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Direct-Friction Riveting of polymer composite laminates for aircraft applications

N.Z. Borba [a], L. Blaga [a], J.F. dos Santos [a], S.T. Amancio-Filho [a,b,*]

[a] Helmholtz-Zentrum Geesthacht, Centre for Materials and Coastal Research, Institute of Materials Research, Materials Mechanics, Solid State Joining Processes, Geesthacht, Germany
[b] Hamburg University of Technology, Institute of Polymer Composites, Hamburg, Germany

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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.

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 joining technologies is required [2].

Friction Riveting (FricRiveting) has been shown as a potential alternative joining process for woven-reinforced thermoplastics [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 Direct-FricRiveting 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 two-step friction phase corresponding to each overlapped base component, while force and time are process responses. 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.

* Corresponding author at: Helmholtz-Zentrum Geesthacht, Centre for Materials and Coastal Research, Institute of Materials Research, Materials Mechanics, Solid State Joining Processes, Geesthacht, Germany.
E-mail address: sergio.amancio@hzg.de (S.T. Amancio-Filho).

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Table 1
Selected joining parameters.

Rotational speed [rpm]	Friction force I [kN]	Friction force II, [kN]	Displacement at friction I [mm]	Displacement at friction II [mm]	Consolidation time [s]	Clamping pressure [bar]
15,000	5	20	4	3.5	10	6

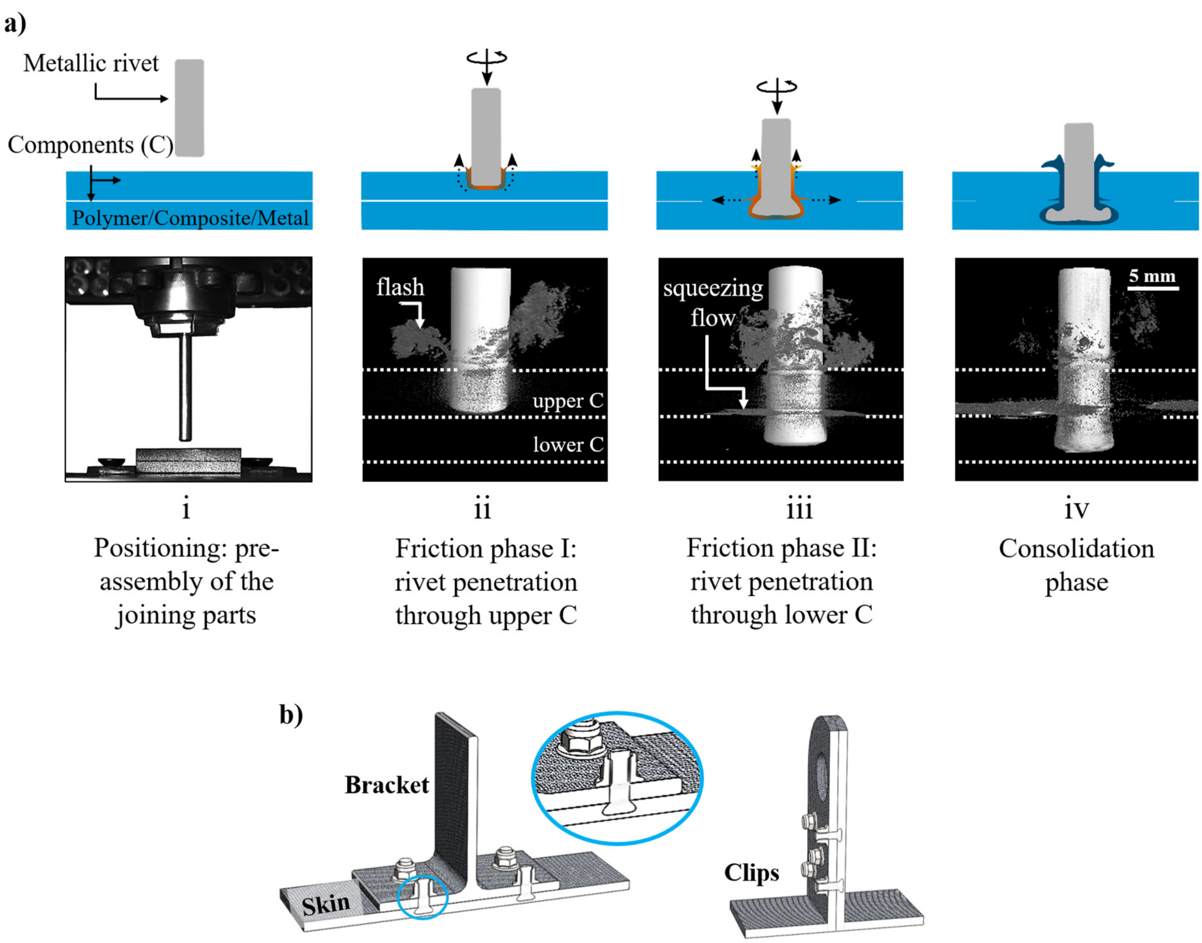

Fig. 1. a) Direct-Friction Riveting process steps along with 3D images of the joint at different joining stages obtained by X-ray microtomography: i. Positioning of the joining parts, ii. Rivet rotation and insertion through the upper component, iii. Rivet insertion through the lower component and rivet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

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 [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, room temperature). Friction-riveted joints were tightened at 0.5 Nm with M5 stainless steel nuts and washers [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.* each joining phase 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 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.

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,