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Machinability Analysis in Drilling Flax Fiber-Reinforced Polylactic Acid Bio-Composite Laminates

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Abstract**—**Interest in natural fiber-reinforced composites (NFRC) is progressively growing both in terms of academia research and industrial applications thanks to their abundant advantages such as low cost, biodegradability, eco-friendly nature and relatively good mechanical properties. However, their widespread use is still presumed as challenging because of the specificity of their non-homogeneous structure, limited knowledge on their machinability characteristics and parameter settings, to avoid defects associated with the machining process. The present work is aimed to investigate the effect of the cutting tool geometry and material on the drilling-induced delamination, thrust force and hole quality produced when drilling a fully biodegradable flax/poly (lactic acid) composite laminate. Three drills with different geometries and material were used at different drilling conditions to evaluate the machinability of the fabricated composites. The experimental results indicated that the choice of cutting tool, in terms of material and geometry, has a noticeable influence on the cutting thrust force and subsequently drilling-induced damages. The lower value of thrust force and better hole quality was observed using high-speed steel (HSS) drill, whereas Carbide drill (with point angle of 130°) resulted in the highest value of thrust force. Carbide drill presented higher wear resistance and stability in variation of thrust force with a number of holes drilled, while HSS drill showed the lower value of thrust force during the drilling process. Finally, within the selected cutting range, the delamination damage increased noticeably with feed rate and moderately with spindle speed.

Keywords**—**Natural fiber-reinforced composites, machinability, thrust force, delamination.

I. Introduction

COMPOSITE materials are replacing conventional metals and alloys in numerous engineering applications in recent years. Considerable attention and significant rise in many areas of research and technology of lignocellulose-based natural fibers as a reinforcement in composites can be seen throughout the past two decades. Due to their particular material properties such as lightweight, high strength to weight ratio, biodegradability, renewability, high corrosion resistance and no additional CO_2 emissions that diminish the effects of global warming and climate change [1].

Amongst the various plant-based natural fibers available, flax fiber has gained a lot of attention owing to its superior properties such as low density, resistance to abrasion and wear, availability, biodegradability and low cost. Flax fiber-reinforced composites are commonly used in numerous automotive interior and exterior parts, interior parts of aircraft, and structural and construction materials [2]. With the growing interest in using NFRCs various engineering fields, these near-net-shape materials still need some secondary machining processes such as drilling to facilitate the joining process of parts for assembly purposes and achieve the final shape. Machining of NFRCs is absolutely different from the machining mechanism of metals owing to the fact that not only the structure of the material is non-homogeneous and anisotropic, but also the material properties are highly dependent on the various reinforcement and matrix properties [3]. Among the many machining operations, traditional drilling is most broadly used for the creation of holes in composite laminates. However, there are several problems associated with the drilling process including delamination, thermal degradation, uncut fiber, fiber pull-out, fiber peel up and spalling which leads to poor finish quality and high tool wear [4]. Delamination is the main limiting factor in drilling of composite materials as it extremely affects the quality of the drilled holes and reduces the structural strengths and integrity of the components. It is believed that the size of delamination damage is mainly dependent upon the machining parameters and thrust force generated during the drilling operation [5]. The key for minimizing the delamination damage in drilling of NFRCs rely on decreasing the cutting thrust force by proper choice of various cutting parameters, drill geometry, drill material and type. It has been reported that the drilling behavior of the composite materials is strongly affected by the drill bit type and material.

Chaudhary et al. [6] investigated the effect of both cutting parameters and drill geometry including drill point angle on drilling characteristic of cotton/polyester fiber reinforced composites. The research results show that low values of feed rate, low point angle, and higher cutting speed in the tested range resulted in better quality of the drilled holes and lower value of thrust force in drilling cotton composites. Debnath et al. [7] studied the influence of drilling parameters and drill type using three different drills (4-facet, parabolic, and step drill) on the thrust force and damage characteristics of drilled holes in sisal fiber-reinforced composites with epoxy and polypropylene matrix. The results show that using parabolic drill results in minimum value of thrust force compared to other types and the value of thrust force decreased by decreasing the feed rate and increasing the cutting speed for all cutting tools employed.

The main objective of the present work is to investigate the effect of cutting parameters such as feed rate and cutting speed

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and drill bit type and material on drilling thrust force, delamination factor and thereby the quality of the holes while drilling flax/PLA fiber reinforced bio-composite laminates.

II. Experimental Procedure

A. Sample Preparation

The woven unidirectional flax fiber with a density of 1.5 g/cm^3 and aerial weight of 180 g/m^2 was supplied by Lineo Company (France). The PLA film used as a matrix in this research was 100 µm thick and supplied by Magical Film Enterprises Co. Ltd (Taiwan). The average glass transition temperature (T_g) was 61.9°C and the crystalline melting temperature (T_m) was around 150°C. The compression molding machine (Carver Inc, Wabash, USA) was employed to fabricate the laminates and the temperature of 170°C, slightly above the PLA melting temperature. Samples were cut to the dimensions of 40 mm × 250 mm × 6.5 mm by the use of laser cutter for the drilling process. The manufacturing process of the specimens is presented in Fig 1. The orientation of the layers was unidirectional and composite volume fraction was around 50%.

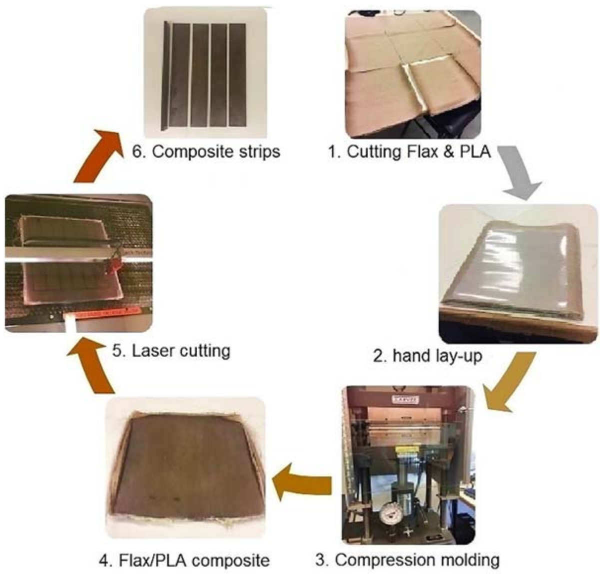

Fig. 1 Manufacturing process of composite samples for drilling

Tensile testing was carried out for fabricated composites based on ASTM D3039 with the crosshead speed of 2 mm/min. The measurement outcomes were gained from an average of five test specimens, with an ultimate tensile strength of 238.62 MPa and the Young's modulus of 21.23 GPa. The tensile strain in the specimens was measured with a 50 mm Instron extensometer attached to the in-plane surface of the sample.

B. Tools and Equipment

All specimens were drilled using three twist drills with two facet point, helix angle of 30^o and same diameter of 8 mm but different materials and point angles as presented in Fig 2. One conventional HSS drill with point angle of 118^o and two Carbide drills with point angles of 118^o and 130^o have been used for the drilling process.

The axial thrust force during the drilling was measured using Kistler 92577B multi-component dynamometer mounted on the machine table. Signals were transferred to a PC by using connecting cables, through an ECON MI-7004 dynamic signal analyzer (DSA) system. Econ Data Acquisition and Analysis software was employed to collect and analyze the results.

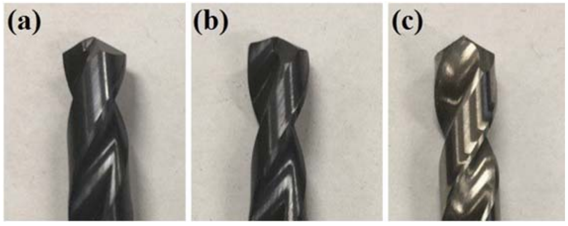

Fig. 2 Three drill bits with helix angle of 30^o and diameter of 8 mm used for the drilling process (a) Carbide drill with point angle of 118^o (b) Carbide drill with point angle of 130^o (c) HSS drill with point angle of 118^o

The evaluation of delamination damage in drilling of NFRCs is very complex, particularly for dark fibers which makes the visual inspection difficult. The universal OLYMPUS BX 40X optical microscope was applied in order to measure the delamination damage after drilling. Several dimensional and non-dimensional evaluation models have been developed to measure the level of damage. In present work, two-dimensional delamination factor (F_{da}) was implemented to assess the delamination damage using (1):

$$F_{da} = \left(\frac{A_{del} - A_{nom}}{A_{nom}} \right) \% \quad (1)$$

where A_{del} is the delamination damage area, A_{nom} is the nominal area of the drilled hole as displayed in Fig 3.

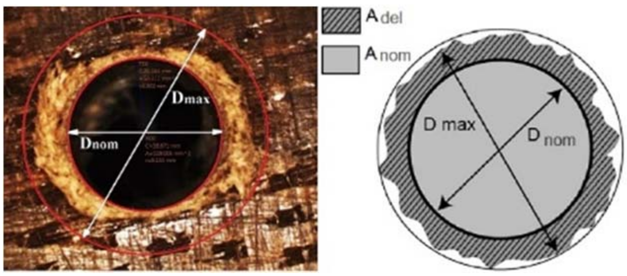

Fig. 3 Schematics of the two-dimensional delamination factor

C. Drilling Experiment

The drilling process was implemented on the HASS CNC machining center. A fixture has been designed with a center hole to clamp the composites on the dynamometer. The composite samples were drilled under dry cutting conditions with three cutting speeds (2550, 1850, 450 rpm) and three feeds (0.08, 0.11, 0.16 mm/rev) using HSS and carbide drills with different point angles. The machining setup is presented in Fig 4. The effect of cutting parameter such as cutting speed, feed rate, drill material and point angle on the cutting thrust force and delamination in drilling flax/PLA bio-composites were investigated. Each drill was used to drill nine holes. The cutting parameters and their levels are shown in Table I.

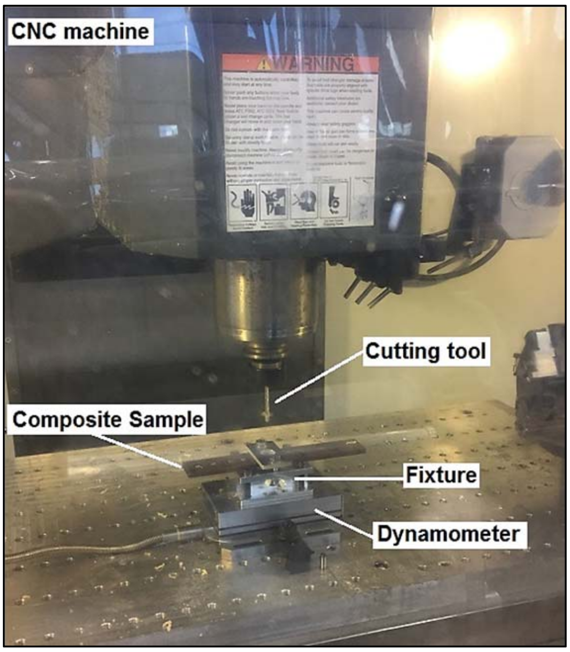

Fig. 4 Machining set-up for drilling composite samples

III. Result and Disscussion

A. Influence of Feed Rate, Cutting Speed and Drill Type on Thrust Force

Effect of cutting parameters on the thrust force is illustrated in Figs. 5 (a)-(c). As can be seen, by increasing the feed rate, the value of thrust force rises for all the drilled samples using different drill bits. This can be attributed to the elevation in the shear area. Drilling at high feed rates increases the self-generated feed angle and results into decreasing the effective clearance angle. The results of experiment indicate the noticeable effect of cutting speed on the value of thrust force. The value of thrust force decreased by almost 50% when cutting speed increased from 450 rpm to 2550 rpm for all three cutting tools. This can be explained by the softening of the material when cutting speed increases. From Fig. 5, the effect of cutting tool material and type can be clearly observed. The HSS tool resulted in a much lower value of thrust force than carbide drills. It is believed that the HSS drills are generally sharper than the carbide drills and they are more suitable for cutting soft materials while carbide drill are more appropriate for cutting abrasive synthetic fiber-reinforced composites owing to their high resistance to wear [8]. Comparing the influence of the three cutting tools tested, it can be concluded that the carbide twist drill with point angle of 130° presented higher thrust force value. As can be seen in Figs. 5 (b) and (c), the decrease in point angle with web thinning has led to a considerably lower value of thrust. By decreasing the point angle, moment of the forces of resistance to cutting process increases. Hence, the appropriate selection of drill bit material together with a proper geometry of the drill can results into achieving the minimum value of drilling thrust force.

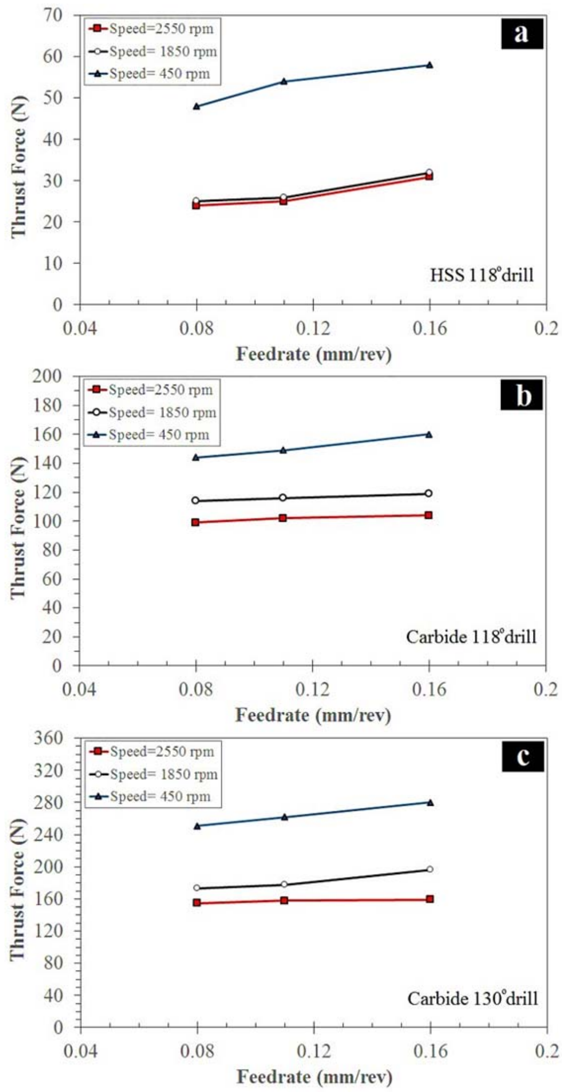

Fig. 5 Effect of feed rate and cutting speed on drilling thrust force using (a) HSS drill (b) Carbide 118° drill and (c) Carbide 130° drill

TABLE I
Drilling Cutting Factors

Drilling Parameters	Symbol	Level 1	Level 2	Level 3	Unit
Feed rate	*f*	0.08	0.11	0.16	rpm
Cutting speed	*S*	2550	1850	450	mm/rev
Drill material	-	HSS	Carbide	Carbide	-
Point angle		118	118	130	degree
Drill diameter	*D*		8		mm

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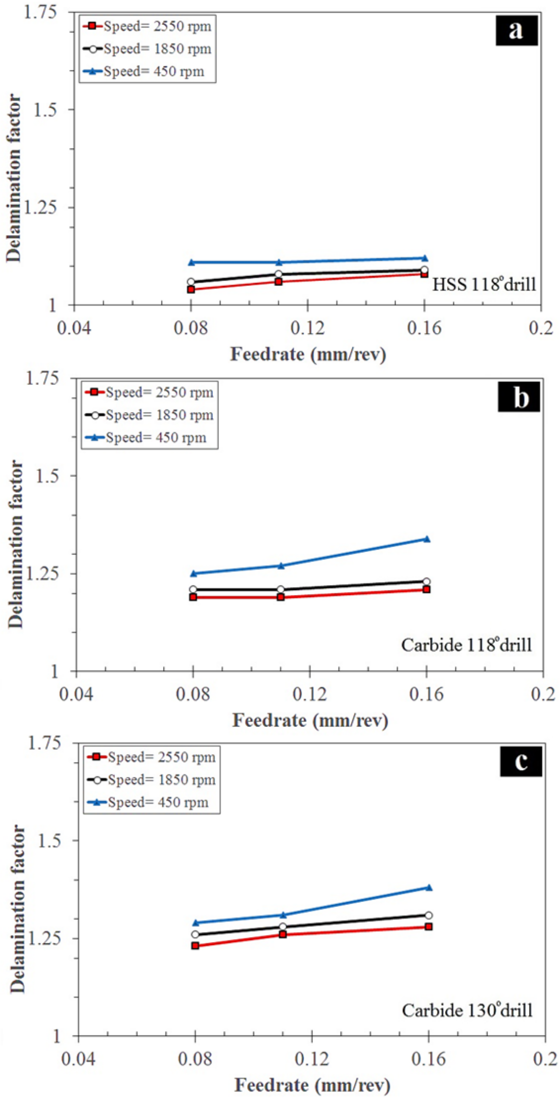

Fig. 6 Effect of feed rate and cutting speed on delamination damage using (a) HSS drill (b) Carbide 118° drill and (c) Carbide 130° drill

B. Influence of Feed Rate, Cutting Speed and Drill Type on Delamination

After drilling the specimens, delamination damage was detected at the surface of the samples. At the periphery of the drill entrance, adjacent plies can be separated by an external force generated by the drill bit due to the slope of the cutting edge flutes. The influence of feed rate, cutting speed and drill material and type on the peel-up delamination factor is displayed in Fig. 6. Observation on the measured delamination damage indicated that drilling induced-delamination rises with increasing the feed rate and decreases by increasing the cutting speed. This can be related to the rise of axial thrust force. The figure also illustrates the effect of cutting tool material on the delamination size. It has been found that regardless of drilling condition, drilling with HSS drill results in better hole quality and less delamination damage compared to carbide drills. The minimum delamination factor of 1.04 was achieved for the sample drill at maximum cutting speed (2550 rpm) and minimum feed rate (0.08 rpm) drilled with HSS drill with point angle on 118°. This behavior can be assigned to the material of drill bit and the value of thrust force with HSS twist drill [9]. Regarding to the effect of point angle, it is observed that the carbide drill with lower point angle created better holes with less delamination damage. This can be explained by the fact that a larger point angle generally allows the cutting lips to engage with cutting material more. As a result, the higher heat generation for larger point angles surges matrix softening and thus increasing the delamination damage size [10]. Fig. 7 shows images of some of the drilled holes for the samples drilled at different drilling conditions by three different cutting tools indicating the effect of feed rate, drill material, and cutting speed on the peel-up delamination damage. As can be seen, the samples drilled with HSS drill bit at highest cutting speed and lowest feed rate resulted in good quality, while using a carbide drill at the same drilling condition and geometry resulted in higher delamination damage and machining defects.

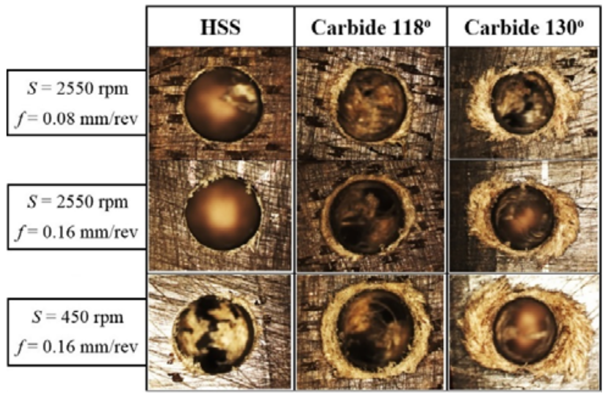

Fig. 7 Photos of samples illustrating the effect of drilling parameters on the quality of the drilled holes

IV. Conclusion

In this experimental investigation, the machinability characteristics of the flax fiber-reinforced polylactic (PLA) bio-composite were studied. The effect of several main cutting parameters such as cutting speed, feed rate, drill material and type on the quality of the drilled hole has been analyzed and the results are as follows:

For all types of drills used in this research, feed rate has been found to be the most influential cutting parameter on the delamination damage, while spindle speed had a great influence on the cutting thrust force.

The cutting thrust force generated by the HSS drill was lower than carbide drills. Drilling with the HSS tool resulted in better hole quality and drilling-induced damages compared to the carbide 118° and carbide 130° drills. This can be related to the low value of thrust force while drilling with the HSS drill and the soft and non-abrasive nature of the flax/PLA composite.

Drill point angle was found to be a critical parameter on the machinability behavior of the composite laminates. Larger point angle resulted in higher values of thrust force and higher delamination factor due to the higher engagement of the cutting lips with the material.

Based on the results of the experiment, the lowest delamination damage and finest hole quality in the drilling of flax fiber reinforced composites was achieved at highest cutting speed and lowest feed rate using a HSS twist drill with point angle of 118°.

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