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Advanced Hybrid Joining for Needle-punched rCF Composite-Metal Structures via Compression Moulding Process

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Advanced joining technology used for composite-metal hybrid structures is highly demanded in various industries, since conventional joining methods, e.g. fastening and adhesive bonding are not satisfied in various engineering scenarios. Fasteners are over-weight and adhesive bonding involves inefficient and environmental destructive processes. Alternatively, thermo-mechanical interlocking (e.g. metal pin interlocking and surface roughening) is promising to achieve decent strength of hybrid joints thanks to reinforcement in the through-thickness direction. In this study, an advanced hybrid joint was developed to improve bonding between aluminum alloy and recycled Carbon fibre/Polyphenylene sulfide composites (rCF/PPS) structures. The rCF/PPS nonwoven preform used for making composites was fabricated via a carding/needle punching process, leading to massive fibre nesting between the plies. To form interlocked joints, the punched preforms were fitted into the pre-drilled holes of the sand-blasted metal part, followed by compression moulding process for composite consolidation. The through-hole composite pins were characterized under X-ray and SEM. Results showed the hybrid joint design combines advantages of clinching joining and thermo-mechanical interlocking joining, leading to an increment of bonding strength. It is also lightweight because interlocking pins were made of fibre reinforcement composite, instead of metals. The bonding strength of the joint was tested with the single-lap shear specimens. The bonding performance was improved by 8.5% in contrast to samples without through-hole fibre reinforcement (pure polymer pin). The effects of fibre reinforcement and key process parameters were discussed. As an outcome of current results, the developed process will be suitable to fabricate composite/composite joint as well.

1. Introduction

Carbon-fiber reinforced polymer composites (CFRC) are increasingly used in various industries thanks to its competitive qualities including high strength, minimal maintenance, and light weight [1-2]. The utilization of CFRC is driven significantly by reducing of fuel consumption and related cost because of weight saving. In addition, it is also demanding to decrease greenhouse gas emissions for whole cycle of product lifespan [2]. Recycling from end-of-life waste has been emphasized as a main aspect of sustainability since more composites will be retiring in upcoming future. For instance, the COVID-19 pandemic has severely boosted the decommissioning of planes [3]. EU also aims that 85% of a vehicle which contains around 30 wt.% CFRC, can be recycled [4]. Although there are numbers of challenges to recycle CFRC, the recycled carbon fibers (rCFs) can be successfully converted into nonwovens via needle punching and compression moulding process. Needle punching is a green and cost-effective process that can tailor the through-thickness properties for mats and laminates, leading to better delamination resistance [5, 6]. Such needle punched nonwovens are always manufactured with thermoplastics such as PPS (polyphenylene sulphide) or even with hybrid fibers. The resulting non-woven composites have discontinuous long fibers which are randomly oriented within matrix. Therefore, materials like rCF/PPS composites can be a good alternative for aviation products with nearly 155% improvement in specific strength and 975% improvement in specific stiffness, comparing to Lexan F6000 [7].

Since rCF composites with through-thickness reinforcement became a reality, many studies were carried out to investigate the properties and performances of such new sustainable nonwoven composites. For instance, Kumar et al. [8] studied static shear behaviour of rCF/epoxy nonwovens by identifying interlaminar failure as a critical factor for shear strength. Ivars et al. [9] revealed effects of the fiber orientation distribution on the anisotropic mechanical properties of needle-punched rCF nonwovens. Barnett et al. [10] showed that rCF/PPS nonwovens offered stable energy absorption under crashworthiness loading. Local flaws, such as micro- porosity, did not impact energy absorption significantly. Although various literatures showed satisfactory properties of rCF nonwovens, one limitation hindered application of rCF nonwovens in more engineering scenarios. Inadequate adhesion between composites and dissimilar materials leads to catastrophic joint damage.

To design and apply a composite/metal joint is the most effective way to enhace the bonding. However, most used methods such as adhesive bonding and mechanical fasteners cannot fulfill high requirements from aerospace, automotive and marine industries. Fasteners are over-weight and adhesive bonding involves inefficient and environmental destructive processes [11]. Recently, the state-of-the-art advanced hybrid joining processes were frequently reported. Many researchers developed thermo-mechanical interlocking features by making small pins or lattices at metal surface [12, 13]. Such interface locking enables a significant delay in damage progression under cyclic loading, but metal pins damaged polymeric partner significantly during debonding. Ramaswamy et al. [14] and Kang et al. [15] investigated effects of surface morphologies on bonding strength considering grooves, speckled patterns, and inward dimples at metal surface. Results showed mode I crack propagation was delayed but the effects were strongly dependent on various geometric parameters of those grooves. Lacking of multiple failure modes, energy absorbed during debonding was limited. Abibe et al. [16] introduced the injection clinching joining process to generate spot joints between a metal with a pre-drilled hole and a polymer-based component. The polymer-based component contained a pre-assembled protruding stud that fitted into the pre-drilled hole on the metal part. Obviously, fiber damage of the composite substrate and residual stress in the metal component could not be avoided when high loads were introduced [17]. Reviewing these ideas of metal/composite hybrid joints, new concepts of combining through-thickness-reinforcement and mechanical interlocking are still needed to improve manufacturing efficiency while reducing joint weight.

In this study, a new advanced hybrid joining concept between metal and rCF/PPS nonwovens was fabricated for aerospace industries. The rCF/PPS nonwoven preform was used for making composites, which was fabricated with a carding/needle punching process, leading to massive fibre nesting between the plies. To form interlocked joints, the punched preforms were fit into the pre-drilled holes on the sand-blasted metal part followed by compression moulding process. The joining process is hence integrated with needle punching process of rCF nonwovens. The hybrid joints were tested by means of single lap shearing. The through-hole composite pins were characterized to investigate sample qualities and potential failure modes.

2. Experimental

The metal/composite hybrid joint was made of Aluminum alloy 2024 plates and rCF/PPS nonwoven composites. Specifically, a prepreg (ELG™ PPS/70 IM56L) containing pyrolyzed rCF and PPS polymer (Carbiso™) was used in this study. The prepreg was a random-orientated fibre mat with a fibre volume fraction (V_f) of 0.4 [18]. Upon assessment of the void content, additional resin was needed to assist fibre-matrix impregnation and filling the voids The additional material was then introduced by interspersing layers of PPS (Ryton, Solvay) film between every layer of Carbiso™. The amount of resin added was controlled by the thickness of the PPS film, as shown in Fig. 1(a). Tensile tests were firstly carried out to evaluate potential in-plane anisotropic performance of Carbiso™ rCF/PPS composites, according to the ASTM standard D3039.

To fabricate the metal/composite joints, arrays of holes were drilled in Al plate with the pattern shown in Fig. 1(b) for fiber-locking. Hole diameter was designed as 2 mm with interval of 4 mm which was roughly the smallest size that allows polymer to flow. The joining aera of 1 × 0.5 inches at Al plate surface was sandblasted. The Carbiso™ composite mat was needle punched towards pre-drilled holes to form through-hole fiber reinforcement, and an additional PPS film was placed at the back of the holes. The mat was aligned with its longitudinal direction. The set up was then processed under the Collin hot press using compression moulding technique. A pressure of 5 bar and temperature of 290 °C were chosen as optimal parameters for 10 min compression moulding process, as illustrated in Fig. 1. As a benchmark, Carbiso™ composites were moulded together with Al plate without fiber carding/punching process. Therefore, pure PPS polymer filled those holes.

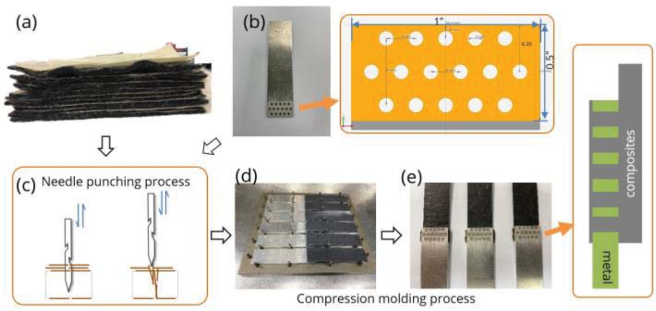

Fig. 1 Advanced joint concept made of (a) rCF/PPS nonwoven mats and (b) Al plate with pre-drilled holes by means of (c) needle punching and (d)(e) compression moulding process.

The joint strength was evaluated by conducting single lap shearing tests according to the ASTM D3163 standard. The specimens were loaded in tension at speed of 1.27 mm/min. Five effective samples were tested for averaging. Morphologies of failed samples were characterized with Scanning electron microscopy (SEM). X-ray CT was undertaken to check joint quality with the High Energy CT system (HECT). In total 2160 projections were completed at 215 kV and 120 µA, with a 0.5 mm copper filter at 1 second exposure duration. Optical microscope was also used to check fiber orientations.

3. Results and Discussions

Fig. 2 shows typical stress-strain curves of rCF/PPS nonwoven composites in longitudinal and transverse directions obtained from tensile tests. Results reflected that longitudinal tensile strength of 258.7 ±3.4 MPa was slightly higher than transverse strength of 247.5±8.3 MPa, indicating effect of material anisotropic is minimal. Modulus values from both directions are close, 24.28±0.47 GPa for longitudinal and 26.58±1.30 GPa for transverse direction. From microscopic picture (Fig 2(b)), a uniform and random fiber orientation was observed. PPS polymer was well impregnated with rCF fibers.

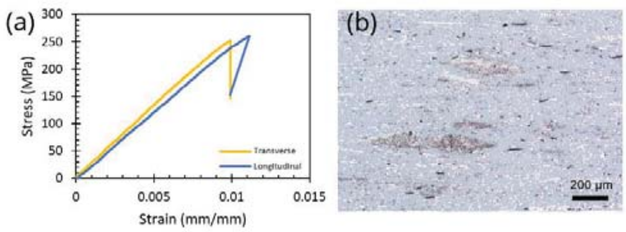

Fig. 2 Tensile testing results of rCF/PPS nonwoven composites in longitudinal and transverse directions; (b) microscopic picture of random fiber orientation.

Fig. 3 presents failure loads of the developed hybrid joints in single-lap shear tests. The benchmark group failed at 2200 N and the proposed concept of hybrid joint failed at 2387 N, by average. Compared with the benchmark, the ultimate failure load of needle-punched joints was 8.5% higher, indicating effect of through-hole fiber reinforcement. Both samples failed at metal/composite interface showing bad adhesion between dissimilar materials. Composite pins were also broken at the same interface, meaning composite pins did not change crack propagation path. Fiber breakage was observed in proposed joint while a clean fracture section was observed in the benchmark group.

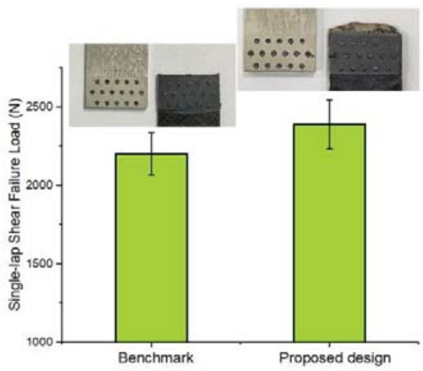

Fig. 3 Single-lap shear strength of prepared hybrid joint samples and corresponding failure faces.

Typical morphologies of failed samples are shown in SEM images in Fig 4. Fig. 4(a) and (b) shows failed pin of the benchmark samples. A relative smooth surface was observed at Al plate. No fiber was observed inside the pin hole. At the fracture surface of the hole, clear fiber imprints were seen, indicating debonding happened between pure polymer pin and rCFs. There was also adhesive interface debonding between polymer pins and metal holes. Fig. 4(c) and (d) displays needle-punched composite pin in the metal hole. It can be seen a relative rougher fracture surface with piecemeal composite clusters. Inside and surrounding the clusters, fiber rupture and fiber pull-out failure modes were identified. Therefore, it is clear that rCFs were successfully punched into locking holes in the hybrid joints. With through-hole fiber reinforcement, multiple failure modes were observed, leading to slightly higher joint bonding strength.

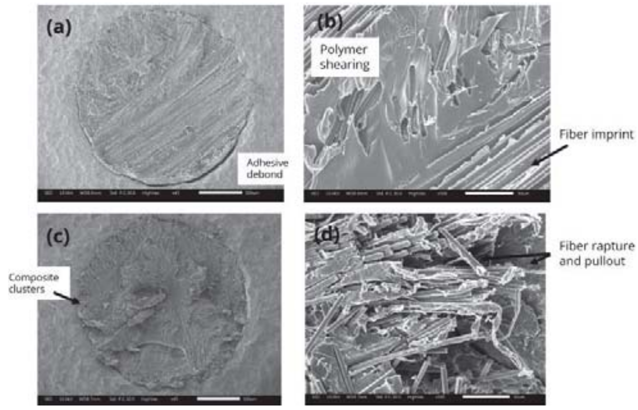

Fig. 4 SEM images of failed single-lap shear testing samples: (a), (b) morphologies at joint holes without needle-punched fiber reinforcement and (c), (d) morphologies at joint holes with needle-punched fiber reinforcement.

Quality of the hybrid joints were characterized with X-ray scanning. Fig. 5 illustrates porosity distribution and flaws as a result of current processes. According to Fig. 5, the PPS polymer was fully transferred and overall well impregnated into locking holes. A good interface was generated between primary metal/composite interface. However, porosity was observed at back side of the holes (Fig. 5(b)), indicating insufficient PPS supply from the back. In addition, small gaps between composite pins and locking holes were captured, showing shrinkage of composite pins during compression moulding process. Such pre-cracks are believed to reduce the locking effect. And sufficient polymer flow is also key factor to achieve good joint quality.

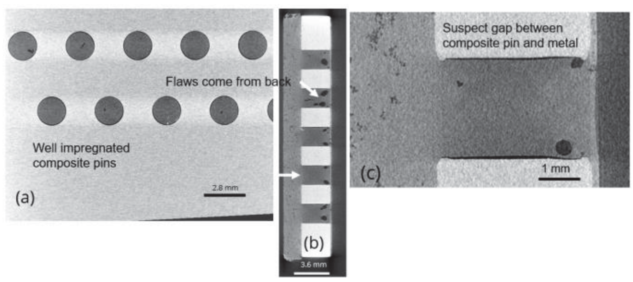

Fig. 5 X-ray scanning of hybrid joints before testing at (a) front view, (b) side view and (c) typical inter-locking hole.

4. Conclusions

In this study, an investigation on performance of rCF/PPS nonwoven composites as an alternative candidate to replace engineering plastics for aerospace interior products was conducted. A new concept of advanced hybrid joint was fabricated for metal/composite interface combining needle-punching and compression molding processes. Results showed that rCF/PPS nonwoven composites had a uniform and random fiber orientation, leading to a minimal in-plane anisotropic effect. The through-hole fiber reinforcement was introduced in hybrid joints bringing 8.5% increment of single-lap shearing strength, compared with the benchmark. Through-thickness reinforcement of composite resulted in multiple failure modes under single-lap shearing, including fiber rapture, fiber pull-out and composite cluster failure at interlocking holes. The joining quality can be further improved since small porosity and cracks were observed under X-ray characterizations. The flaws can be mitigated by adding polymer flow from the back and control fiber volume fraction through inter-locking holes. In the future studies, hole size and shape could be further optimized. Fiber stitching effect can be introduced into the system which allows continuous fibers wrapped through adjunct holes.

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