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Direct-Friction Riveting of polymer composite laminates for aircraft applications

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Abstract: Friction Riveting is an alternative joining technology to the conventional mechanical fastening suitable for woven-reinforced polymer composites. In this paper, the feasibility of Direct-Friction Riveting is demonstrated for Ti6Al4V rivet and carbon-fiber reinforced polyether-ether-ketone laminate single lap joints. Due to high shear rates, elevated process temperatures (500-900°C) and fast cooling rates (38 ± 2°C/s) experienced by the rivet tip, α'-martensitic structures were identified in the rivet anchoring zone along with fiber and polymer entrapment at the rivet-composite interface. An average ultimate lap shear force of 7.4 ± 0.6 kN similar to conventional lock-bolted single lap joints was achieved. These results indicate that Direct-Friction Riveting is a competitive method with potential for improvement and further application in aircraft structures.

Keywords: Direct-Friction Riveting, Ti6Al4V, woven carbon-fiber reinforced composites

1. Introduction

As fuselages and wings have been increasingly manufactured out of composites, many of the structural metallic clips and brackets holding the major interior assemblies are changing to thermoplastic composites, such as carbon-fiber reinforced polyether-ether-ketone (CF-PEEK). These structures are currently mechanically fastened to fuselage skins, leading to design challenges due to intrinsic material proneness to early crack initiation [1]. To overcome these limitations, the development of advanced ~~and sustainable~~ joining technologies is required [2].

Friction Riveting (FricRiveting) has been shown as a potential alternative joining process for woven-reinforced thermoplastics ~~composites~~ [3]. The technique uses frictional heat and pressure to plasticize and deform a cylindrical metallic rivet, joining composite parts through mechanical interference and adhesion forces by polymer reconsolidation. The technique eliminates additional steps (e.g. pre-drilling), decreasing joining cycles [4]. Friction-riveted overlap joints can be produced either by pre-riveting the lower base component and assembling the upper pre-drilled part [3] or by Direct-FricRiveting, as reported in [4] for unreinforced polymers. While the former is simpler, the latter is complex in nature, as the direct rivet insertion through overlapped joining parts highly modifies the heat generation, material flow and joint formation mechanisms. There is limited knowledge on the joining mechanisms and mechanical behavior of such overlap joints. Moreover, Direct-FricRiveting has not been reported for thermoplastic composite laminates.

In this study, an improved approach for ~~the~~ Direct-FricRiveting ~~process~~ is proposed for thermoplastic composite laminate single-lap joints. Woven-carbon-fiber-reinforced polyether-ether-ketone (CF-PEEK) sheets were joined with Ti6Al4V rivets. This process introduces a novel displacement process control with ~~a~~ two-step friction phase corresponding to each overlapped base component, while force and time are process responses. ~~For this purpose~~Consequently, two new process control parameters were introduced in the friction phase: Displacement at Friction in Step I and Step II. Therefore, a phenomenological process description is required to describe the new process variant. Process temperature evolution, microstructural features, local and global quasi-static joint mechanical properties and failure modes were addressed to describe the fundamentals of the new process variant.

2. Materials and methods

4.34 mm (nominal thickness) CF-PEEK laminates with 58 wt% nominal fiber content and the stacking sequence of $[(0,90)/(\pm45)]_3/(0,90)]_s$ (Toho Tenax Europe GmbH, France) were joined with extruded plain rivets of Ti6Al4V alloy with 5 mm diameter and 60 mm length.

Joining was performed using an automated FricRiveting gantry system (RNA, H.Loitz-Robotik, Germany). The selected joining condition (Table 1) was determined based on previous investigations on conventional FricRiveting for a similar material combination ~~of materials~~ [5] and on parameter pre-screening. Process temperature was monitored by infrared thermography in the expelled material (Image IR8800, InfraTec, Germany) and type-K thermocouples placed between the composite parts. The cooling rate was calculated by linear fitting of the thermometry curves. Microstructural analysis was performed on joint mid-cross sections using reflected-light optical and scanning electron microscopy. The metallic partner was etched with Kroll reagent. Local mechanical properties were investigated through Vickers microhardness mapping, while quasi-static mechanical performance was evaluated by lap shear testing according to ASTM D5961 (2 mm/min~~, at~~ room temperature). Friction-riveted joints were tightened at 0.5 Nm with M5 stainless steel nuts and washers [6].

Table 1. Selected joining parameters.

Rotational Speed [rpm]	Friction Force I [kN]	Friction Force II, [kN]	Displacement at Friction ~~at Step~~ I [mm]	Displacement at Friction ~~at Step~~ II [mm]	Consolidation Time [s]	Clamping Pressure [bar]
15000	5	20	4	3.5	10	6

3. Principles of Direct-Friction Riveting

The principles of Direct-Friction Riveting are based on conventional Friction Riveting, which consists of friction-based heat generation followed by rivet tip plastic deformation due to axial force increases [3,5]. In its simplest configuration, Direct-Friction Riveting is controlled by force and limited by displacement (*i.e.* ~~limitation of~~ each joining phase ~~was based on~~limited by rivet displacement) and divided into two main phases: a two-step friction phase - characterized by rivet rotation and applied axial force - and a subsequent consolidation phase without rivet rotation. Fig. 1 (a) depicts the process phases ~~based on an illustration of the process~~ along with the evolution of joint formation monitored by X-ray micro-tomography in different joining stages. Fig. 1 (b) shows potential applications for skin-bracket and clips in aircraft structures for directly friction-riveted overlap joints.

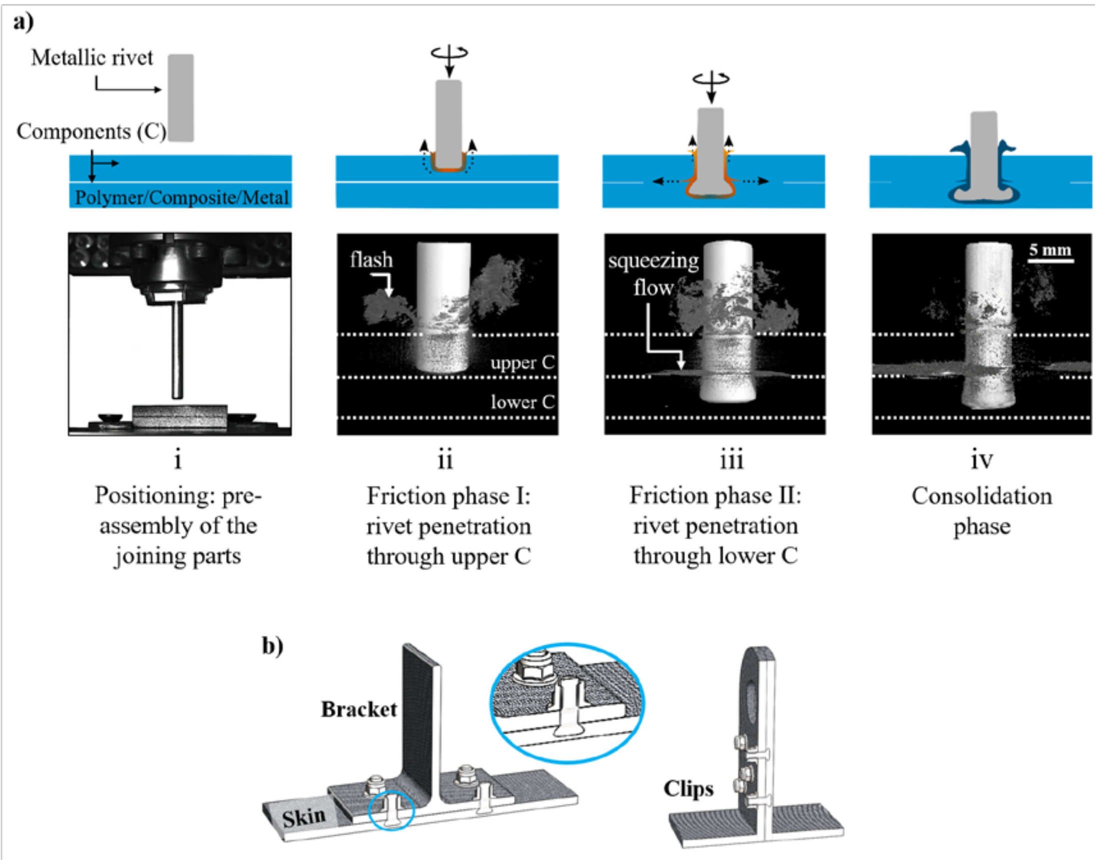

Fig. 1. a) Direct-Friction Riveting process steps along with 3D images of the joint at different joining stages obtained by X-ray microtomography: i. positioning of the joining parts, ii. rivet rotation and insertion through the upper component, iii. rivet insertion through the lower component and rivet plastic deformation, iv. joint consolidation. b) Potential applications of friction-riveted joints for aircraft structures.

After the positioning of the components (Fig. 1 (a-i)), the rotating rivet moves toward the surface of the upper component applying constant force. In Step I of the friction phase, heat is generated, and a polymeric layer is softened or molten in the rivet vicinities (Fig. 1 (a-ii)). Due to the continuous controlled insertion of the rivet into the upper base component, the softened polymeric material is expelled as flash outwards the joining area (Fig. 1 (a-ii)). In Step II of the friction phase (Fig. 1 (a-iii)), the rivet rotates with constant speed while the axial force is increased to favor rivet insertion in the second composite part. The internal stress distribution within the joint leads to changes in the material flow, promoting certain polymer squeezing flow between the base components (Fig. 1 (a-iii)). By the end of the friction phase, when the frictional heat generation stops, the local temperature at the rivet tip reaches the metal plasticizing temperature. The cold polymeric volume underneath the plasticized rivet tip creates resistance to the rivet insertion, plastically deforming the rivet tip in the lower base component (Fig. 1 (a-iii)). At this moment, the rotation halts, whereas no further axial force is applied (Fig. 1 (a-iv)); although not investigated in this study, a larger ~~axial force (*i.e.* a~~ forging force ~~)~~ may be applied. The joint consolidates under ~~same~~ constant axial pressure to reduce relaxation effects during natural cooling and dimensional changes of the joining parts.

4. Results and discussion

The typical microstructure of direct-friction-riveted joints is presented in Fig. 2 (a). The plastically deformed rivet tip is restricted to the thickness of the lower based component; outward flow of molten polymer and a few broken fibers are consolidated along the rivet shaft. Temperatures of 500°C in the composite flash and of 900°C on the metallic surface were measured (Fig. 2 (b)). The high shear rates and temperatures promoted a combination of metallic deformational flow and wear in the rivet tip. As a result, a final rough surface at the deformed rivet tip is formed (Fig. 2 (c-i)), where polymer and broken fibers are entrapped. Such features can contribute to the mechanical performance of the joints through micromechanical interlocking, as reported by Goushegir *et al*. [7] for AA2024-T / CF-PPS friction~~-~~spot joints ~~of AA2024-T3 and CF-PPS~~.

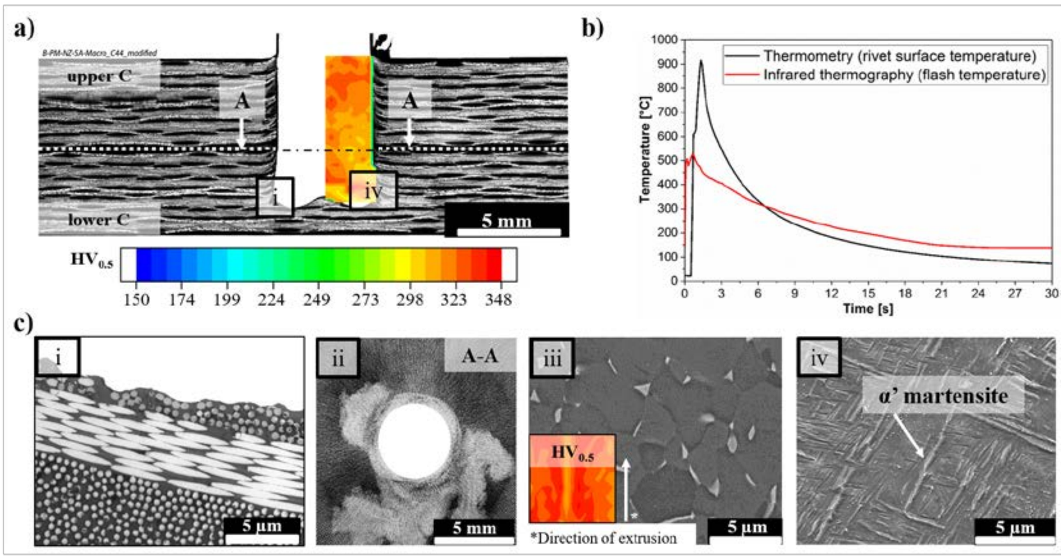

Fig. 2. a) Cross-section of direct-friction-riveted joint, showing the microhardness distribution ~~map of~~in the metallic rivet; b) typical thermometry and infrared thermography curves; c) details~~ed regions~~ of the

cross-section, showing features in the metal-composite interface (c-i), ~~composite ~~squeezed composite~~ing flow~~ (c-ii), microstructures and microhardness of Ti6Al4V base material (c-iii) and -microstructure of the rivet tip (c-iv).

During the rivet insertion through the second composite component, stress fields are modified inducing slight bending of the base components and composite squeezing flow between the composite plates, as shown in Fig. 2 (c-ii). Although the consolidated squeezing flow might contribute as additional joining mechanism by adhesion forces, it slightly separates the~~ composite~~ plates forming structurally undesired small gaps. Current studies involving process optimization are being carried out to reduce this side effect.

Although no significant changes in the microhardness of the rivet (Fig. 2 (a)) in comparison to the base material (Fig. 2 (c-iii)) were identified, the thermo-mechanical processing along with the natural cooling rate of 38 ± 2°C/s ~~were sufficient to ~~changed the microstructure of Ti6Al4V from equiaxed morphology (Fig. 2 (c-iii)) to martensitic structure (Fig. 2 (c-iv)) in the rivet tip~~anchoring zone~~. Moreover this cooling rate is higher than the ones experienced during laminate~~is higher thanthe ones experienced during laminate~~ manufacturing (0.08°C/s [8]). Therefore, a decrease of 60% in PEEK crystallinity (11 ± 1%) measured by differential scanning calorimetry in the joint expelled material. Thermal degradation (onset temperature of PEEK at 575°C [9]) may be expected in a narrow volume of composite in the rivet surroundings, as ~~typically ~~reported in FricRiveting [4].

Fig. 3 shows the ~~top and cross-sectional views of ~~friction-riveted (Fig. 3 (a)) and reference lock-bolted joints (Fig.3 (b)) while Fig. 3 (c) compares their ultimate lap-shear forces (ULSF). At this development stage, friction-riveted joints displayed ULSF of 7.4 ± 0.6 kN, whereas the reference joints withstood an average of 8.7 ± 0.2 kN (Fig. 3 (c)). Due to lower penetration depth of the deformed rivet tip (see inset figures in Fig. 3(a) and (b)), friction-riveted joints failed by full-rivet pull out, while reference joints failed by shear through the rivet. Nonetheless, the strength of friction-riveted joint is expected to be improved through ongoing process, joint design and tightening torque optimization.

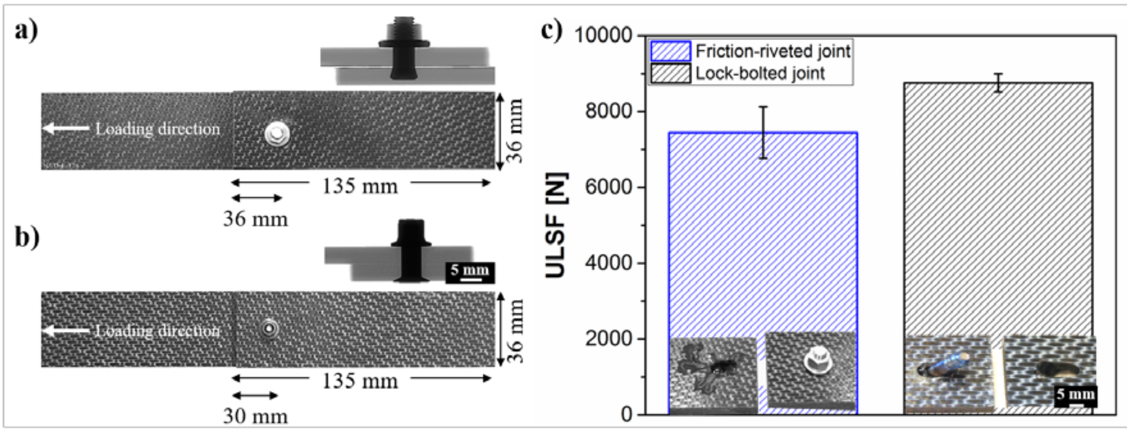

Fig. 3. L~~Illustration of l~~ap-shear specimen geometry for a) friction-riveted and b) lock-bolted joints; c) comparison of the lap-shear strength between friction-riveted and reference joints ~~(reference joints~~ produced in the work of [5]~~)~~.

5. Final remarks

Direct-Friction Riveting was introduced as a promising solution for woven-carbon-fiber reinforced thermoplastics. Preliminary results on Ti6Al4V/CF-PEEK friction-riveted joints displayed microstructural changes in Ti6Al4V rivet due to high process temperature (500°C in the composite flash and 900°C on the metallic rivet surface), fast cooling rate (38 ± 2°C/s) and shear rates. Micro-mechanical interlocking due to fiber and polymer entrapment to the metal surface was identified as additional joining mechanism to the macro-mechanical rivet anchoring. Friction-riveted joint strengths (7.4 ± 0.6 kN) were similar to conventional lock-bolted joints (8.7 ± 0.2 kN) in this exploratory study, but higher values may be achieved through further process and design optimizations.

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