the drilled hole surface was analyzed using SEM and presented in Figure 3(a-e) and 3(f). These images correspond to the hole wall with highest measured surface roughness. Figure 3(a) & 3(b) corresponds to the surface of hole drilled in U and TJFRP respectively. On analyzing the morphology of the drilled hole surface, it can be concluded that UJFRP, which recorded higher thrust force during drilling, has comparatively produced the least smooth surface. Bending of fibers, smearing of fibers, fiber pull out, micro pits and redeposition of the matrix were observed on the walls of the hole drilled in UJFRP (Figure 3(a)). Kishore *et al*. reported similar mechanisms of damage during drilling sisal fiber reinforced epoxy composite laminates.[10] It can be seen that the microcracks greater than 50 micron were present in Figure 3(a), indicating the debonding of the matrix and fiber. Protruded and bent fibers were also seen. From Figure 3(b), it can be observed that the extent of damage has been reduced, which shows the effect of alkali treatment. The enhancement in bonding has reduced the crack width in TJFRP. Fibre pull out and bending were also observed to be minimal. However, matrix cracking and debonding was predominant with cracks greater than 20 micron were observed. Smearing and redeposition of matrix could also be seen.

Figures 3(c~e) correspond to the surface of hole drilled in L, M, and HJFRP. From Figure 3(c) the details of the microcracks formed on the wall of hole drilled in LJFRP could be observed. Some matrix smearing and redeposition were observed in it. Fiber protrusion and bending mechanisms of damage were not observed in nanocomposites. The cracks observed were less than 10 microns in LJFRP. However, matrix debonding and redeposition were present as surface imperfections, leading to less surface finish. In MJFRP the amount of cracks were found to have further reduced. The surface also showed comparatively little imperfections than in LJFRP. On comparing Figures 3(c) & 3(d) (L and MJFRP respectively), it can be observed that the surface of the drilled hole is smoother in MJFRP than LJFRP. Lesser matrix cracking and protrusions were observed. The extent of the damage was observed to be lesser than that in neat epoxy composites. Figure 3(e) gives the crack and adjacent surface of a hole drilled in HJFRP. It can be seen that the size of the gap or crack is less than 5 micron, which resulted in a very good surface finish of the hole. The cracks could have formed due to possible agglomerates of graphene that acted as a stress concentrator. At higher graphene microcracks of smaller dimensions were observed. Graphene particles not only have effectively conducted the heat away from the drilling zone but also have offered smooth surface to the drilled holes by reducing the crack growth. This was due to the effective bridging of cracks formed during drilling, as shown in Figure 5(e) and 5(f). By the pinning action, graphene has taken up the major drilling forces and prevented further damage to the surface by suppressing the crack growth. Graphene particles may have taken the major portion of drilling forces thereby preventing the hole wall from getting affected. From Figure 3(f), it could be seen that graphene particles effectively bridged the crack. Few graphene particles were also observed to have broken or failed. This indicates the role of graphene in improving the quality of holes drilled. Bodo Fiedler reported similar behaviour by carbon nanotubes while studying the role of nanofiller in enhancing the properties of nanocomposites.[18] Also on analyzing the areas around the crack on HJFRP in Figure 5(e), it can be concluded that the surface imperfections like matrix smearing and deposition have been minimized effectively. This has been achieved due to the addition of graphene, which has effectively controlled the damage mechanisms observed in neat epoxy composites. The role of graphene in enhancing the quality of hole has thus been established.

Conclusions

Graphene filled jute fiber reinforced epoxy composites were prepared and drilled. Drilling characteristics such as surface roughness, thrust force, and torque were studied. The effect of fiber surface modification and graphene addition were reported.

· The higher value of thrust force recorded during drilling UJFRP indicates the low hole quality in it, which also resulted in higher surface roughness. Surface modification and graphene addition produced a lower thrust force. UJFRP produced the lowest torque due to thermal softening of the matrix during drilling.

· Surface roughness increased with increase in feed rate. Alkali treatment of fiber and graphene addition has improved the surface roughness characteristic. Graphene has played an effective role in improving the surface roughness of the nanocomposites. An improvement of 64.7% was observed due to the addition of graphene.

· Morphological study of the drilled holes revealed the matrix cracking, fibre pullout and smearing of the polymer matrix as the mechanisms of damage in neat epoxy composites. The role of graphene in effectively controlling the damage was also observed.

· Graphene filled composites have shown better drilling characteristics than the neat epoxy composites.

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