Measurement 114 (2018) 109–121

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Drilling of pultruded and liquid composite moulded glass/epoxy thick composites: Experimental and statistical investigation

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A R T I C L E I N F O

Keywords:
Drilling
Pultrusion
Liquid composite molding
Special geometry
Ultrasonic C-scan
Self-excited vibration

A B S T R A C T

Composites are often one of the foremost difficult-to-machine materials. Out of many defects due to hole making process, the prime concern is delamination. This investigation aims to reveal the best drill geometry and corresponding optimal process parameter levels for making defect tolerance holes in thick pultruded and liquid composite moulded (LCM) composites. The novelty in this work are carrying out drilling operations with special geometry drills in thick composites, considering the entire depth of hole for assessing the damage and studying the influence of self-excited vibration of the work material. Minimization of drilling forces, drilling-induced damage and tri-axial self-excited vibration of the work material have been executed simultaneously to reveal the optimum process parameter levels for drilling the tested composite materials with each of the selected drill tools. It has been found that three flute and four-facet WC twist drills are more suitable for pultruded and LCM composites, respectively.

1. Introduction

Glass fibre-reinforced plastic (GFRP) composites are widely utilized materials, since its introduction in the early 1940s, due to its range of benefits in terms of high strength-to-weight ratio, high fracture toughness, high stiffness-to-weight ratio, low density, better chemical and corrosion resistance, excellent impact characteristics, greater mechanical properties, low price and specifically more flexibility in design. Zarif Karimi et al. [1] stated that GFRPs find a gorgeous alternative to metals and alloys because of the above attributes. Conventional drilling is the main operation and most often used process [2] in making holes for fasteners, which occupy about 40% [3] of the total manufacturing operations. Komanduri [4] states that high speed steel (HSS) tools with low cutting speeds can be used for machining GFRPs, so that there won't be overheat of tool and rapid wear.

In drilling composites except the value and productivity, that are commonly taken as criteria for optimizing any general machining process, the quality of drilled holes i.e., structural integrity of the holes made should be the first criterion, that was reported by Arul et al. [5]. Shew & Kwong [6] stated that for making good quality holes with high dimensional accuracy, surface integrity and to possess extended tool life and higher productivity, it is necessary to go looking at the optimum cutting tool and drilling parameter levels, which are influenced by drilling forces and drilling-induced damage. The fabrication industries that assemble the components made of composites will realize the importance of possible reduction/elimination of drilling-induced damage [7,8].

The review of closely related literature is presented here briefly. Durao et al. [9] found that for laminate drilling, low feed (0.02 mm/rev) is not acceptable as it results in matrix degradation due to thermal softening and also less productivity which is a major concern in industries seeking high productivity as their first priority. Further they pointed out that low feed which reduces the axial thrust force and delamination is of no use. They found that for higher feed (0.12 mm/rev) twist drill with 120° point angle is the most adequate tool followed by step drill. Sevkat & Brahimi [10] ascertained that the method of manufacturing of composites decides their load carrying capacity. Based on the above, they stated that vacuum assisted resin transfer moulding method is superior than hand lay-up method and this is due to inevitable void contents within the hand lay-up specimens. They also found that as the diameter of the pinhole (d) and edge distance to pin hole diameter ratio (e/d) increase, the maximum bearing strength and tensile load will increase.

Faraz et al. [11] expressed that conventional twist drill is not

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http://dx.doi.org/10.1016/j.measurement.2017.09.026
Received 6 August 2017; Accepted 14 September 2017
Available online 18 September 2017
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suitable for drilling GFRP composite material as it produced higher magnitudes of drilling force and push-out delamination. They found no direct relation between the mechanical loads (drilling thrust force and torque) and damage at the hole exit for the chosen specialized drills. They found that the chosen specialized tools were far better than their conventional counterpart because it produced a comparatively lesser drilling forces and push-out delamination. Khashaba et al. [12] found that at high feeds (0.45 mm/rev), regardless of the thrust force value, the drill point acts as a punch piercing the composite laminate with approximately same size of delamination at the hole exit. They found that drill wear affects the thrust force significantly, solely at high–speed and feed (2015 RPM and 0.45 mm/rev), that successively will increase peel-up and push-out delaminations. Durao et al. [13] compared the hole delamination factor with adjusted delamination factor based on the radiographic image data and further compared them with hole bearing strength. They also found that higher feed (0.20 mm/rev) results in loss of bearing strength due to higher delamination extension and therefore they suggested to avoid higher feed when drilling composites.

Bhatnagar et al. [14] found that the drilling-induced damage is also influenced by torque. They also found that the major axis of the elliptical damage zone is approximately along the direction of fibres of unidirectional (UD)-GFRP laminates. Further they found that in woven fabric composites, the damage is spread around the circumference of the drilled hole and also much smaller than that in UD-GFRP laminates. They suggest 8-facet and Jodrill as the best-suited drill point geometries and do not suggest standard drill point geometry which is comparable to 4-facet drill point for drilling GFRP laminates. Tsao et al. [15] proposed that application of back-up nearer to the drill tool results in effective suppression of delamination along with a low level of back-up force.

Rajamurugan et al. [16] carried out the experiments using "Brad & spur" cemented carbide (K10) drill. They observed that the delamination factor increases with increase in feed rate and drill diameter whereas, decreases slightly with rise in spindle speed. Durao et al. [17] compared the performance of HSS twist drill, carbide twist drill, brad and bidiametral carbide drills of diameter 6 mm during drilling UD carbon/epoxy laminates of 4 mm thick. They found that among the above drills, carbide twist drill yields higher bearing strength and lesser delamination at lower feed (0.03 mm/rev).

By using response surface methodology (RSM), Palanikumar [18] modelled the delamination factor and surface roughness while drilling polymeric composites. He has found that feed rate is directly proportional to delamination factor and surface roughness. He has also found that the delamination factor and surface roughness are indirectly proportional to spindle speed. Further he has found that the increase of drill diameter will increase delamination factor and has no much influence on surface roughness. Uysal et al. [19] studied tool wear within the drilling of sheet moulding compound composites having 30% glass fibre weight fraction and 8 mm thick. They found that for minimum tool wear, 80° drill point angle, 0.6 mm/rev feed and 15 m/min cutting speed are the optimum drilling parameters.

Sadek et al. [20] demonstrated the process capability of vibration-assisted drilling in the low frequency-high amplitude regime ($<$ 200 Hz, $<$ 600 μm) for eliminating the hole exit delamination and thermal damage while drilling carbon fibre-reinforced epoxy laminates. They stated that optimized vibration-assisted drilling conditions will not affect productivity and also produce delamination-free holes by reducing cutting temperature (50%) and axial force (40%). Joshi et al. [21] studied the impact of modulation-assisted drilling and conventional drilling on hole oversize and delamination around the holes while drilling 4 mm thick GFRPs manufactured by hand lay-up process. They stated that in both conventional and modulation-assisted drilling, drilling-induced damage is affected by both the cutting speed and feed, whereas the hole oversize is affected by feed. Debnath et al. [22] conceptualized and developed rotary-mode ultrasonic drilling process for making holes in 4 mm thick glass fibre-reinforced epoxy (GFRE) laminates. They observed that rotary-mode ultrasonic drilling produces lesser delamination, both at the entry and exit, and higher hole circumferential edge quality than that of conventional drilling.

Most of the research work executed so far is about the usage of twist drill and some special geometry drills towards quality hole making in thin ($\leq$ 6 mm) composite laminates. Therefore, their results are not applicable to thick ($>$ 6 mm) laminates and thin/thick non-laminates. This can be substantiated by the statement made by [23,24], that the material constituent and thickness have great influence on drilling forces which in turn have on hole quality during drilling of GFRP composites.

Also so far in composites, most of the researchers have investigated the delamination/damage factor only at the entrance and exit side of the drilled hole i.e. they have concentrated only in the planar region observation. They have not considered the entire depth of hole for assessing the damage around the hole. The statement made by Wang et al. [25] that the delamination distribution is not only on the surface, but also inside the work material, should be noted. As the durability and reliability of the fastening operation depend on the bearing strength of the entire depth of the hole, the optimal drill geometry and drilling conditions declared so far by considering only the delamination/damage factor at the entrance and exit side of the drilled hole might not be applicable, specifically for thick composites. Also, the influence of self-excited vibration of the work material in the directions parallel and perpendicular to the feed of a drill is rarely studied. Because of the potential applications and enhanced properties of thick pultruded and liquid composite moulded (LCM) composites, the composite fabrication industry is in need to find out the best tool material and geometry and corresponding optimal process parameter levels for making defect tolerance holes in these composites.

2. Materials and methods

2.1. Details of work material

Pultruded solid composites, having fibre orientation parallel and perpendicular to the feed direction, and LCM solid composite having a thickness of 20 mm is taken as work material as shown in Fig. 1. Hereafter pultruded composites, 0° and 90° represents, the composites having fibre orientation parallel and perpendicular to the feed direction, respectively. Because of the method of manufacturing, composite produced by pultrusion and liquid composite moulding method are called as non-laminate and laminate, respectively. Both pultruded and LCM composites are made up of E-CR glass fibre and epoxy resin. The reinforcements for pultruded composites are made of UD multi-end continuous glass rovings of 600 GSM and that for LCM composite are made of bi-directional woven multi-end continuous glass roving fabric of 360 GSM and are as shown in Fig. 2.

Pultruded and LCM composites are manufactured with high fibre volume fraction, 68% and 59%, respectively, that is maximum with respect to its method of manufacturing. This high fibre volume fraction is purposefully achieved to ensure higher order energy absorption [26] that is the requirement in ballistic applications like construction of military vehicles. The following are the dimensions of the work materials (Fig. 1) used: pultruded composite (0°): 25 mm diameter and 20 mm height; pultruded (90°) and LCM composites: 85 mm length, 55 mm width and 20 mm thick. Tables 1 and 2 provide detailed information on mechanical and physical properties of the work materials considered in this investigation, respectively. Also, the 1st natural frequency of pultruded (0° and 90°) and LCM composites are, 100.71 Hz, 57.98 Hz and 54.93 Hz, respectively.

2.2. Details of drill tools used

So far declared as best special geometry tungsten carbide (WC) drills

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