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Reducing drilling-induced delamination in composite tube by magnetic colloid back-up

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ABSTRACT

Drilling is an indispensible machining process for building a load-carrying structure of composite materials. Delamination defect is often produced at the exit of drilling, which threatens the service safety of the structure. There are back-up methods to reduce delamination when drilling the open flat-plate composite structure, but none for drilling into the curved-surface or hollow-shape structures. This study describes an innovative method using electromagnet and the deformable inexpensive colloid mixed with iron powder to produce magnetic back-up force at drilling exit to suppress delamination in industrial tube parts. The delamination extent can be reduced by 60–80%. The optimal volume ratio of powder-to-colloid is found 1:3.

1. Introduction

Composite materials have gained wide applications in industry ranging from aerospace to construction and leisure sectors thanks to the excellent specific strength and stiffness, corrosion resistance and ability of adapting to tailor-design of directional strength in a part. One example is the airframe of Euro fighter Typhoon built of 50% composites by weight and 70% by surface area [1]. Drilling is among the most frequently applied machining processes to composite materials due to the need of structural joint. The operation in industrial practice often causes serious defects around the hole edge at exit side in the drilled composites, called delamination, which lowers bearing strength of the joints and threatens safety in use as well as shortens the service life of the parts. This defect from drilling creates the unwanted non-uniform mechanical strength across the laminate structure and needs to be reduced [2]. The ultrasonic C-scan is well accepted method to measure the extent of delamination as shown in Fig. 1. The computerized tomography provides more precise measurement at higher costs [3]. The mixed colloid used in this research is a thick magnetorheological fluid which is also a damper in civil engineering [4–6].

The extent of delamination observed at the exit side of drilling is proportional to the drilling thrust force, while there is a critical thrust force below which no delamination occurs [7]. Increasing the feed rate of drilling enlarges the delamination extent [8]. The thrust force in drilling is in fact directly proportional to the feed rate by cutting increased chip thickness. Various types of drill bit produce different levels of delamination [9–11]. How to adopt the appropriate drill bit and machining conditions to reduce the delamination induced from drilling remains a vital challenge in the drilling operation in industry. There has been a simple practice of using a piece of back-up to support the exit side of drilling to withhold the occurrence of delamination [12–14]. The analysis of using back up in drilling composites shows that the threshold of

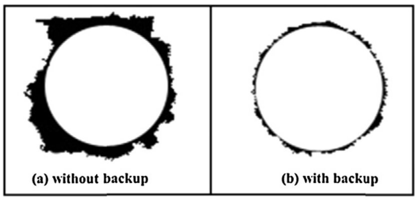

Fig. 1. Ultrasonic C-scan shows the extent of drilling-induced delamination (a) without and (b) with active backup (feed rate of 0.1 mm/rev, spindle speed of 1000 rpm) [16].

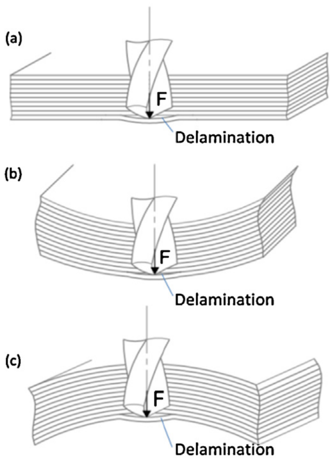

Fig. 2. Drilling composite (a) on a flat plate (b) on a curved plate along curvature and (c) on a curved plate against curvature.

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the critical thrust force of composites is significantly increased. In other words, the occurrence delamination in drilling is much retarded under the same cutting conditions [15]. A further development using the active back-up force to suppress the growth of delamination with high efficiency is demonstrated [16]. Fig. 1 illustrates the effect of suppressing delamination by back-up. Several back-up techniques for reducing delamination area in drilling are reported. However, they are applicable to drilling flat-plate structures but not those with curved surface or hollow shape. Fig. 2 shows the drilling into different surface geometries of composites in schematics. Drilling into the curved plates will produce different levels of delamination defects on the exit side. Drilling against the curvature, as shown in Fig. 2(C) is the most disadvantageous case among the three types. Drilling holes on walls of a tube belongs to this sever case. Tubes are the common shapes of the composite parts in the industrial practice, such as the frame work of the high-performance bicycles, for which the conventional back-ups for the flat-shape parts are obviously not useful. This paper describes a novel approach of using magnetic colloid material inside the tube as the back-up for reducing delamination when drilling hole on composite tube from outside.

2. Analysis of magnetic back-up of mixed colloid

To perform the back-up in drilling composite material in tube shape, a magnetic colloid is mixed with iron powder and polymer colloid and applied inside the tube. The schematic of the concept is shown in Fig. 3. An external electromagnet on top of drill chuck will be passed by the electrical current. It attracts the magnetic colloid inside and introduces the back-up force from inside upward against the downward bending deformation of the last laminate underneath the drill bit when drilling holes from outside of tube is conducted. The bending deformation of the laminate and the further developed delamination at the exit of drilling can be reduced. The used colloid is able to free fill the tube and also adapt to the workpiece shape in more general cases.

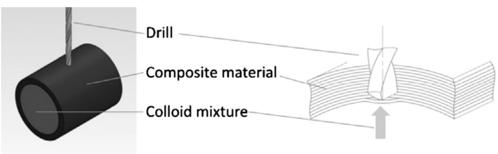

Fig. 3. Using magnetic colloid for back-up in drilling tube.

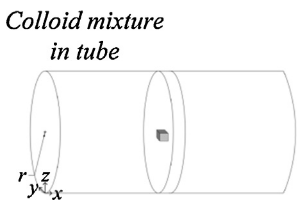

Fig. 4. Representative volume of magnetic colloid in tube.

The generated electromagnetic force can be calculated by commercial software Magnet. Fig. 4 shows the representative volume and coordinate axis for the analysis of the mechanical effects of the colloid inside the tube, where the *x*-axis goes along with the axis of tube. Fig. 5 shows the maximal available electromagnetic back-up force, F_i, of ten equally divided segments of the colloid along *x*-axis at various level of passed electrical current based on the assumption of filling iron powder in tube to 100% volume ratio. One can see the central segment, where the drilling is actually conducted, provides the strongest back-up. The nonuniform values are attributed to the spatial arrangement of the external electromagnet and tube. The actual value of the back-up force according to the applied iron powder concentration is $F_{\varnothing}$,

$$F_{\varnothing} = F_i \varnothing \tag{1}$$

where $\varnothing$ is the volume ratio of iron powder in the mixed colloid.

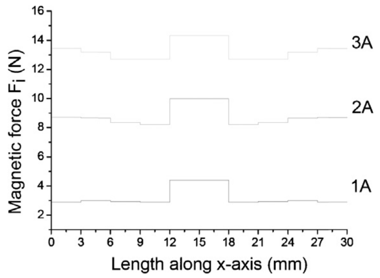

Fig. 5. 100% ferrous magnetic back-up force along *x*-axis.

The mixed colloid is considered an incompressible viscous Newtonian flow, namely the viscosity of mixed colloid, μ_s, is linearly dependent on the ratio of shear stress over shear rate,

$$\mu_s = \frac{\tau}{du/dx} \tag{2}$$

A part of the work done by magnetic back-up force is provided to suppress the laminae bending in drilling through the small vertical movement of colloid flow. One considers first a small representative element of volume as shown in Fig. 4. The work done by the magnetic back-up is calculated by the magnetic force pushing the mixed colloid through a vertical distance along *z*-axis,

$$E_s = \int F_{\varnothing}\, dz \tag{3}$$

Eq. (1) is valid not only for the representative small volume but also across the radial volume of each thin disk segment of the mixed colloid along *x*-axis, in which the shear stress can be expressed as the electromagnetic force dived by the stressed area,

$$\tau = \frac{F_{\varnothing}}{\pi r^2} \tag{4}$$

The moving velocity of the back-up colloid material along *z*-axis is

$$u = \frac{dz}{dt} \tag{5}$$

The combination of Eqs. (5) and (3) yields

$$E_s = \int F_{\varnothing}\, dz = \int F_{\varnothing} u\, dt \tag{6}$$

Eq. (2) tells *u* can be rewritten as

$$u = \frac{1}{\mu_s} \int \tau\, dx \tag{7}$$

The substitution of Eqs. (4) and (7) into Eq. (6) leads to

$$E_s = \int \frac{F_{\varnothing}}{\mu_s} \left(\int \tau\, dx \right) dt = \frac{(F_i)^2 \varnothing^2}{\pi r^2 \mu_s} \int \int dx\, dt \tag{8}$$

Eq. (8) expresses the push-up work done to counteract the laminae bending for reduction of delamination over the period in drilling when using the magnetic colloid as back-up. For a fluid mixed with suspended fine particles, the viscosity is [17]

$$\mu_s = \frac{\mu_0}{1 - 2.5\varnothing + 11\varnothing^5 - 11.5\varnothing^7} \tag{9}$$

where μ_0 is the viscosity without fine particles. The substitution of Eq. (9) into Eq. (8) yields

$$E_s = \frac{(F_i)^2 (1 - 2.5\varnothing + 11\varnothing^5 - 11.5\varnothing^7)}{\pi r^2 \mu_0} \int \int dx\, dt \tag{10}$$

One notices that there exists an optimal value of $\varnothing$ at which the back-up work E_s is maximized. The derivative of Eq. (10) with respect to iron powder volume ratio $\varnothing$ tells the optimal back-up work appears at $\varnothing$ = 28.3%, given that μ_0 = 400 pa s, *r* = 0.01 m, and *t* = 60 s, as shown in Fig. 6. At the optimum $\varnothing$ of the mixed colloid, the minimum delamination defect in drilling composite tubes will be achieved.