A Review of Backup Mechanism for Reducing Delamination when Drilling Composite Laminates

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Abstract: Over the past decades, composite materials have been increasingly utilized in various industries because of their superior mechanical properties and resistance to corrosion. Drilling is essential to produce precise holes when load-carrying structures are produced using composites. Because of the non-homogeneous and anisotropic property of composite laminates, delamination often occurs at the point where the drill exits, which affects reliability and safety. Some studies present a suppressed mechanism to prevent delamination when drilling composite laminates. The experimental results demonstrate delamination is significantly reduced by various suppressed mechanisms and greater feed rates produce the same level of delamination. The use of special drill geometries and backup has been demonstrated to be more advantageous than the use of adapted feed controls. The basis for the future development of a suppression mechanism for drilling composite laminates is determined.

Keywords: Composite materials, Drilling, Delamination, Suppressed mechanism, Backup.

1. INTRODUCTION

In recent years, composites have become commonly used for the production of structural components for the aerospace, military and transport industries because of their superior mechanical properties. However, the integration of composite structural components still requires assembly processes that require riveting and fastening using drilled holes. For some economic and quality considerations, drilling is the most common method for generating a precise hole. As composites are either non-homogeneous or anisotropic, drilling causes specific damage such as delamination at the exit of the hole and this reduces the bearing and fatigue strength of the composite components [1-3]. Many studies have shown that thrust force is the main cause of delamination [4, 5]. Reducing thrust force at the drill exit can prevent drilling-induced delamination. However, a reduction in the thrust force is not the best solution in terms of the manufacturing process as a whole and the production costs of accommodating a slow drilling process during the manufacture of components that use composite materials are high.

Several studies have reported that a delamination-free hole is critical in the machining of composite laminates [6-10]. Teti presented an overview of conventional machining of composite materials, such as metal matrix composites and fiber reinforced

composite laminates [6]. Hocheng and Tsao summarized the critical thrust force models for various special drill bits, pilot holes and backup plates and the feasibility of using non-traditional machining to ensure delamination-free drilling of composite laminates [7]. Abrão *et al*. studied the effects of tool materials and geometry, as well as machining parameters on the thrust force and the drilling quality in drilling composite materials [8]. Liu *et al*. also summarized progress until 2012 in the mechanical drilling of composite laminates, in terms of drilling operations, drill geometry and materials, drilling-induced delamination and methods for suppressions, thrust force and tool wear [9]. Singh *et al*. reported an automated drilling operation that produces delamination-free drilling in polymer-matrix composites (PMCs) using a neural network, fuzzy logic, supervisory, proportional-integral (PI), proportional-integral and derivative (PID), pole placement and adaptive controllers [10]. However, there is no comprehensive study of the mechanical drilling of suppressed mechanisms. This study involves the use of suppression mechanisms that allow delamination-free drilling of composite laminate.

2. SUPPRESSION METHODS

Hocheng and Dharan showed that peel-up at the entry and push-out at the exit are two distinguishable delamination mechanisms that are associated with drilled holes at the periphery of composite laminates [11]. Figure **1** shows the favorable and unfavorable process forces (axial component only) for the drilling of composite laminates. Certain strategies, such as three-axial milling [12, 13] and auxiliary devices [14-17], may

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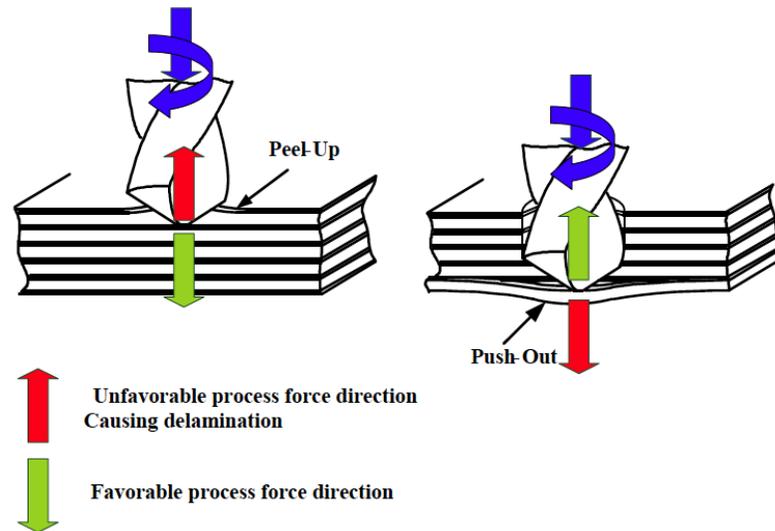
Figure 1: Schematic of delamination mechanisms as well as the favorable and unfavorable axial machining force directions.

reduce machining damage and give better drilling quality and longer tool life, as well as greater workpiece strength after machining [18]. Over the past decades, adapted feed controls [19], the use of special drill geometries [5, 20] and backup plates [11, 21-25], which support the outer or remaining layers beneath the workpiece, have been frequently used to reduce push-out delamination for drilled holes. However, peel-up delamination, is not affected by either the presence of a support or the pre-heating. Capello proposed a damping system that reduces delamination by reducing the speed of the drill, relative to the workpiece, during the release stage without the need for backing [26].

2.1. Passive Backup

The thrust force during drilling characterizes the machinability of composite laminates and this directly affects the quality of drilled holes. Many studies have reduced the thrust force from tool geometry, machining parameters and the use of passive backup (consumed plate) [4-10, 14]. Passive backup is a method of supporting the back of a composite laminate to prevent exit delamination and this is commonly used in some manufacturing industries. Hocheng and Dharan first developed a critical thrust force model for twist drills using linear elastic fracture mechanics (LEFM), which is used as a guide to prevent drilling-induced delamination [11]. Hocheng and Tsao developed comprehensive analytical models for critical thrust force for saw drills and core drills with a backup plate and compared these with the model for a conventional twist drill without a backup plate [27, 28]. The theoretical models were shown to be acceptable and are summarized in Table **1**. However, the use of passive

backup to support a composite laminate during drilling as a backup is not ideal. This increases the cost of the production, especially for large composite components.

2.2. Active Backup

In order to overcome the shortcomings of passive backup, some drilling devices that provide active backup force on the back of a workpiece reduce delamination during drilling, without a reduction in the thrust force or the feed rate for the drill bit and the passive plates need most be scrapped. Figure **2** shows drilling-induced delamination at the exit of a hole without and with the active backup, using a twist drill [27]. Figure **2b** shows significant suppression and a reduction in drilling-induced delamination when there is active backup. The active backup force can be a mechanical force (hydraulic, pneumatic, motor and linkage driven) [26], an electromagnetic force [27, 29] or a thermal/cold force [30].

2.2.1. Simple Electromagnetic Force

Tsao *et al*. developed comprehensive analytical models for the critical thrust force for a twist drill with an actively suppressed mechanism and compared this with the model for a conventional twist drill without a backup plate [27]. This is summarized in Table **2**. Figure **3** shows that the critical thrust force when drilling composite laminate is increased when there is an active backup force to suppress the delamination crack as the drill approaches the last lamina. Where γ is the ratio between critical thrust force with suppressed position (F_B^*) and critical thrust force without suppressed position (F^*), ξ is the distance betweeen radius of drill (c) and radius of suppressed load (c_R),

Table 1: The Comprehensive Analytical Models of Critical Thrust Force for Saw Drills and Core Drills with Passive Backup

Drill type	Schematics of delamination	Model of critical thrust force	Remarks
Saw drill		$$F_{SF} = \frac{\pi}{2s^2\|\ln s\|}\sqrt{32G_{IC}M}$$	G_{IC} : critical strain energy release rate (in mode I fracture) $M = \dfrac{Eh^3}{12(1-v^2)}$: flexural rigidity of the plate E : Young's modulus v : Poisson's ratio H : workpiece thickness h : uncut depth under tool F_{SF} : thrust force of saw drill with backup $s = c/a$ c : outer radius of core drill a : radius of delamination $\beta = t/c$ t : thickness of core drill
Core drill		$$F_{RF} = \pi\sqrt{\frac{32G_{IC}M}{(k_8 + k_{23} + k_{24}\ln s + k_{25}\ln^2 s)s^4}}$$ $k_8 = (2-\beta)^2[-\frac{1}{4}-\frac{1}{4}(2-2\beta+\beta^2)\ln\frac{c(1-\beta/2)}{a} - \frac{(1-\beta)^4}{\beta(2-\beta)}\ln(1-\beta)\ln\frac{c(1-\beta/2)}{a}$ $+(2-2\beta+\beta^2)\ln\frac{c}{a}\ln\frac{c(1-\beta/2)}{a}]$ $k_{23} = -\frac{1}{2}(2-2\beta+\beta^2)+\frac{1}{16}(2-2\beta+\beta^2)^2-\frac{(1-\beta)^2}{\beta(2-\beta)}(2-2\beta+\beta^2)\ln(1-\beta)$ $-\frac{2(1-\beta)^4}{\beta(2-\beta)}\ln(1-\beta)+\frac{(1-\beta)^4}{2\beta(2-\beta)}(2-2\beta+\beta^2)\ln(1-\beta)$ $-\frac{4(1-\beta)^6}{\beta^2(2-\beta)^2}\ln^2(1-\beta)+\frac{(1-\beta)^8}{2\beta^2(2-\beta)^2}\ln^2(1-\beta)$ $k_{24} = 2(2-2\beta+\beta^2)-\frac{1}{2}(2-2\beta+\beta^2)^2+\frac{2(1-\beta)^2}{\beta(2-\beta)}(2-2\beta+\beta^2)\ln(1-\beta)$ $-\frac{2(1-\beta)^4}{\beta(2-\beta)}(2-2\beta+\beta^2)\ln(1-\beta)-\frac{8(1-\beta)^6}{\beta^2(2-\beta)^2}\ln^2(1-\beta)$ $k_{25} = (2-2\beta+\beta^2)^2+\frac{8(1-\beta)^2}{\beta(2-\beta)}(2-2\beta+\beta^2)\ln(1-\beta)$	F_{RF} : thrust force of core drill with backup
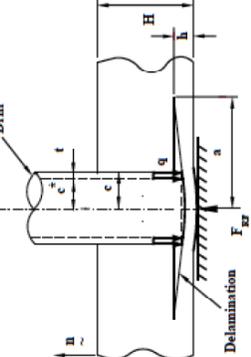
Table 2:   The Comprehensive Analytical Models of Critical Thrust Force for Twist Drill, Saw Drill and Core Drill with Active Backup

Drill type	Schematics of delamination	Model of critical thrust force	Remarks
Twist drill		$$F_{AS} = \pi \sqrt{\frac{32 G_{IC} M}{[(1-\alpha_S^2)+2\alpha_S^2 \xi^2 s^2 - \alpha_S^2 \xi^4 s^4]}}$$	c: radius of drill $\alpha_S = F_{AS}/F_A$ F_A: thrust force of twist drill without backup F_{AS}: thrust force of twist drill with backup
Core drill (inner suppressed load)		$$F_{RI} = \pi \sqrt{\frac{32 G_{IC} M}{(1-\gamma^2)-s^2[K_1-2\gamma^2(1-\xi)^2]+s^4[K_2-\gamma^2(1-\xi)^4]}}$$ $$K_1 = (2-2\beta_S + \frac{3\beta_S^2}{2}) + \frac{4(1-\beta_S)^2}{\beta_S(2-\beta_S)} \frac{ln(1-\beta_S)}{2}$$ $$K_2 = \frac{(2-4\beta_S+5\beta_S^2-3\beta_S^3+\beta_S^4)}{2} + \frac{2(1-\beta_S)^2(2-2\beta_S+\beta_S^2)}{\beta_S(2-\beta_S)} ln(1-\beta_S)$$	$\xi = c - c_{RI}$ c: outer radius of core drill c_{RI}: radius of inner suppressed load $\gamma = F_{RI}/F_R$ F_{RI}: critical thrust force with inner suppressed position F_R: critical thrust force without inner suppressed position $\beta_S = t/c$ t: thickness of core drill
Core drill (outer suppressed load)		$$F_{RO} = \pi \sqrt{\frac{32 G_{IC} M}{(1-\gamma^2)-s^2[K_1-2\gamma^2(1+\xi)^2]+s^4[K_2-\gamma^2(1+\xi)^4]}}$$	$\xi = c_{RO} - c$ c: outer radius of core drill c_{RO}: radius of outer suppressed load $\gamma = F_{RO}/F_R$ F_{RO}: critical thrust force with outer suppressed position F_R: critical thrust force without inner suppressed position
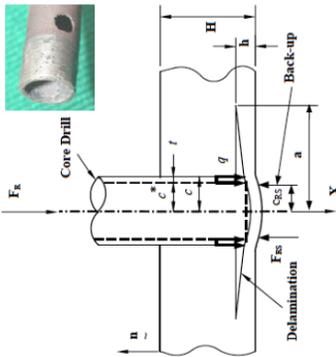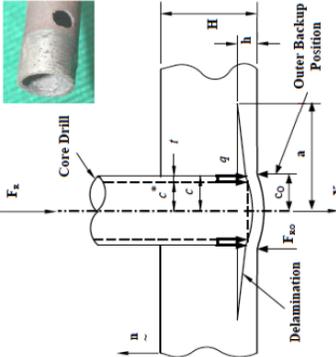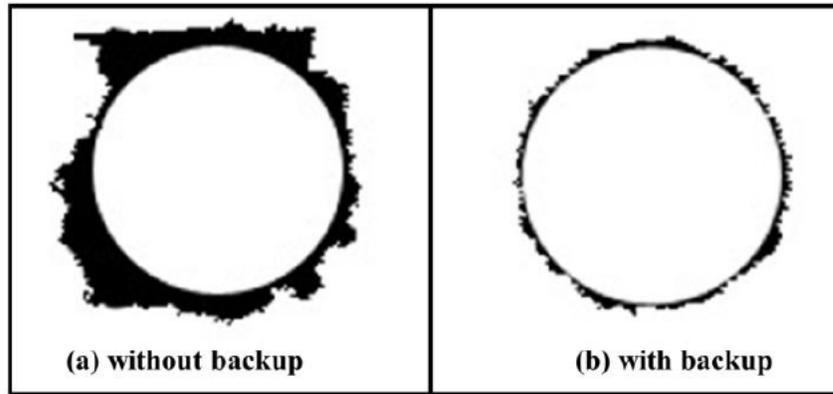
Figure 2: Extent of drilling-induced delamination (**a**) without and (**b**) with active backup [27].

and s is the ratio between radius of drill (c) and radius of delamination (a). Therefore greater drilling thrust is needed to propagate a delamination. Drilling of the composite uses a faster feed rate and there is less risk of delamination. The magnitude of the active backup force is limited to about $\gamma <2$ in practice by the rigidity of the fixture that holds the workpiece during drilling. This effect is very much significant at large value of *s* when the crack propagates far beyond the drill's diameter. The larger the active backup force, the smaller is the likelihood that the delamination will grow.
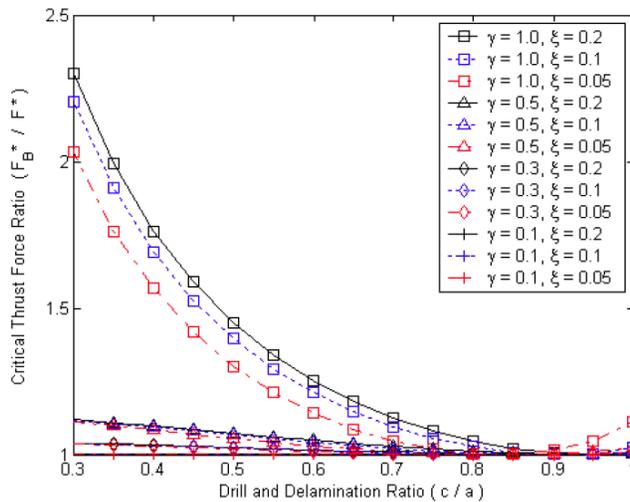
Figure 3: Critical thrust force varying with various levels of γ and ξ.

Figure **4** shows that the thrust force increases with the feed rate, as commonly seen in practice. The use of backup results in an increase in the drilling force in axial thrust because of the increased rigidity of the structure that is underneath drill bit. The closer distance the suppress load is to the drill bit, namely smaller ξ, the more rigid is the structural subject to drilling. This effect is slightly greater at higher feed rates so the thrust force is greater when there is active backup than when there is simple drilling without backup.
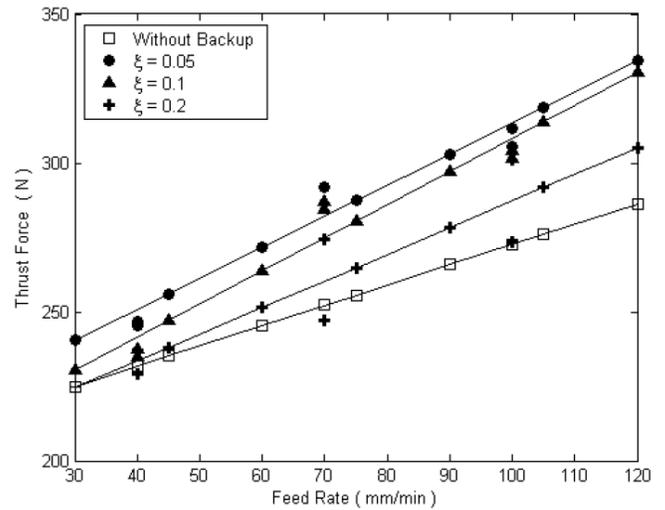
Figure 4: Effects of backup at various location on thrust force.

Figure **5** shows that the extent of any delamination is reduced by 60-80% at high feed rates when an active backup force is applied. Delamination often
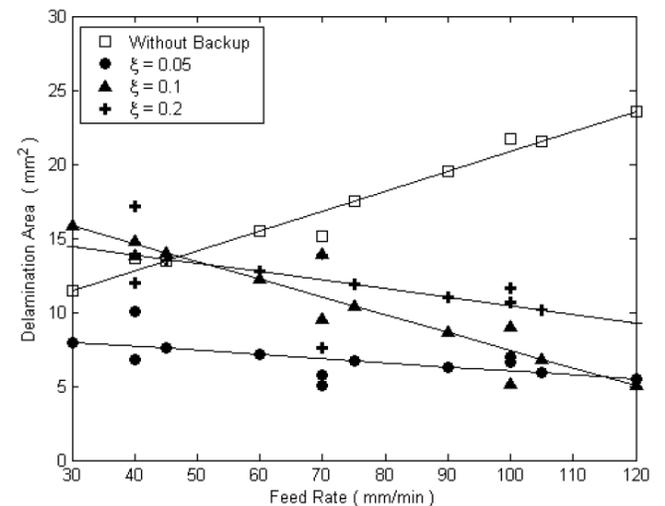
Figure 5: Effects of active backup at various location on delamination reduction.

increases with feed rates when no backup is provided. When there is active backup, the greater the feed rate, the lesser is the likelihood of delamination. However, when ξ is 0.05 there is less sensitivity on delamination for a given feed rate than when ξ is 0.1 or 0.2 with active backup. Smaller ξ means that there is less bending deformation in the laminate due to pushing by the drill bit.

Figure **6** shows that there is a reduction in delamination when the active backup force is small (R=13N) and the force is electromagnetic. There is little difference when the backing force is greater, which is advantageous in practice. The effect of a reduction in delamination when the active backup force is small is one of the main causes for the strength of brittle fracture/breakage between CFRP and epoxy resin because of the tool thrust on the last lamina during drilling.
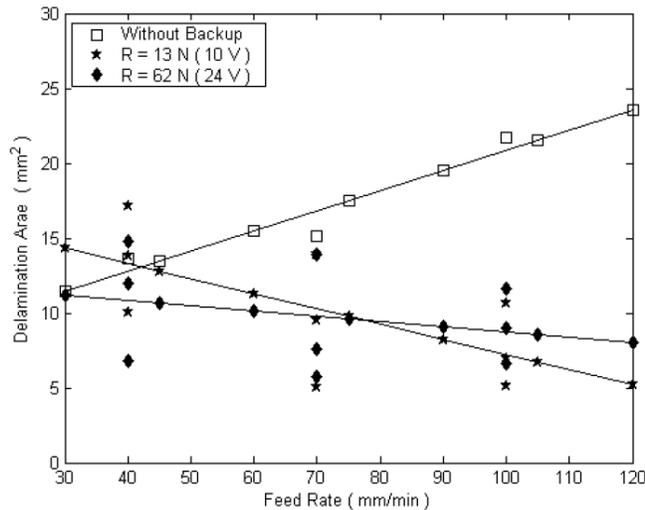
Figure 6: Delamination reduction by active backup.

2.2.2. Electromagnetic Force and Iron Powder Colloid

Figure **7** shows schematics for drilling into different surface geometries of composite laminates. Drilling into curved-plate structures produces different degrees of delamination defects on the exit side. Hocheng *et al*. used an electromagnetic force to suppress the growth of a delamination at the exit side when drilling curved-plate structures using an electromagnet and an inexpensive deformable colloid mixed with iron powder [29]. The area of the delamination is reduced by 60-80%. The optimal volume ratio for powder-to-colloid is 1:3.

The feed rate for the drilling of composite laminates determines not only the cutting efficiency, but also the
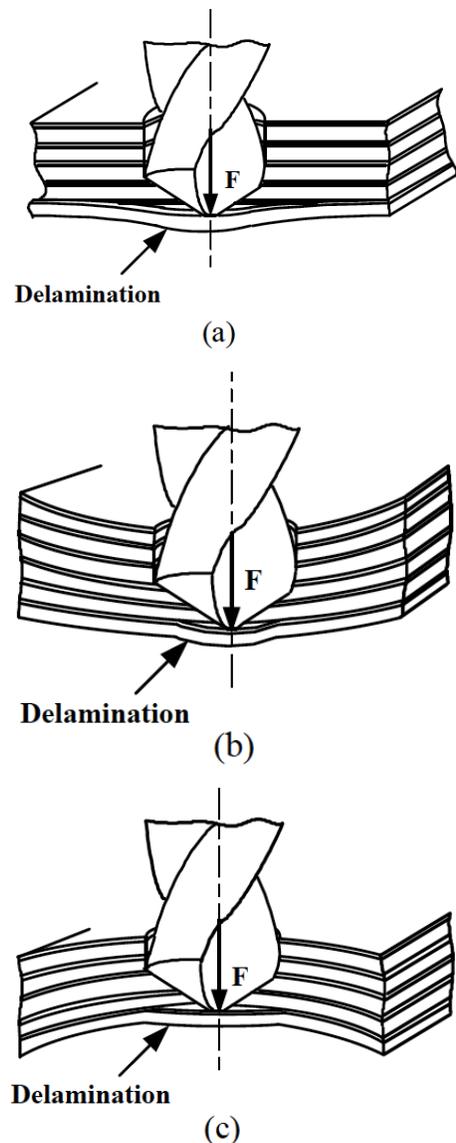
Figure 7: Drilling composite (**a**) on a flat plate (**b**) on a curved plate along curvature and (**c**) on a curved plate against curvature.

quality of the machined holes. Fast feed rate accompany large thrust, which produces large delamination defects when drilling composite laminates, as shown in Figures **8** and **9**. Figure **8** shows that the addition of iron powder generates enough electromagnetic backup to reduce the extent of delamination damage. The initial addition of 12 wt% results in a reduction of 30-50%, while the addition of 24 wt% to 36 wt% does not produce any further effects. Figure **9** shows that a strong electrical current is more effective for electromagnetic backup. A current of 2A is required to suppress delamination at fast feed rates.

The area of the delamination when drilling composite laminates becomes smaller as the electrical current increases, as shown in Figures **10** and **11**. The

drilled delamination area at 3A is smaller than that at 2A and 1A. Figure **10** shows that the backup effect of 1A does not prevent the growth of a delamination when drilling at a high feed rate. However, the reduction of the area of the delamination at 0.1 mm/rev is more significant than that at 0.06 mm/rev and 0.03 m/rev, when sufficient electrical current is supplied.
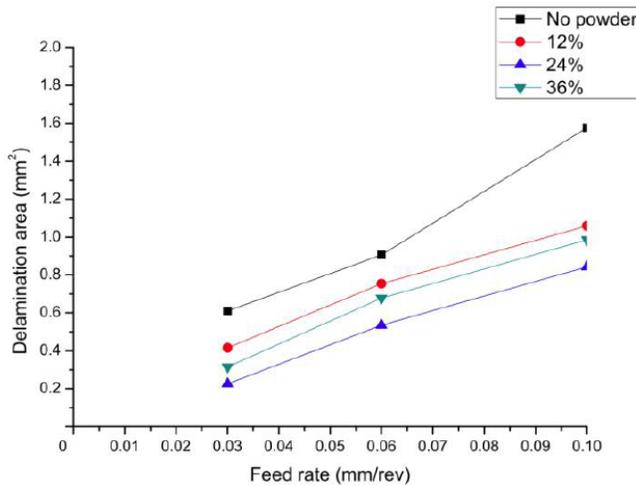
Figure 8: Correlation between delamination area and feed rate at various iron powder volume concentration [29].
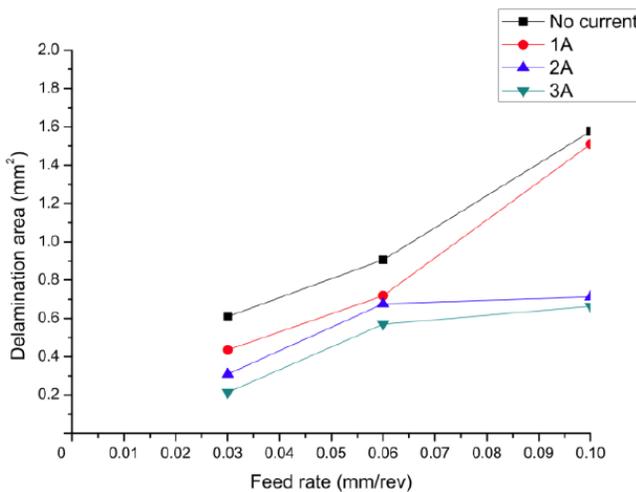
Figure 9: Correlation between delamination area and feed rate at various electrical current [29].

The iron powder provides the desired electromagnetic force for the colloid. More powder produces stronger electromagnetic attraction when drilling. The addition of iron powder into the mixed colloid does not increase the suppression forces proportionally. A greater powder content makes the colloid more viscous so it is less fluid in response to an electromagnetic force. 24% of iron powder by volume concentration is an optimal value that gives the largest

backup force and the associated minimum of delamination when drilling, as shown in Figure **12**. This optimal iron powder volume concentration reduces delamination by up to 82% at low feed rates and by 67% at fast feed rates.
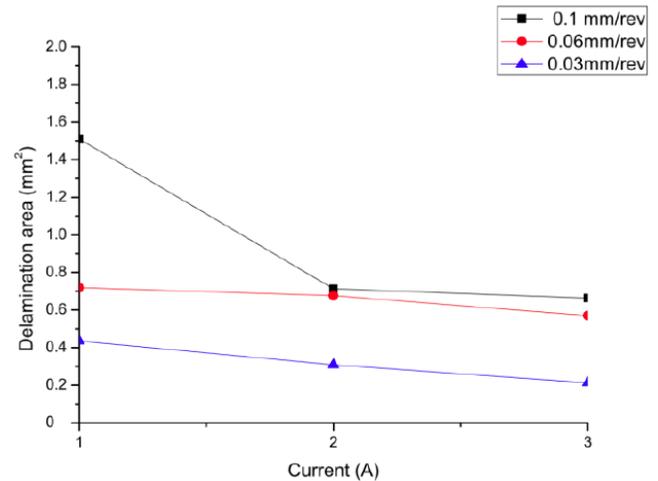
Figure 10: Correlation between delamination area and electrical current at various feed rate [29].
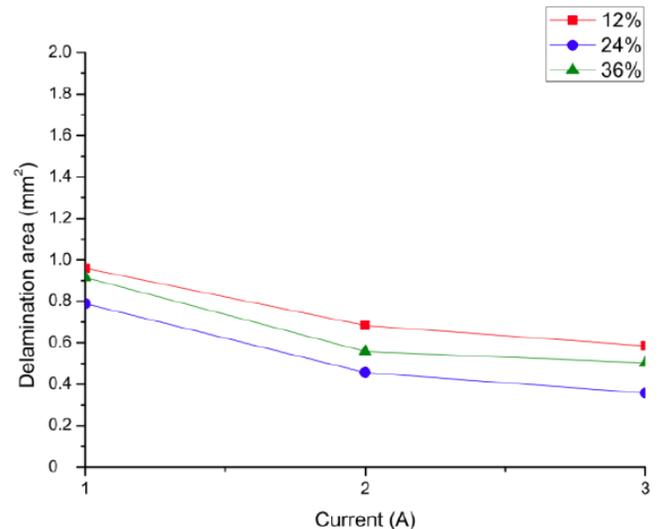
Figure 11: Correlation between delamination area and electrical current at various iron powder volume concentration [29].

2.2.3. Icing Force

Figure **13** shows that there is a proportional relationship between the thrust force and the feed rate because of the icing force against delamination when drilling composite tubes. When there is internal icing, the thrust force for drilling increases by 22% on average. When the spindle speed increases, the thrust force decreases slightly for the same feed rate and drill bit [9, 31-33]. This is due to the properties of the
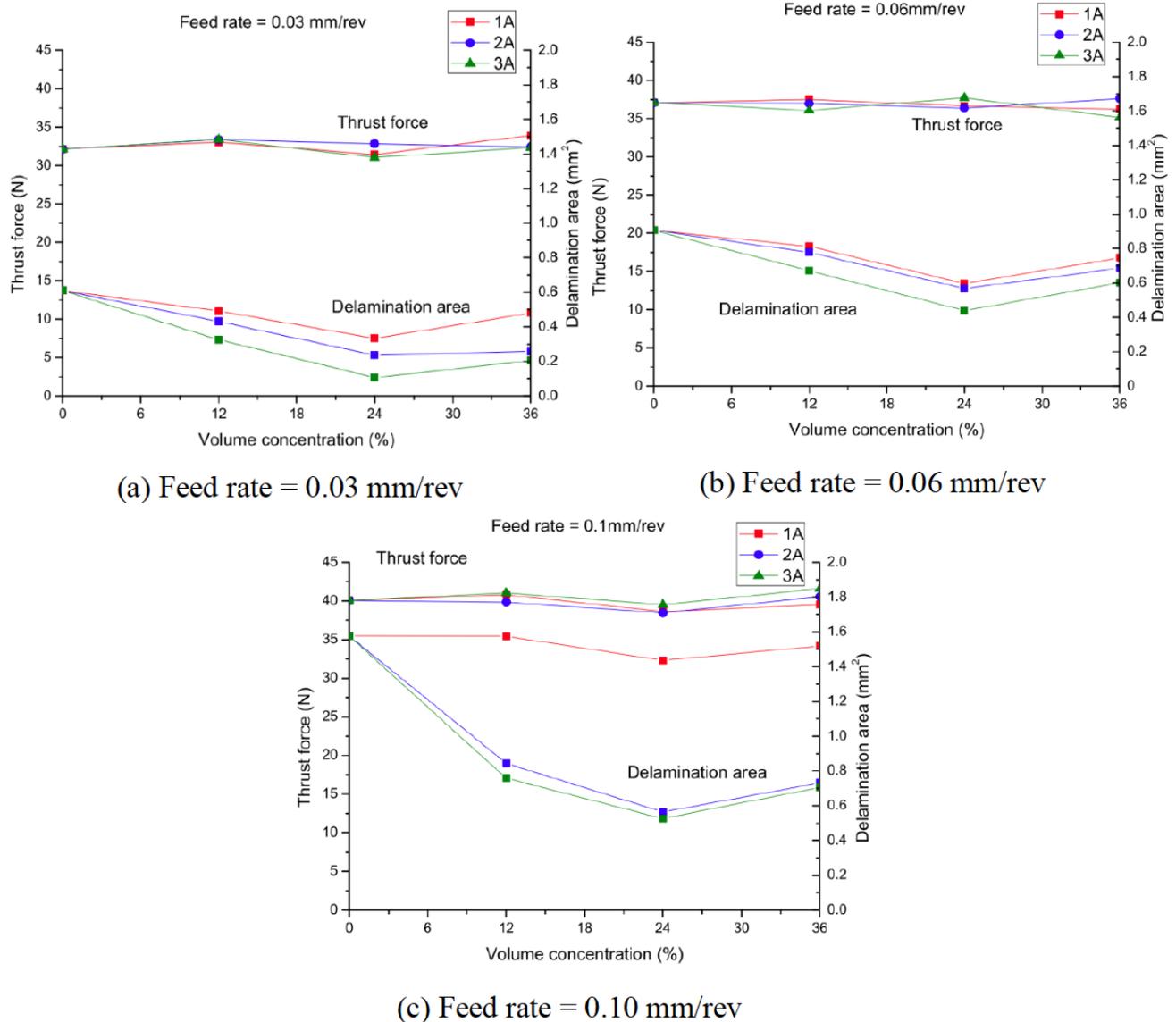
Figure 12: Thrust force and delamination at various powder concentration and electrical current [29].

composite material, in which the matrix is mainly resin polymer. The tensile strength of polymer-matrix composites increases as the ambient temperature decreases so the thrust forces are increased when there is a stronger workpiece. However, the thermal softening effect is slightly greater at higher feed rates. Figure **14** shows the correlation between thrust force and spindle speed without and with backup icing, when drilling composite tubes. The icing-induced lower temperature initially hardens the matrix resin and then the material is softened locally during drilling. The difference in the change in resin strength when there is backup icing is greater than at room temperature. The thrust forces without and with backup icing are respectively reduced by 12.1% and 12.3% when the spindle speed is increased from 600 rpm to 1200 rpm.

Figure **15** shows the correlation between delamination area and feed rate for various spindle speeds. The drilling-induced energy, which causes delamination, is stored during deformation and becomes surface energy (clustered together crack) when the drill passes through the workpiece. A high feed rate produces a large delamination area. This observation is in agreement with the results for past studies [4, 5, 7-11]. Drilling-induced delamination is reduced for both cases, without and with backup icing operations, as shown in Figure **15**. The interlaminate fracture strength is significantly reduced when the temperature is reduced, so the stored bending energy in the laminate during drilling is released to produce a less delamination area. The feed rate can be increased by more than 400% as the area of the delamination

(a) without backup icing   (b) with backup icing
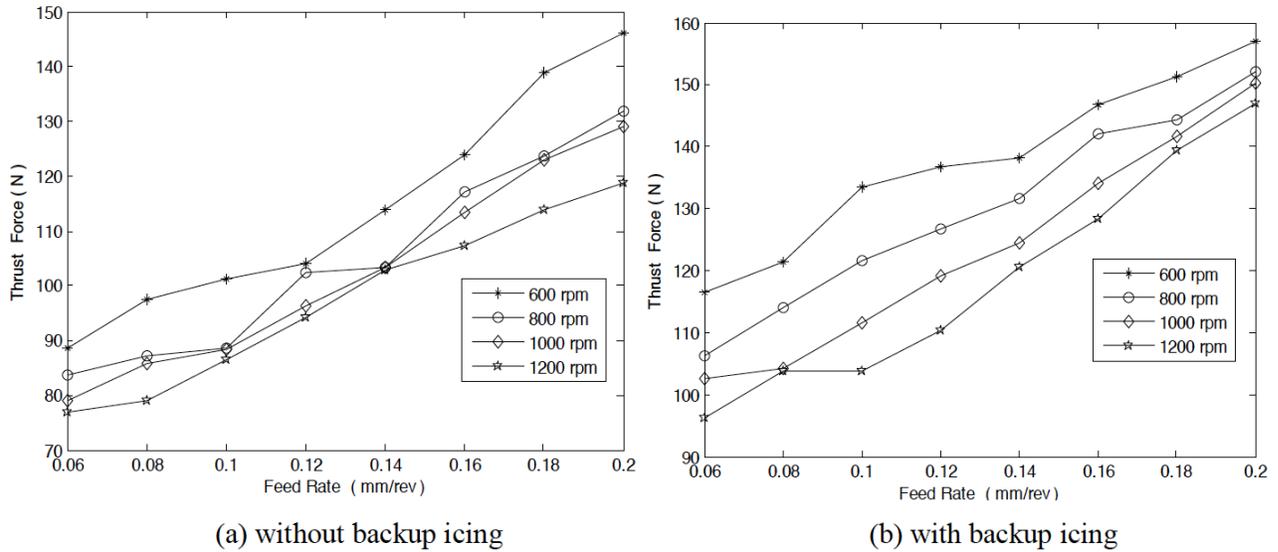
Figure 13: Correlation between thrust force and feed rate (**a**) without backup icing (**b**) with backup icing.

(a) without backup icing   (b) with backup icing
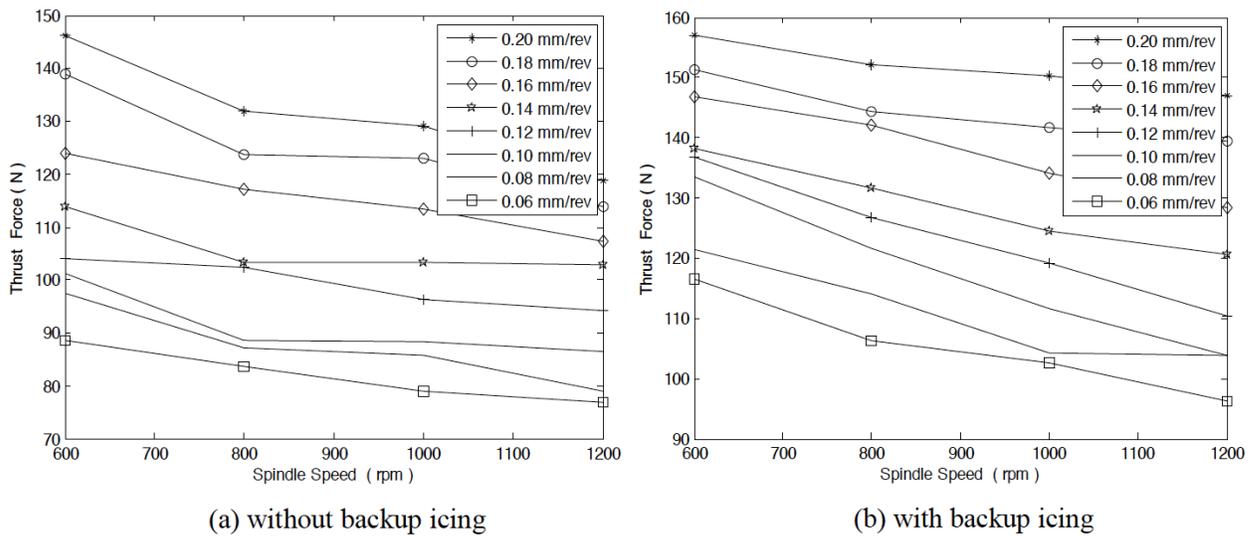
Figure 14: Correlation between thrust force and spindle speed (**a**) without backup icing (**b**) with backup icing.

remains the same. When the feed rate is increased from 0.06 mm/rev to 0.20 mm/rev, the delamination remains at 2.5 mm^2. The area of the delamination is reduced to more than 40% when there is internal icing backup, as shown in Figure **16**. However, the area of the delamination is less when there is icing than without icing, although the thrust force is greater.

3. CONCLUSIONS

Previous studies have rarely focused on the suppression mechanism for the active backup force that reduces delamination when drilling composite laminates. Although using a consumed plate (passive backup force) is a common method of reducing delamination, it is not ideal because it slows production
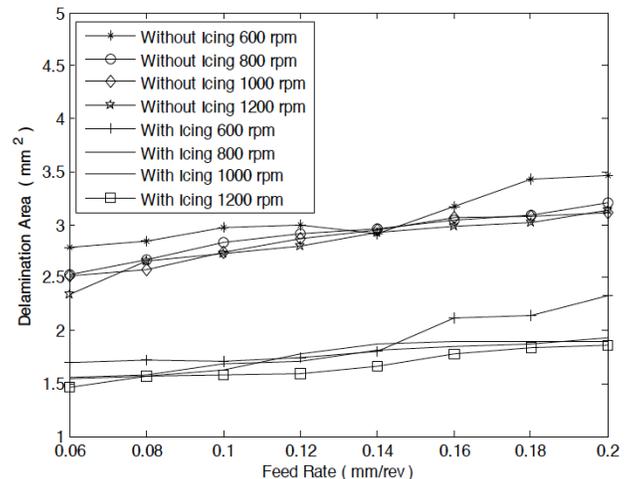
Figure 15: Correlation between delamination area and feed rate.

(a) Without backup icing
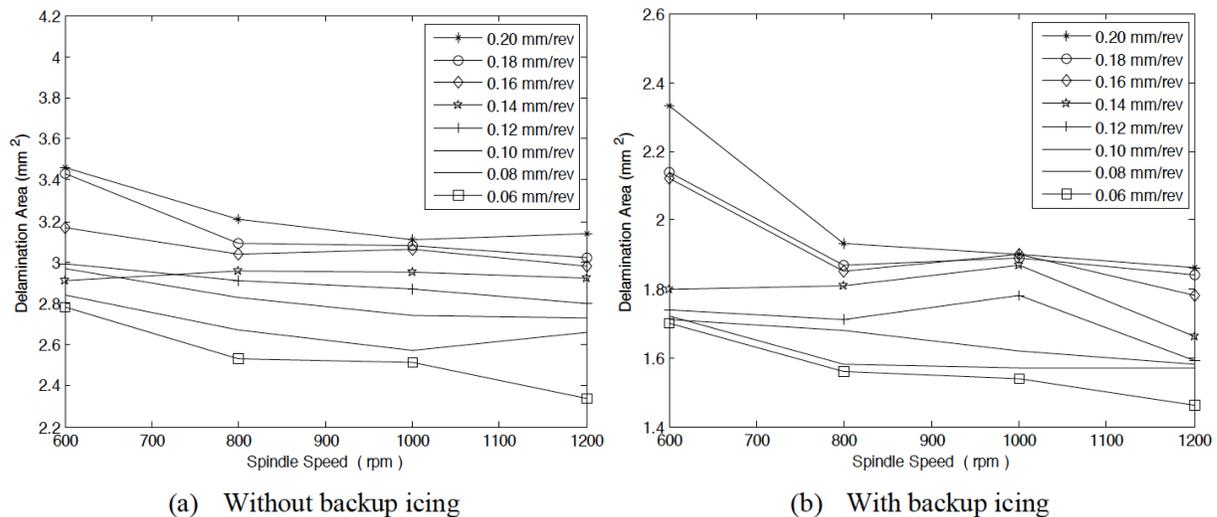
(b) With backup icing

Figure 16: Correlation between delamination area and spindle speed (**a**) without backup icing (**b**) with backup icing.

and has economic and quality disadvantage. This study summarizes current methods that use mechanical, electromagnetic and thermal principles when drilling composite laminates. This requires minimal cost and equipment and gives a significant reduction in delamination damage. The method mainly uses a suppression mechanism to provide an active backup force that suppresses drilling-induced delamination during the drilling of composite laminates. The proposed strategies offer an effective and inexpensive method to achieve delamination-free drilling of composite laminates.

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