Composite Structures 201 (2018) 112–120

Contents lists available at ScienceDirect

Composite Structures

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

Investigation on delamination and flexural properties in drilling of carbon nanotube/polymer composites

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ARTICLE INFO

Keywords:
Composites
Multi-walled carbon nanotube
Drilling process
Delamination
Flexural properties
Multi performance optimization

ABSTRACT

The drilling of composite laminates is difficult to control and often leads to delamination that significantly affects the strength of the structure. Of the mechanical properties of composite materials affected by drilling-induced damage, flexural strength has received very little attention. In the present paper, experiments were conducted to analyze the thrust force, delamination factor and residual flexural strength in the drilling of woven E-glass fiber-epoxy composites reinforced with functionalized multi-walled carbon nanotubes. The process parameters considered for the experiments are the feed rate, spindle speed, drill diameter, and the weight percentage of carbon nanotubes present in nanocomposite laminates. Drilling experiments were conducted based on Taguchi design of experiment and three-point bending tests were then done to assess the residual flexural strength of drilled specimens. Analysis of variance and Taguchi S/N ratio analysis were performed to investigate the influence of input parameters on each individual drilling characteristics. In addition, the orthogonal array with grey relational analysis was employed to simultaneously optimize the multiple performance characteristics of the drilling process. According to the results, the feed rate is the factor which has the greatest influence on the thrust force and delamination factor, followed by spindle speed. Residual flexural strength, however, is mostly influenced by nano content, followed by feed rate.

1. Introduction

Nanomaterials, and, in particular, nano-reinforcements for composites have in recent years been the subject of intense research, development, and commercialization. The use of nano-reinforcements in a wide variety of metallic, ceramic and polymeric matrices allows access to the maximum theoretical strength of the material since mechanical properties of these materials become significantly insensitive to flaws at nanoscale [1]. Carbon nanotubes (CNTs) are among the most commonly used nanomaterials because of their distinctive mechanical properties including high strength and stiffness. Due to these properties and their low density, CNT-polymer composites become an ideal replacement for metals and ceramics to satisfy the needs of technologies relating to the aerospace, automobile and other industries [2,3].

Even though composite components are often made near net shape, some machining operations are often indispensable in order to bring the components into dimensional requirements for assembly. Some of the common machining processes are milling, drilling, countersinking, and grinding. In aircraft and automobile manufacturing, drilling is essential in making accurate and high-quality holes to rivet and fasten components together. Poor hole quality results in poor assembly tolerance, poor structural integrity, and has the potential to cause long-term performance deterioration. That 40% of the machining time is devoted to hole-making justifies the numerous efforts and investigations made by researchers [4–10].

Drilling of composites is a very challenging operation due to the anisotropy, inhomogeneity and abrasive nature of these materials. Several forms of damage arise during the drilling process; delamination is one of the major concerns because of its serious threat to structural reliability. Delamination is caused by the low interlaminar strength of the laminate and high cutting forces. El-Sonbaty et al. [11] identified two forms of delamination called ‘peel-up’ at the drill entry point and ‘push-out’ on the exit side of the workpiece. In practice, it has been found that the delamination associated with push-out is more severe than that associated with peel-up [12]. The onset of delamination and the size of the damage on the back-side are governed by the cutting forces developed during the drilling process. High cutting forces, in turn, result from the use of improper drilling parameters, and improper tool geometry. The proper choice of these governing parameters suggests delamination-free drilling.

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https://doi.org/10.1016/j.compstruct.2018.06.041
Received 7 November 2017; Received in revised form 5 May 2018; Accepted 7 June 2018
0263-8223/

During the past decades, remarkable advances have been made in the field of composite drilling. Several researchers studied the effects of process parameters, feed rate and cutting speed, on cutting forces and associated damage by Taguchi and ANOVA analysis. Almost all studies revealed that both thrust force and delamination increase with feed rate [13–18]. On the contrary, different behaviors were observed as the cutting speed changes. Davim et al. [19], Sardinas et al. [20], and Kilickap [21] observed that delamination increases with cutting speed during conventional drilling of composite laminates. However, Khashaba [22], Karnik et al. [23], and Rubio et al. [24] noticed that decreases during high-speed drilling. Sorrentino et al. [25], studied the thermal damage in high speed drilling of FRP laminate. Also they developed new method to reduce delamination during drilling of FRP laminates by feed rate control [26]. Besides feed rate and cutting speed, drill bit geometry influence thrust forces and delamination. An increase in drill point angle leads to an extension of the area responsible for the extrusion effect on the uncut layers of the laminate and consequently a higher thrust force [27–29]. Gaitonde et al. [16,23] reported that the delamination tendency increases with increasing point angle for carbon fiber reinforced composites. By contrast, Kilickap [21] observed that the delamination size decreases with an increase of point angle for glass fiber reinforced composites. The chisel edge was also found to be a major contributor to thrust force in such a way that a reduction of the chisel edge can prevent delamination propagation [30–32]. In addition, a drill with a small diameter produces lower thrust force and consequently less delamination [33].

Drilling-induced delamination affects the mechanical properties of the composite structures. For this reason, the study of damage tolerance which refers to the experimental determination of the residual mechanical properties of the damaged laminates needs attention. Several researchers studied the effects of delamination on residual strength in tension and compression. Zarif et al. [34] studied the significance of the feed rate, cutting speed and drill point angle on the residual tensile strength of drilled woven GFRPs. According to their results, all drilling parameters that govern delamination can affect the residual tensile strength. Similar results were also obtained for unidirectional GFRPs [35]. On the contrary, Tagliaferri et al. [36] indicated that the tensile strength of the drilled specimens of woven GFRP is independent of the amount of damage extent. Ghasemi et al. [37] studied the compression behavior of woven CFRPs with moulded-in and drilled holes and indicated that the strength of the moulded-in hole panels are always greater than those of the drilled hole ones. Zarif et al. [38] studied the effects of the drilling parameters on the compression behavior of GFRPs and reported that the residual compressive strength is most affected by feed rate.

Of the mechanical properties of composite materials affected by drilling-induced damage, flexural strength has received very little attention. In this paper, we aim to investigate the influence of nanomaterials and drilling parameters (feed rate, cutting speed and drill diameter) on the drilling thrust force, the delamination size, and the residual flexural strength of E-glass-epoxy/MWCNT laminates. To achieve this, an approach based on the Taguchi method with grey relational analysis for optimizing the drilling process with multiple performance characteristics was adopted.

2. Experimental procedure

2.1. Material preparation

2.1.1. Materials

The epoxy used in this study was a two-part epoxy resin; part A: an epoxy polymer based on bisphenol A/epichlorohydrin derived liquid epoxy resin (Epon resin 828) and part B: cycloaliphatic amine curing agent (F205). Functionalized multi-walled carbon nanotubes (COOH-MWCNTs) containing 1.2 wt% carboxyl groups (–COOH) were manufactured using catalytic chemical vapor deposition technique. These CNTs had an average diameter of 10 nm, an average length of several microns and carbon purity of > 95%. E-glass woven fabric with a density of 2.6 g/cm^3 and Young's modulus of 72 GPa was also used as reinforcement in composites.

2.1.2. Preparation of nanocomposites

The functionalized MWCNTs at four different weight fractions, i.e. 0, 0.1, 0.5 and 1 s wt.%, were mixed with epoxy resin using a high-speed mechanical stirrer for 3 h to ensure chemical interaction between the functional groups on the surface of the MWCNTs and the resin chains. In order to obtain a uniform dispersion of the CNTs and prevent the agglomerations, the mixture was then placed in an ultrasound bath at 150 kW/cm^2 intensity and 5 µm amplitude for half an hour. Cycloaliphatic amine curing agent was then added to the modified resin and mixed by a mechanical stirrer at 3000 rpm for 1 h. The mixture was then placed in a vacuum oven at 60 °C for 15 min for degasification to remove entrapped air bubbles.

2.1.3. Preparation of fiber-reinforced nanocomposites

E-glass/epoxy nanocomposites were manufactured by using vacuum assisted hand lay-up technique. Twelve layers of E-glass fabric were used to fabricate all specimens. Curing was carried out in the autoclave at 60 °C/1MPa. The fabricated composite plate had an average thickness of 2.6 ± 0.1 mm and a fiber volume fraction of 55%. Finally, test samples measuring 12.7 × 200 mm were cut using a waterjet cutting machine. The mechanical properties of Epoxy/MWCNT composite material are shown in Table 1.

2.2. Test apparatus

Drilling experiments were performed on a Deckel FP4M drilling machine using standard high-speed steel twist drills. High-speed steel tools wear quite rapidly when machining FRPs because of the high abrasiveness of the fibers, and their use generally becomes impractical. To avoid the effect of tool wear, each of the five holes was made using a new drill bit, and the tests were run without coolant. The drilling tests were carried out using commercial HSS twist drills with the constant geometry (Table 2).

The specimens were fixed in the machine using a drilling fixture. The entire fixture was mounted on a Kistler 9255B piezoelectric dynamometer for measuring the cutting forces (Fig. 1). The holes were generated at the center of the specimens and each experiment was replicated twice.

To determine the impact of drilling-induced delamination on the residual properties of specimens, three-point bending tests were carried out. The setup of these three-point bending tests was in accordance with ASTM D790-03. For laminated composites, the span length should be chosen such that failure occurs in the outer fibers of the specimen and is due only to bending moment. Hence, a span-to-depth ratio of 60:1 was chosen to eliminate shear effects; i.e. the support span was L = 156 mm. To avoid excessive indentation, or failure due to stress concentration directly under the loading nose, the radii of the loading nose and supports were chosen as 5 mm. It should be noted that the specimens were placed on the supports with the drill exit side uppermost, i.e. the compression side. This was done to expose the generally more serious delamination to compressive load, which typically causes the failure. The specimens were loaded at a constant crosshead speed of 1 mm/min until failure. Fig. 2 shows a typical specimen during the

Table 1
Mechanical properties of GFRP/MWCNT.

Mechanical Properties	Tensile strength	Interlaminar shear strength	Flexural strength
GFRP/MWCNT	450 MPa	35 MPa	365 MPa