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Comprehensive study on machinability of sustainable and conventional fibre reinforced polymer composites

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ABSTRACT

The conventional homogeneous materials can no longer effectively satisfy the growing demands on product capabilities and performance, due to the advancement in products design and materials engineering. Therefore, the fibre reinforced composites (FRCs) with better properties and desirable applications emerged. These enhanced qualities of the FRCs have emphasized the need for analysing their machinability for further improvement of performance. Hence, this paper presents a comprehensive investigation on the machinability effects of drilling parameters (feed rate, cutting speed and thrust force), drill diameters and chips formation mainly on delamination and surface roughness of hemp fibre reinforced polymer (19/HFRP) and carbon fibre reinforced polymer (MTM 44-1/CFRP) composite laminates, using high speed steel (HSS) drills under dry machining condition. The results obtained depict that an increase in feed rate and thrust force caused an increase in delamination and surface roughness of both samples, different from cutting speed. Also, increased drill diameter and types of chips formation caused an increase in both delamination and surface roughness of both samples, as the material removal rate (MRR) increased. Evidently, the minimum surface roughness and delamination factor of the two samples for an optimal drilling are associated with feed rates of 0.05–0.10 mm/rev and cutting speed of 30 m/min.

1. Introduction

Recently, there has been growing interest in the composites technology. The composites technology has enabled the production of outstanding FRCs with respects to better damage tolerance, impact resistance, toughness, sustainability, renewability, strength, electromagnetic transparency, biodegradability, environmental superiority, cost and ease of productions, part count reduction, stiffness, design flexibility, low weight, mechanical damping, strength properties as well as chemical, thermal, high corrosion and wear resistance when compared with the conventional metallic engineering materials [1–6]. These desirable general inherent and better properties have increased the areas of application of these heterogeneous materials as both functional and structural components. The areas of application include, but are not limited to, telecommunication, automotive, oil and gas, building and construction, sports and recreation, aviation, biomedical, marine (naval), electronics, defense or military, power generation, consumer products, food and packaging industries [1–4,7–15]. Also, the environmental and economic global treats today have called for the production of natural fibre reinforced, bio-resourced and sustainable composite materials as a substitute for a synthetic (conventional) fibre reinforced polymer (FRP) composites [5,10]. For instance, based on the directive issued by the European Union, it requires that the greatest percentage of 85%, followed by 10% and just only 5% of all new automobiles should be reusable (recyclable) by weight, for energy recovery and used in landfills respectively, starting from year 2015 [16]. However, the application of some synthetic fibre reinforced composites has not been totally replaced with the natural fibre reinforced composites in engineering structures, because of the remarkable properties of these synthetic or conventional FRCs which include, but are not limited to, relative high tensile and impact strengths, strong fibre–matrix interface adhesion and high melting points.

The hemp fibre is a bast lignocellulosic natural fibre, which reinforced a fully biodegradable thermoplastic matrix, known as polycaprolactone (PCL), while the carbon fibre is an inorganic and synthetic fibre, which reinforced a non-biodegradable

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thermoset matrix, known as Epoxy resin (EP) [5]. Therefore, the hemp fibre reinforced polymer (HFRP) is an example of a natural (sustainable) fibre reinforced composite, while carbon fibre reinforced polymer (CFRP) is referred to as a synthetic (conventional) and inorganic composite, as shown in Fig. 1. Drilling holes on a FRP composites is an indispensable and inevitable operation that is required for an assembly operation [6,8,17].

The quality and the integrity of the holes obtained during drilling of various fibre reinforced composite laminates are quite different from that of drilled metals [17]. The drilled metal surfaces are smoother and more regular than the drilled composite surfaces under the same conditions [18], due to the abrasive nature, heterogeneity and anisotropy of fibre reinforced composite (FRC) materials [17]. In addition, the combination of the poor thermal conductivity of the resin matrix as well as the tough and abrasive properties of some FRCs cause their poor machinability. The effects of these properties on a drilled composite result in some severe drilling-induced damage, including delamination, surface roughness, crack development, fuzzing, spalling, fibre-uncut and pull-out, matrix sintering or burning and de-bonding, as well as drill edge chipping and excessive wear which are associated with drills [9,19–22]. These damage make drilling of high quality holes on FRP composites with a little or no damage a serious challenge [7]. The delamination and surface roughness defects have been reported as the most critical defects on drilled composite materials [7,23,24].

Delamination is simply defined as the main form of failure of laminated composites whereby the laminates or layers separate along their interfaces [1]. Delamination sometimes forms as a crack between the adjacent plies; it occurs often between two anisotropic and heterogeneous materials as an interface crack. Furthermore, it occurs under a tensile loading, bending loads, but it grows mostly under the critical compressive and fatigue loading conditions [1]. Many researchers have reported causes of delamination, namely; it was reported that increase in feed rate increased the delamination, whereas an increase in cutting speed reduced the delamination [25,26]. Therefore, low feed rates coupled with high cutting speeds reduced delamination [27–29], meanwhile the feed rate, among other drilling parameters, has the greatest influence on delamination [27]. Principally, the acted thrust force on the chisel edge of drills caused delamination defect [7,8]. Capello [30] concluded that drilling with a supported plate significantly reduced delamination defect. The use of HSS drills is rampant due to its availability, low cost and highest toughness, making it the most widely used tooling material, as reported by Ismail et al. [22], Davim and Reis [31], Che [32] and Hocheng and Tsao [33].

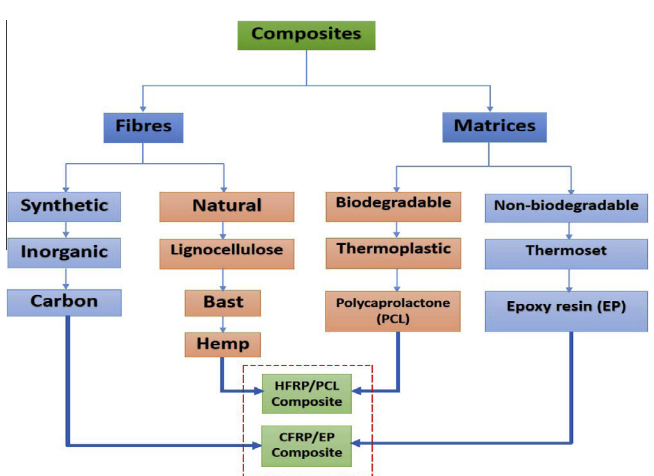

Fig. 1. The main compositions, properties and architecture of the FRCs (workpiece) used.

Surface roughness, R_a is defined as the average mean of the deviation of the roughness profile from the average line within the estimated length. Surface roughness is a very vital quality in a drilled hole, because mechanisms of creep, wear, fatigue and corrosion depend on it. Babu et al. [28,29] performed experiment on HFRP and recorded lowest delamination factor and surface roughness when compared with glass, jute and banana FRCs. Surface roughness differs at a various cutting speeds, but feed rate has a significant effect than the cutting speed [34,35]. It was concluded that an increase in feed rate resulted to an increase in surface roughness of drilled holes, while an increased cutting speed caused a decrease in surface roughness of the drilled holes of the materials used [34,36]. In addition, the drill diameter, MRR and types of chips formation during drilling process have significant effects on the quality and integrity of the drilled holes. It has been reported that an increase in diameter of the drill bit produced an increase drill designed geometries such as chisel edge, web thickness and area of cut. Likewise, an increase in these drill bit geometries caused an increase in the drilling forces (thrust force and torque) [37]. The occurrence and intensity of both delamination and surface roughness depend mostly on these forces, developed during drilling operation. The increase in MRR leads to an increase in the types of chips formation. Also, the outcomes (Pareto's front) of the research study conducted by Sardinas et al. [38], using genetic algorithm evidently showed the relationship between the MRR and the maximum delamination factor. It was reported that the maximum delamination factor increased with the MRR. The greatest value of MRR, also known as the point of maximal productivity produced the greatest value of delamination factor (point of worst surface roughness or quality). The lowest delamination factor was produced at a point of corresponding value of the lowest MRR. Therefore, a lower MRR produced by a smaller diameter, lower feed rate and moderately higher cutting speed favoured the reduction of delamination drilling-induced damage on FRC materials.

While much research has concentrated on synthetic or conventional composites, but very little is known about the machinability of natural or sustainable composites, and a deep comprehensive experimental study of these two classes of composites, mainly on the material samples considered under the same drilling parameters and condition, is very rare and scarce. Consequently, this paper presents the results of an experimental analysis of the effects of drilling parameters (feed rate, thrust force and cutting speed), drills diameters and types of chips formation mainly on drilling-induced damage, known as delamination and surface roughness in the samples HFRP and CFRP composites, using Taguchi technique for design of experiment.

2. Experimentation

2.1. Materials and methods

The 197 × 197 mm, 5 mm thickness MTM 44-1/CFRP and 19/HFRP samples were used as experimental samples, simply referred to as CFRP and HFRP respectively. The HFRP was made up of aspect ratio (AR) of 19. The AR is the ratio of the fibre length to its diameter (L/D). The mean fibre element length, L and diameter, D are 432 μm and 22.4 μm respectively. The HFRP composite samples were fabricated using an extrusion process. A resin bio-binder; PCL, a semi-crystalline polymer having a specific gravity of 1.1 at a low melting temperature of 60 °C, as well as a flash point of 275 °C, was used. It was provided by Perstop (UK) (Capa© 6800). The hemp fibres reinforced the PCL at 20 wt% concentration. The hemp fibre used was Fedora 17 specie, delivered by FRD©. The hemp fibre is a very strong lignocellulosic natural fibre that requires less processing energy. The low pressure vacuum bag