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A Review on thrust force and torque in drilling of glass fiber reinforced polymer composite

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Abstract: The Composites are widely used as a material for assembling goods and components due to their superior properties, with machining of these materials is to be expected. Although most of the polymer matrix composites are manufactured to a near-net shape during primary processing, a certain degree of complexity in product design necessitates machining (secondary processing) to ascertain the structural integrity of final product for facilitating the assembly operations. Thus, many researchers in past decades or more have been attempted to study machining of composite materials for identifying the effect of various process parameters on quality of machining features. In this paper an attempt has been made to review the work of some researchers who had conducted the experimental studies on drilling of polymer matrix composite material, namely drilling on glass fibre reinforced plastics. Aspects such as tool material, geometry and process parameters like spindle speed, feed rate and their influence on the multi responses namely thrust force, torque and delamination was investigated.
Keywords: GFRP, Drilling, thrust force, torque, HSS, delamination.

1. Introduction

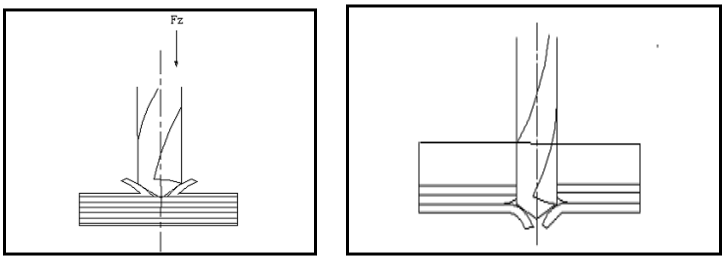
Glass fiber reinforced polymer(GFRP) have been widely used in manufacturing aircraft and spacecraft structural parts due to its suitable mechanical and physical properties such as high specific strength and high specific stiffness. As structural materials, joining composite laminates with other metallic material structure is inevitable, when bolt joining efficiency and quality depends critically on quality of machined holes. Several undesirable damages such as delamination and fiber push out are induced during drilling, of holes which reduces fatigue strength and degrades the long-term performance of composite material. Although composites are produced with near-net shape and machining is needed to fulfill the commercial requirements related to tolerances of assembling needs. Among available machining process, drilling is said to be most indispensable method used for fabrication of products with composite materials. The performance of these products purely dependent on surface quality and dimensional accuracy of the drilled hole. The quality of the hole drilled is influenced by the cutting parameters such as tool material and geometry[1,2]. Mainly conclude the critical thrust force models of various drill bits for delamination free drilling of composite material developed themselves as well as several non- traditional machining processes for composite material, Reducing thrust force depends on the geometry and materials of the tool, work piece materials[3].To evaluate the drilling of GFRP composite materials on assembling component and reveals that the increase of cutting speed with reducing the thrust force[4]. The fuzzy logic modeling technique for the prediction of thrust force in drilling of GFRP composites reports that the feed rate is the main factor which influences the thrust force in drilling of GFRP composites. Spindle speed have impact on thrust force, the interaction between spindle speed and feed rate proves have moderate work effect in the drilling of composite materials[5].

The behavior of the cemented and tungsten-carbide drilling with distinct geometrics (stub length and brad and spur) when machining a glass fiber reinforced plastics. The results reveals that the thrust force increased with feed rate, however lower values of thrust force were recorded when using the Brad and spur drill, additionally the effect of cutting speed on both thrust force and torque was negligible within the cutting range speed[6]. Evaluate that the thrust force for the composites varied from lower to higher. The minimum thrust force was achieved when the parameters were set as follows, tool point angle at 130º, with spindle speed at rpm that exhibits a great on thrust force, followed by the drill point angle and feed rate factors. The low feed rates level provides lower thrust forces, leading to less vibration during the cutting process, the increase of chatters consequently affect the geometry of the hole, the results reveals that increase of spindle speed probationary increases the cutting temperature, mainly when drilling the unreinforced material(PA6)[7]. The effect of process parameters such as spindle speed, feed rate, drill diameter, point angle and material thickness on thrust force and torque that are generated during drilling of GFRP composites material using solid carbide drill bit. The impact of various responses like thrust force, torque, delamination during drilling in numerous composite materials are analyzed,experimented using full factorial design of experiment (DOE) that has been adopted and the results indicates the spindle speed is the main contributing factor for variation in torque. The integrating of Taguchi DOE method and response surface methodology (RSM) can be very effective in process parameter optimization. As combining of the results of the two methods can not only optimize the parameters, but also indicate the values of response, through which process parameter selection can be refined and the results are optimally justified. The results are based on the subjective range of values for speed, feed, material thickness, drill diameter and drill point angle and hence the inference drawn cannot be generalized[8]. To evaluate the surface roughness in the drilling of composite material, result indicate that the feed rate and spindle speed contribute the most to the surface roughness, Delamination associated in drilling is one of the imperative concerns which affects the hole surface and strength of the joined laminate. The delamination in particular on drilling of composite materials is mainly due to the thrust force developed during drilling. In the drilling of composite materials, many factors affect drilling operations. The most empirical parameters are the thrust force and surface roughness that impacts the cutting parameters, namely spindle speed, and feed rate[9]. Among all drilling operations, most commonly applied was twist drills for generating holes[10].

2. Machining of GFRP

Machining of GFRP material is difficult due to their material discontinuity, homogeneity, and anisotropic. In which the various damage mechanisms such as fiber pullout, fiber fragmentation, delamination, matrix burning, matrix cracking and surface damage that lead to poor cut surface quality. Machining of GFRP composites by traditional and non-traditional methods done by drilling, turning, milling, abrasive water jet and laser machining. The experimental study on the drilling of GFRP composites to predict the thrust force using fuzzy logic, a fuzzy rule based model developed and compared with RSM, the machining experimentation was carried out using L27 orthogonal array(OA). The process parameters considered during experimentation were spindle speed, feed rate, and drill diameter. The results revealed that feed rate and drill diameter are the factors that influence the thrust force in impact drilling of GFRP composites. Spindle speed only shows a very limited effect on thrust force[11]. The Taguchi method with fuzzy logic to optimize machining parameters in turning GFRP composites using a carbide tool. The process parameters are fiber orientation, cutting speed, feed rate, depth of cut and machining time that were optimized with consideration of multiple performance characteristics of material removal rate, tool wear, and surface roughness. Results showed that fiber orientation and machining time were the significant parameters in the machining of GFRP composites[12]. It is conclude the thrust force is a major factor responsible for delamination and it was mainly depends on tool geometry and feed rate, trepanning tools, which were used in this paper that were found to give reduced thrust force while making holes on thin laminated composites. In this working the peculiarities of trepanning over the drilling of unidirectional composites were emphasized. The models for prediction of critical thrust and critical feed rate at the onset of delamination during trepanning of unidirectional composites based on fracture mechanics and plate theory that were also covered. Mathematical models correlating thrust and torque with tool diameter and feed rate were developed through statistically designed experiments. It was observed that sub-laminate thickness is the most decisive parameter from the viewpoint of critical feed rates[13]. The drilling of polymeric composites which aimed to establish a technology that would ensure minimum defects and longer tool life. Specifically, conceived a new drilling type that imparts a low-frequency, high amplitude vibration to the workpiece. Using high speed steel (HSS) drill, a series of vibratory drilling and conventional drilling experiments were conducted on GFRP, composites to assess thrust force, flank wear, and delamination factor. In addition, the process status during vibratory drilling was also assessed by monitoring acoustic emission from the work piece. From the drilling experiments, it was found transparently that vibratory drilling proves to be a promising machining technique that uses the regeneration effect to produce axial chatter, facilitating chip breaking and reduction thrust force[14]. Deals with the machining of GFRP fabricated in their laboratory using E-glass fiber with unsaturated polyester resin, machining studies were carried out using two different alumina cutting tools Ti (C, N) mixed alumina cutting tool and SiC whisker reinforced alumina cutting tool. The machining process was performed at different cutting speeds at a constant feed rate and depth of cut. The performance of the alumina cutting tools was evaluated by measuring the flank wear and surface roughness of the machined GFRP composite material. The SiC whisker reinforced alumina cutting tool produced a better surface finish than Ti (C, N) mixed alumina cutting tool. The results reveals performance of SiC whisker reinforced alumina cutting tool is better than that of the Ti (C, N) mixed alumina cutting tool on machining of GFRP composite[15]. The machinability in turning processes of GFRP manufactured by hand lay-up processing. Planning of the experiment was performed on controlled machining with cutting parameters prefixed in work piece. A statistical technique, namely orthogonal arrays and analysis of variance (ANOVA), has been employed to know the influence of cutting parameters on specific cutting pressure and surface roughness. Polycrystalline diamond tool (PCD) presents smaller values of surface roughness and specific cutting pressure than a cemented carbide tool (K15), the feed rate is the cutting parameter that has the highest physical as well statistical influence of surface roughness (Ra) and specific cutting pressure (KS). PCD provides a better machinability index (MI) in comparison to the cemented carbide tool (K15). Therefore, the PCD cutting tool gives the overall best performance than K15[16]. To study the chip formation, and assesses the machinability of two composite materials (Thermoset–based and Thermoplastics-based) and concluded that from cutting chips the former presents a large amount of deformation in chip formation, while the latter tends to fracture. It is also noticed that the carbon/ABS is superior to carbon/epoxy for surface quality and hole edges[17]. The machining of composite materials, more specifically on drilling of glass and carbon fiber reinforced plastics, namely tool materials and geometry, machining parameters and their influence on thrust force and torque are also investigated[18]. Machining induced damage predicted by the model for both materials, While damage extended widely ahead the interface and beneath the tool tip in the case of GFRP, damage was located in a much smaller zone in the case CFRP[19].

2.1 Drilling of GFRP:



(a) (b)

Fig.1. Drilling induced damage, (a) Peel-up, (b) Push-down delamination[26].

Drilling is one of the most imperative, frequently practiced and inevitable machining operations for components used in GFRP composite structures, also it is an important process for making and assembling composites madeup of GFRP. Various processes like conventional drilling, vibration assisted drilling and ultrasonic assisted drilling have been attempted during drilling of GFRP. In order to maintain the integrity of material and obtain the necessary accuracy in drilling of GFRP. The drilling of composite materials with various drill bits, presents a comprehensive analysis of delamination by using various drill types, such as candle stick drill, core drill, and step drill. In their analysis the delamination is predicted and compared with a twist drill[2]. The influence of cutting parameters and above mentioned four drills with distinct geometry and composition on delamination and thrust force[20]. The effect of cutting parameters on drilling carbon/epoxy and carbon/PEEK concluded that the drilling of carbon composites is dependent on the effect characteristics of the matrix with helical PCD drill geometry gives the best overall performance. In addition the problems of tool wear, which is very difficult to achieve the quality of surface needed accurate assembly of components in mechanical structure[21]. The drilling on CFRP composite at high speed and concluded that an increase of the cutting velocity leads a increasing of the drill wear. In this way the effect of increasing the wear of drill causes a rising of thrust force[22]. Drilling parameters with multiple performance characteristics based on the Taguchi method with grey relational analysis(GRA) and orthogonal array with L16, 4-level has been used for the experimentation with feed rate was influential parameter than spindle speed[23]. Drilling of composite materials is significantly affected by damage tendency of these materials under action of cutting forces(Thrust force and torque). The thrust force of step core drill with drilling parameters(Diameter ratio, feed rate and spindle speed) in drilling CFRP laminates, the results Indicated that diameter ratio and feed rate had the most significant influence on the overall performance of step-core drills and step-core saw drill produces the highest drilling thrust force[25]. The influence of machining parameter on the delamination damage on GFRP during drilling. In conventional drilling feed rate, tool material, and cutting speed are the most influential factor on the delamination hence machining at higher speed, harder tool material and lower feed rate gives lesser delamination on machining of GFRP. The use of high speed machining is suitable for drilling GFRP that ensures low damage levels and it is also technically capable of improving productivity and lowering production costs. Vibration assisted drilling and ultrasonic assisted drilling have low thrust force and lower delamination compared to conventional drilling. Which indicate that both vibration assisted drilling and ultrasonic assisted drilling are more appropriate for drilling in GFRP[26]. The influence of the cutting parameters, such as cutting speed, feed rate and point angle an delamination produced when drilling a GFRP composite. The damage generated associated with the drilling of GFRP composites were observed, both at the entrance and the exit during the drilling. The optimum drilling parameter combination was obtained by using the analysis of signal to noise ratio(S/N). The conclusion indicated feed rate and cutting speed were the most influential factor on the delamination. The best results of the delamination were obtained at lower cutting speeds and feed rates[27]. In the present era conventional drilling is used most commonly, but grinding, drilling, vibration assisted twist drilling and high speed drilling provide better quality of drilling holes as well as high efficiency. Considerable efforts have been focused on better understanding of the phenomena induced by drilling. The most applications of special drill bits, support plate, pre-drilled pilot hole, vibration- assisted twist drilling, and high speed drilling provide significant quality improvement of drilling holes. The feed rate is to make the largest contribution to delamination, thrust force, and tool wear during drilling of composite laminates. The use of low feed rate and high cutting speed favor the minimum drilling- induced delamination and extend the tool life[10].

3. Tool material and geometry

Tool geometry proves to be a empirical factor that is to be considered in drilling of glass fiber reinforced plastics, particularly when the quality of the machined hole is critical. The effect of the machining parameters proven to be an another aspect to be considered. Fig.2 illustrate the reported cutting parameters (cutting speed and feed rate) typically employed when performing drilling of polymeric composites using HSS and tungsten carbide (WC) drills. It can be seen that cutting speeds varies from 20 to 60m/min are usually employed, whereas feed rate values lower than 0.3mm/rev are frequently used, Cutting is not a limiting factor when drilling of polymeric composite was performed. Fig. 2 shows that tungsten carbide tools are preferred when drilling at higher cutting speeds, in contrast to metals, with higher feed rates.The influence of using a trepanning tool on thrust force and torque drilling of GFRP, The investigation showed that the performance of the trepanning tool was superior to that of conventional twist drill, that resulting in 50 and 10% of thrust force and torque respectively each other[13,18].

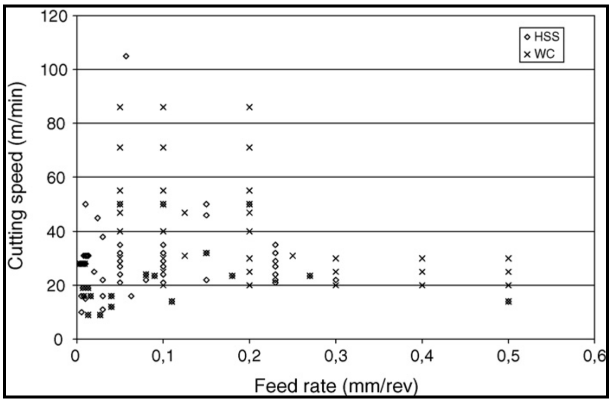


Fig.2. Cutting speeds and feed rates typically employed when drilling polymeric Composites with high speed steel (HSS) and tungsten carbide (WC) drills.

In order to investigate the effect of the drill diameter on the thrust force and torque, the conventional high speed twist drills with diameters of 8, 9,10,11,12, and 13mm are employed for machining glass fiber reinforced plastic using a constant rotational speed of 875 RPM and feed rates of 0.1-0.23 and 0.5mm/rev. The results obtained indicated that thrust force and torque increases with drill diameter and feed rate, due to the increase in shear area, increase in the cutting speed also resulted in higher thrust force and torque, however not to the same extent as when feed rate is elevated[28]. The effect of delamination during drilling of composite material is proven to be a critical problem and step by step procedure to capture complex drilling dynamics via mathematical model for a glass fiber reinforced plastic composite material while performing drill at a constant thrust force and feed rate identified using a toolbox of Mat lab. The effect of tool material and tool geometry has been investigated by different researchers include drilling with HSS and tungsten carbide (K10&K20) as tool materials. A third order model representing the drilling of GFRP captures the dynamics in a better way as compared to lower order model visualizing the thrust force, feed rate behavior and control of thrust force is concerned as a third order model during drilling of polymer matrix composites between thrust force and feed rates gives good match between experimental and simulated thrust force response[29]. Investigate the effect of machining parameters on delamination factor during drilling by using 3-D surface plots. They have concluded that the feed rate and drill diameters are the factor which influence the delamination during drilling of GFRP composites. Spindle speed shows only on delamination in the drilling of GFRP composite. Now most of the studies on the cutting of GFRP have been concentrated on the mechanism of tool wear and surface roughness[30].

4. Thrust force and torque

The relationship between the machining parameters namely thrust force, torque and delamination during drilling GFRP composite materials, where numerous of investigations are done due to fact that they directly impact the quality of machined hole. Investigates the influence of drilling parameters namely cutting velocity ratio, feed rate and inner drill type are the most imperative variables among the five control factors that influence the thrust force[31]. The effect of point geometry on thrust and delamination, drill point has considerable influence on thrust, delamination and point geometry produce the least delamination damage. Thrust indicates a critical feed rate of 0.01 mm/rev and above which there is a rapid increase in thrust[32]. The behavior of two cemented tungsten carbide drills with distinct geometric (Stub length and Brad & Spur) when machining a glass fiber reinforced plastics. The results indicated that the thrust force increased with feed rate, however, lower values were recorded using the Brad & Spur drill. Additionally, the effect of cutting speed on both thrust force and torque was negligible within the cutting range test to be evaluated[25]. Similarly, glass fiber reinforced plastic had been tested using five cutting speeds ranging from 5.5 to 46.5m/min and three feed rates (0.05-0.1 and 0.23mm/rev). The researchers found that there is a delay between the response for thrust force and torque, after which the former reaches a maximum value.when compared to other from this point the thrust force value is reduced and the torque increases due to the fact that the last fibers are not shared, but entangled in the drill. They noticed that the effect of cutting speed on thrust force, whereas torque increases with cutting speed. Surface roughness were not significantly affected by both cutting speed and feed rate[30]. The machining of GFRP composites produced using distinct matrix materials (epoxy and polyester resins) and reinforcing shapes are chopped, cross winding, continuous winding and woven. The investigator reported that in contrast to other reinforcing shapes, when drilling the composite a gradual decrease in thrust force was observed at the drill exit, resulting in a surface without delamination. When machining the woven composite with different matrix materials, the matrix had a negligible effect on thrust force. However, torque was higher when drilling the polyester composite. Increasing cutting speed resulted in lower thrust force and torque due to the higher temperatures produced by the increases in heat generation associated with the low coefficient of thermal conduction together with the low transition temperature of plastics[33].

Figs. 3 and 4 show the influence of feed rate on the specific cutting coefficients related to the thrust force (K_f) and

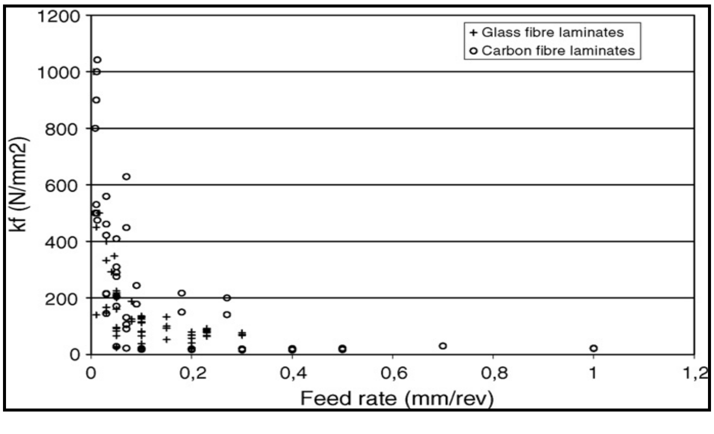


Fig.3. Influence of feed rate on the specific cutting coefficient (K_f) associated to the thrust force.

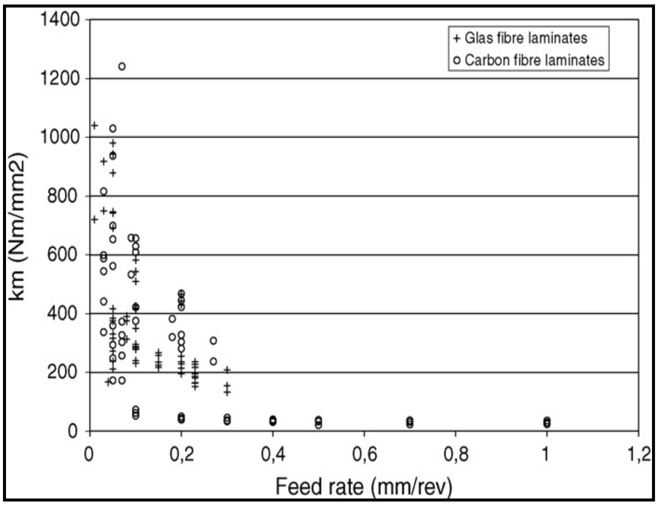


Fig.4. Influence of feed rate on the specific cutting coefficient(K_m) associated to torque. .

torque (k_m), respectively, calculated from Eqs (1) and (2)[18,24].

$$k_f = \frac{2F_f}{fd} \quad (1)$$

$$k_m = \frac{8B}{fd^2} \quad (2)$$

Where F_f is the thrust force (N), if the feed rate (mm/rev), d the drill diameter (mm) and B is the torque (Nmm). Observing from Fig. 3 it can be noticed that as feed rate increases, the K_f values decreases substantially owing to the fact that, at higher feed rates, number of fibers to be shear will be reduced. Differences in K_f values obtained for the same feed rate are due to differences in drill geometry, reinforcing material, volume fraction, fiber orientation and laminate thickness.

Fig.4 presents the influence of feed rate on the k_m for glass and carbon fiber reinforced plastics. Similarly to Fig.3, it can be seen that for the same reasons, the km values decrease drastically as feed rate is elevated[18].

5. Conclusion

Some of the conclusion have been revealed from the above study,

(i) The influence of the machining parameters such as spindle speed, and feed rate over the thrust force and surface roughness have been discussed. (ii) Delamination of GFRP composite material is mainly determined by feed rate and drill tool diameter. (iii) All these parameters have major contribution over the quality of the hole, the cutting speed is inversely proportional to the thrust force and torque. This paper have provided a literature review on the drilling of polymer matrix composite machining over the last 10-15 years with a specific focus on the process of conventional drilling. GFRP widely used for aeronautical, manufacturing aircraft and spacecraft structural applications requires an inevitable secondary processing of GFRP machining. As per the work material is concerned, glass fiber reinforced polymer, composites have been equally investigated with conventional high speed steel twist drill which are used in equal to cemented, and tungsten carbide drills. However it seems to be an wide scope availability agreement among the researches on the necessity of developing tools with special geometry to achieve impetus performance with consequent concomitant.

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