



Damage assessment of fibre reinforced laminates



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ABSTRACT

The use of solid wastes and natural fibres to the production of innovative composites is now a matter of environmental need. A set of hybrid composites constituted of waste rubber particles and sugarcane bagasse fibres into a thermoset composite material are drilled to determine the effect of rubber particle addition and size, sugarcane fibre addition and length and fibre chemical treatment on damage extension and related mechanical properties. Damage extension is determined by enhanced radiography for further damage measurement – diameter and areas – and correlated with mechanical test results – bearing test. The results demonstrated significant effect of the rubber and fibre additions on mechanical properties of the composites.

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1. Introduction

The characteristics of fibre reinforced laminates have widened their use from aerospace to domestic appliances. Their ability to be tailored for use and endless possibilities provided by the combination of reinforcements together with their alignment and fibre fraction, allow design engineers to have almost total freedom in the design of new parts. Unique properties such as low weight, high strength and stiffness are normally referred to whenever the advantages of these materials are listed. In the later stage of parts production, machining operations like drilling are frequently needed in composite structures, as the use of bolts, rivets or screws is required to join the parts. Generally, machined parts have poor surface appearance and tool wear is higher. One of the problems related with composites' machining is the nature of the fibre reinforcement, which is usually very abrasive and causes rapid tool wear and deterioration of the machined surfaces. The special characteristics of these materials make them difficult to machine when compared to traditional materials. It is known that a drilling process that reduces the drill thrust force can decrease the risk of delamination thus increasing reliability. Delamination is the most usual damage and can reduce the bearing capacity of the plate. The most usual solution to this problem is to use higher levels of safety factors with the consequent penalty in terms of final weight

of the structure. This solution can be particularly penalising in the case of vehicles where the final structural weight is an important factor. For that, damage assessment methods based on data extracted from images of drilled plates are of primordial importance [1].

Hybrid composites are made by more than two phases (fibres and/or particles) into the same matrix. Hybrid composites consisted of natural fibres and waste can be designed to obtain a low-cost material with sustainable manufacturing and recycling aspects. A combination of natural fibres and rubber particles is quite promising to achieve high tenacity with moderate mechanical strength with a promising use in secondary transport applications (car parts, aircraft seats) and re-usable external biomedical implants and supports. In addition, increased use of rubber waste and recycling of bagasse fibres will relieve the pressure on the environment in terms of disposal of non-biodegradable products and elimination of bagasse by-products therefore enhancing the resilience of Brazilian but also European ecosystems.

Among the solid waste produced in the transport industry, scrap tyres constitute a clear example of a product with significant impact to the environment. One billion tyres are scrapped every year, and 5 billions more are expected to be discarded on a regular basis until 2030. A small part is recycled, but millions of tyres are just stockpiled, landfilled or buried [2]. In Brazil, 67.3 million tyres were produced in 2010, corresponding to a rise of 15% compared to the production in 2009 [3]. In the USA more than 300 million tyres are currently stored [4], while the UK disposes approximately 46 million tyres each year. Since European Union directives have banned the disposal of used tyres (whole and shredded) in

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landfills, there is a real and urgent need to identify routes for reuse or recycling of the scrapped tyre rubber [5].

Bagasse is a waste generated by the production of fuel, sugar and other products from the extraction of sugarcane. Brazil has the highest production of sugarcane in the world. In 2008, the total amount of sugarcane produced on a global scale was 1557 Mt [6], including 604 Mt in Brazil, which means a production of 200 Mt of bagasse. Many research activities have been carried out to identify new ways to recycle this waste product. The bagasse burning has not been recommended since it implies large pollution levels and wasted energy [7].

In this work a set of hybrid composites constituted of waste rubber particles and sugarcane bagasse fibres into a thermoset composite material were drilled to determine the effect of rubber particle addition (25 and 50 wt%), rubber particle size (50–80 and 100–200 US-Tyler), sugarcane fibre addition (3 and 5 wt%), sugarcane fibre length (5 and 20 mm) and fibre chemical treatment (with and without) on damage extension and related mechanical properties. Damage extension is determined by enhanced radiography and images are then processed for damage measurement – diameter and areas [8,9]. A number of published criteria for damage assessment based on images obtained by different techniques – microscopy, radiography, TC, C-Scan [10–12] – are compared and correlated with bearing test results – ASTM D5961M-13 [13].

The results identified the effect of the rubber and fibre fractions on the mechanical properties of the composites, enhancing specific properties for structural applications. An adequate assessment of damaged area and proper selection of machining parameters is desired to extend the life cycle of these laminates as a consequence of enhanced reliability.

2. Machinability of polymeric matrix composites

2.1. Composites drilling and delamination

Drilling is one of the most common machining operations in composites industry. Drilling is a complex process, characterised by the existence of two mechanisms: extrusion and cut. The extrusion mechanism is performed by the drill chisel edge that has almost null linear speed and the cutting mechanism is due to the existence of rotating cutting lips at a certain speed. The most common drill is the conventional conical point drill. The cutting process is unique and can be divided into two distinct regions: chisel edge and cutting lips. In a common drill, there is a small region around the centre of the chisel edge, called the indentation zone, where the tool does not cut the material, but extrudes it instead. At the region outside the indentation zone, called the secondary cutting edge area, the rake angle is highly negative. As polymeric composites are generally more brittle than metals, it is unlikely that extrusion really takes place and orthogonal cutting could be assumed for the entire chisel edge. However, model predictions based on this assumption do not agree with the experimental data. Along the cutting lips, cutting action of a drill is a three-dimensional oblique cutting process. The cutting speed, rake angles and other geometrical parameters vary along the cutting lips with the radial distance from the centre. The cutting action is more efficient at the outer regions of the cutting lips than near the drill's centre [14]. When considering the drilling of a composite part, good results are mainly fibre related and less dependent on the matrix material [15].

Due to the abrasive nature of reinforcement fibres, combined with the laminar nature of parts, several damages are due to occur during drilling operations, like push-down delamination, fibre pull-out or thermal damages [16]. The most frequent and noticeable evidence of these damages is the existence of an edge around

the machined hole, namely at the exit side of the drill, as a consequence of the drilling process. In this region, it is possible to observe, by visual or enhanced inspection, the separation of adjacent plies of the laminate. This damage is known as delamination and is normally classified as peel-up, Fig. 1(a) or push-down, Fig. 1(b), according to the zone of the plate where it is prone to occur, respectively, at the primary tool-plate contact zone and as the tool tip approaches the lower end of the laminate during its cutting action. Peel-up delamination, Fig. 1(a), is a consequence of the cutting force pushing the abraded and cut materials to the flute surface. Push-down delamination, Fig. 1(b), is a damage that occurs in interlaminar regions, so it depends not only on fibre nature, but also on resin type and respective properties. This damage is a consequence of the compressive thrust force that the drill chisel edge always exerts on the uncut laminate plies. There is a certain point at which the loading exceeds the interlaminar bond strength and delamination occurs. Analysis of delamination onset mechanisms during drilling using Linear Elastic Fracture Mechanics (LEFM) based approach have been developed and different models presented. The one most referred to is the Hocheng–Dharan [17] delamination model. In this model, the critical thrust force for the onset of delamination, F_{crit} , is related with properties of the unidirectional laminate, such as the elastic modulus, E_1 , the Poisson ratio, ν_{12} , the interlaminar fracture toughness in mode I, G_{Ic} , and the uncut plate thickness (h):

$$F_{crit} = \pi \left[\frac{8G_{Ic}E_1h^3}{3(1-\nu_{12}^2)} \right]^{1/2} \quad (1)$$

Delamination is considered as one of the most critical damages that can occur as it can contribute to a decrease in the mechanical strength of the part. These damages can affect not only the load carrying capacity of laminated parts but also strength and stiffness, thus reliability [18]. Rapid tool wear, due to material abrasiveness and matrix softening, due to heat build-up, can also be an important factor in damage occurrence [19]. Another consequence is the need of frequent tool changes that affects the production cycle and raises the final cost. Therefore, the reduction of this damage is of capital importance to the industry of composites. The importance of tool geometry in delamination reduction is evidenced by numerous published papers on this subject, see [20–26].

2.2. Delamination Assessment

As composite materials are sometimes opaque some damages could not be visible in a visual inspection, so it is needed to establish non-destructive testing (NDT) techniques in order to determine the extension of internal damages, such as delamination. Some of these techniques are usually found in published papers like the use of a tool maker's microscope [27,28], ultrasound techniques

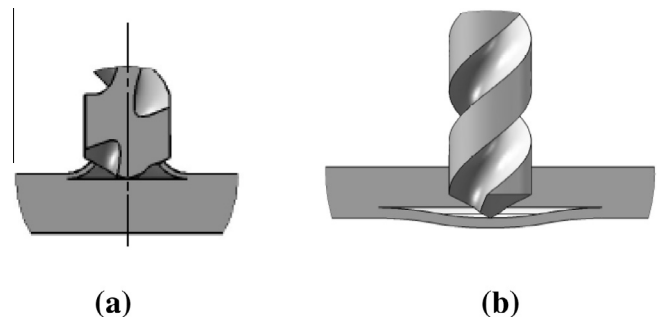


Fig. 1. Delamination mechanisms: (a) peel-up delamination at entrance; (b) push-down delamination at exit.

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