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Friction Riveting of glass-fibre-reinforced polyetherimide composite and titanium grade 2 hybrid joints

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Abstract: In this work, the feasibility of Friction Riveting on thermoplastic composite laminates with metals was investigated on glass-fibre-reinforced polyetherimide with titanium grade 2. Microscopy analysis (light optical and laser scanning confocal microscopy), temperature monitoring (infrared thermometry) and quasi-static mechanical testing (T-pull tensile testing) were used to investigate joint properties. Joints with reduced amounts of thermo-mechanically modified composite material with moderate to high tensile strengths (1.9 to 4.0 kN) were achieved. The average process temperatures (430 to 464 °C) of the molten matrix were below the range inducing the extensive thermal degradation of the polyetherimide matrix and out of the range inducing the plasticising of titanium grade 2. The Volumetric Ratio, a simplified analytical model describing the anchoring efficiency of the rivet, was demonstrated to be directly proportional to the tensile strength of the joint and therefore an adequate analytical model to describe the mechanical performance of joints. Finally, a correlation between the rotational speed, heat input, process temperature and rivet plasticising was observed. The higher the rotational speed was, the higher the heat input, temperature and deformation of the plasticised rivet tip became, leading to higher rivet anchoring performances.

Keywords: Friction Riveting, composite-metal joining, polyetherimide, titanium

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1. Introduction

Glass fibre reinforced polymer (GFRP) composite laminates have demonstrated their efficiency in a wide range of engineering applications, mostly due to their good mechanical and chemical properties, such as high specific resistance (strength-to-weight ratio), durability and environmental and chemical resistance [1]. The most commonly used glass fibre in GFRP laminates is electrical grade glass (E-glass) due to its mechanical and electrical properties and reasonable cost [2]. Regardless of the design freedom associated with composites, one of the main issues facing the use of GFRP in engineering applications is the joining of polymeric composite parts. Available technologies include adhesive bonding, mechanical fastening and welding, but there is a constant surge in the development of alternative joining technologies to minimise the limitations of state-of-the-art processes, such as joint performance, production time and cost [3, 4].

Previous studies on friction-riveted unreinforced polyetherimide (PEI) / aluminum AA2024 joints [5] have demonstrated the feasibility of this technology in producing unreinforced thermoplastic / lightweight alloy hybrid joints. In this work, the feasibility of Friction Riveting (FricRiveting), a new riveting technology, was investigated using titanium grade 2 / glass fibre reinforced thermoplastic polyetherimide (PEI-GF) to produce metallic-insert joints. Joint microstructure (optical and laser scanning microscopy) and tensile resistance were studied to evaluate joint performance.

2. Materials and methods

Polyetherimide glass fibre reinforced laminates, PEI-GF (E-glass fibres, 8H satin, $[0,90]_{14}$, TenCate, Netherlands), measuring 70x70x6.2 mm were joined by commercially pure titanium grade 2 plain rivets (density 4.51 g/cm^3, composition:

99.2% Al, 0.30% Fe, 0.25% O) measuring 5 mm in diameter and 60 mm in length .

Metallic-insert joints (i.e., metallic bolts, screws or rivets inserted into polymeric or polymeric composite substrates), usually applied in the fabrication of connectors and brackets used in the transportation industry, were achieved using a commercially available friction welding system (RSM 400, Harms & Wende GmbH & Co. Germany).

An extensive investigation of the feasibility of FricRiveting for the current hybrid joints was performed based on qualitative evaluation criteria concerning joint properties (geometry of the deformed rivet tip, rivet anchoring efficiency and qualitative analysis of the amount of thermal flaws in the composite) [6]. After evaluating the process feasibility for the given material combination, the optimal process parameter range was established and the three best joints - with the greatest extent of rivet anchoring and fewest thermal flaws - were selected for the analysis of mechanical performance.

The microstructure of the joints was evaluated by light optical microscopy (Leica DC 300 stereomicroscope) and laser confocal microscopy (Keyence VK-9700). The process temperature was measured on the polymeric flash formed during joining, by infrared thermometry (procedure presented in [7]). T-pull tensile specimens were selected to study the tensile strength of the joints based on DIN EN 10002 [8]. Tests were performed at a strain rate of 1 mm/min at 21ºC (room temperature).

3. FricRiveting of PEI-GF / Ti gr.2

FricRiveting is an innovative joining technique developed by Helmholtz-Zentrum Geesthacht in Germany to create polymer-metal hybrid structures [9]. The basic configuration of the process (Figure 1) consists in rotating a cylindrical metallic rivet and inserting it into a polymeric base plate. Frictional heat is generated by the high rotational speed and the axial pressure. Due to the local increase in temperature, a molten polymeric layer is formed around the tip of the rotating rivet during the initial plunge stage. At the end of the heating phase, the heat input rate exceeds the heat outflow rate due to the low thermal conductivity of the polymer. The local temperature increases, leading to the plasticising of the tip of the rivet at temperatures below the alloy melting point [10]. As the rotation is decelerated, the axial pressure increases, the so-called forging pressure is applied and the plasticised tip of the rivet is deformed. As a result, the diameter of the original rivet increases, whereby the deformed rivet tip assumes a parabolic pattern due to the opposite reactive forces related to the colder polymeric volumes. After consolidation under pressure, the joint is held by the anchoring forces related to the deformed tip of the rivet, as well as by adhesive forces at the consolidated polymer/metal interface [11].

“Figure 1”

FricRiveting combines the advantages of both mechanical fastening and welding, and with an adequate joint design, the benefits of this innovative process are as follows: little or no surface preparation is needed; no obligatory through-holes are required, leading to less stress concentration; hermetically sealed joints can be achieved without the use of sealants; reduced number of process steps and short joining cycles, leading to potential cost savings; simple and low-cost machinery is needed; robotic applications are possible; joints exhibit high mechanical performance [7]. Because it is still in its development stage, FricRiveting has some limitations, which may be overcome with further research. Currently, the process is directly applicable to thermoplastic polymers only, friction-riveted joints cannot be disassembled and only spot-like joints can be achieved [5].

Since FricRiveting is based on the principles of mechanical fastening and friction-based joining processes, such as friction stir welding, some considerations have to be made on the applicability of the two technologies on GFRP-metal multi-material joints and also their comparison to FricRiveting. While the resistance of friction-riveted joints is based mainly on the mechanical interaction between the composite material and the anchored metallic rivet, FricRiveting differentiates from classical mechanical fastening techniques by the fact that it does not involve through-holes and has a thin layer of consolidated polymer sealing the joint, reducing thus stress concentrations. This process characteristic is very convenient considering that mechanically fastened GFRP joints usually exhibit high susceptibility to stress concentrations due to their brittle nature [12, 13]. Further information on the advantages and problems regarding mechanical fastening are presented in [14].

Similar to friction stir welding of metals, in the FricRiveting process frictional heat is generated by a rotating tool (in this case consumable, the actual rivet), creating a softened plasticized region around the immersed probe [15]. However, in the FricRiveting process, the heat input becomes larger than the heat outflow at a certain insertion depth. Due to the increasingly thermal insulation effect associated with the low thermal conductivity of the composite, the rivet tip plasticizes. With the application of the forging pressure the plasticized rivet deforms creating the anchoring zone [9]. Moreover, a physical interaction of the two materials is not likely to take place as in welding, due to the extremely dissimilar nature of metals and composites; when embedded in polymers, metals tend to form clusters instead of mixing themselves up [16]. Further information on the physical phenomena of friction welding of metals and composite welding can be found in [17-22].

4. Results and discussions

Joints were successfully produced within the following parameter ranges: rotational speed of 6000 - 20000 rpm, joining times of 1.9 - 4.2 s and joining pressures of 0.6 – 1.0 MPa. Under these conditions, microscopic analysis revealed the anchoring of the deformed rivet tip inside the composite plates [6].

In this work, selected results of the friction-riveted PEI-GF/Ti gr. 2 joints are presented. A typical cross-sectional view through the centre of a PEI-GF/Ti gr.2 joint (rotational speed 10000 rpm, joining time 3.2 s, joining pressure 1.0 MPa) is shown in Figure 2. The formation of the anchoring zone (the deformed rivet tip) can be observed; only few volumetric thermal flaws around the rivet could be identified using light optical microscopy and laser scanning confocal microscopy, as shown in Figure 2B and 2C.

“Figure 2”

The rivet locally perforates the glass-fibre-reinforced composite woven, while pieces of broken fibres and molten PEI matrix are expelled as flash material. The network of cut fibres formed around the anchored rivet is not thermally damaged but reoriented in the direction of the polymeric material flow (Figure 2A). The glass-fibre-reinforced woven is shifted upwards from its original plane by approximately 45 degrees, while it visually appears to remain largely in contact with the rivet shaft after the consolidation of the molten polymeric layer. Further microstructural investigation is required to better understand the microstructural changes in the joint area, but this is not within the scope of the present work.

The influence of the rotational speed on joint formation and mechanical performance was evaluated under three different joining conditions (Figure 3A): constant joining time (3.2 s) and joining pressure (1.0 MPa) and varying rotational speeds of 8000 rpm (Specimen A1), 9000 rpm (Specimen A2) and 10000 rpm (Specimen A3). The anchoring efficiency of the rivet can be estimated through the

Volumetric Ratio (VR), which takes into account, on a simplified geometrical basis, the ratio of the volume of dislocated polymeric material, the volume of the deformed metallic rivet and the volume of the remaining polymeric resistive material over the deformed shape of the rivet [6, 23].

Figure 3-B1 and 3-B2 show the geometrical simplifications and a 3D view of the interaction volume of the polymer used to calculate the Volumetric Ratio, where W is the maximal diameter of the deformed rivet, H is the insertion depth of the metallic rivet into the composite base material, H-B is the height of the remaining composite material over the deformed rivet shape, B is the height of the anchoring zone and D is the undeformed rivet diameter. The Volumetric Ratio varies between 0 and 1 and is dimensionless. The Volumetric Ratio represents the anchoring efficiency of the friction riveted joints and can be analytically expressed by the model in Equation 1.

“Figure 3”

$$VR = \frac{(H - B) \cdot (W^2 - D^2)}{W^2 \cdot H} \qquad (1)$$

The analytical model of the anchoring efficiency in Equation 1 includes, in a simplified way, the reactive forces that oppose the axial movement of the loaded deformed rivet inside the composite material, as well as adhesion forces (this additional bonding mechanism was previously reported to be present in FricRiveting [5]) due to the metal-composite contact interfaces. The graph in Figure 4A shows the interaction between the calculated VR and the ultimate tensile force achieved in the three mechanically tested T-pull tensile specimens.

“Figure 4”

It can be observed that the anchoring efficiency of the rivet, expressed as VR, is correlated to the ultimate tensile force (UTF) of the joint: the higher the VR is, the higher the rivet anchoring and the ultimate tensile force of the joint become. This trend was also observed for the unreinforced polyetherimide joined with aluminium rivets [24]. All specimens failed with an average UTF of 1.8 to 4.0 kN by “full rivet pullout” fracture, a ductile failure mode observed either in polymers with high ductility or in cases where the rivet tip is not highly deformed [24, 25]. In this failure mode, as shown in Figure 4A, a crack nucleates at the polymer-metal interface around the anchoring zone, separating the adhesively linked area; the polymeric interaction volume is plastically deformed by the pulling action of the deformed rivet, which is completely removed from the composite plate.

The influence of the rotational speed on the increased deformation of the rivet in Specimen A3 over that of A2 and A1 (increase in width, W, of approximately 16.5% for A3 compared to A1, as shown previously in Figure 3A) and therefore the higher ultimate tensile force can be explained by analysing its effect on the theoretical heat input using the equation proposed by Amancio-Filho [5]:

$$Q_{total} = \left[\left(\frac{2}{3} \cdot \mu \cdot P(r) \right) + \frac{\eta \cdot V_{\max}}{H} \right] \cdot V_{\max} \quad (2)$$

where

μ is the kinematic friction coefficient

P(r) is the normal pressure distribution over the frictional area

η is the molten polymer viscosity

$V_{\max}$ is the maximal tangential speed of the rivet obtained from the angular speed (ω) and the radius of the undeformed rivet (R):

$\omega = V_{max}/R$

H is the average width of the consolidated polymeric layer

Equation 2 shows that A3 will lead to higher theoretical heat input than A1 and A2 due to the higher rotational speed (in the model represented as $V_{\max}$), which is directly proportional to the heat generated, and quadrically proportional to the average total heat input, thus leading to a higher heat input and the plasticising of the rivet tip in specimen A3. The increase in the heat input could be verified from the infrared thermographical measurements shown in Figure 4, which shows that the measured process temperature increases with the rotational speed. Therefore, increases in heat input induced by rotation speed lead to higher metal plasticising, higher rivet tip deformation and volumetric ratios and thus stronger joints.

The process temperatures varied between 430 ºC and 464 ºC (Figure 4B) or 25-30% of the melting point of titanium grade 2 (1665 ºC). The temperatures required for the hot forming of commercially pure titanium range from 480 ºC - 705 ºC [26]. The measured temperatures were at the lower limit of this range, therefore explaining the formation of the rivet anchoring zone. The influence of the rotational speed on the process temperature, the formation of thermal flaws in the polymeric material and the tensile strength was studied previously by Amancio and dos Santos on unreinforced PEI/aluminium 2024 friction-riveted joints [27]. They reported that the amount of thermomechanically degraded polymer did not follow any clear pattern, most likely due to the high thermal resistance of the PEI, which presented only a small level of thermal degradation [10]; similar behaviour (very small amount of volumetric flaws) was observed in the present work. This can be explained by the fact that the current composite laminate contains the same thermoplastic matrix and the process temperatures were in the same range as those in the referred work.

5. Conclusions

The present study successfully proved the feasibility of FricRiveting of hybrid composite-metal PEI-GF/Ti gr.2 joints. The process parameters were optimised to a fair level of thermo-mechanical modification of the polymeric matrix, with a reduced amount of volumetric flaws at the anchoring zone and without inducing extensive damaging in the fibre network of the reinforcement glass fibre woven. Tensile tests revealed moderate to good mechanical performance, with specimens withstanding ultimate tensile forces of up to 4 kN with ductile fracture at the composite plate ("full rivet pullout" fracture type). The anchoring efficiency of the rivets, which provides an estimate of the mechanical performance of the corresponding joints, was evaluated using the Volumetric Ratio, which proved to be directly proportional to the ultimate tensile force achieved by the joints, with the highest Volumetric Ratio (0.25) leading to the highest ultimate tensile force (4 kN). Therefore, this approach of calculating the anchoring performance appears to provide an adequate estimate of the tensile strength of metallic-insert riveted joints. Additional analyses are required to further understand how mechanical performance is affected by the anchoring zone.

The measured process temperatures, influenced mainly by the rotational speed of the process, ranged between 430 ºC and 464 ºC, close to the temperatures required for the hot forming of commercially pure titanium. Moreover, the monitored process temperatures can be related to the small level of thermal degradation in the polymeric matrix and to the formation of the rivet anchoring zone.

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Figure Captions:

Figure 1

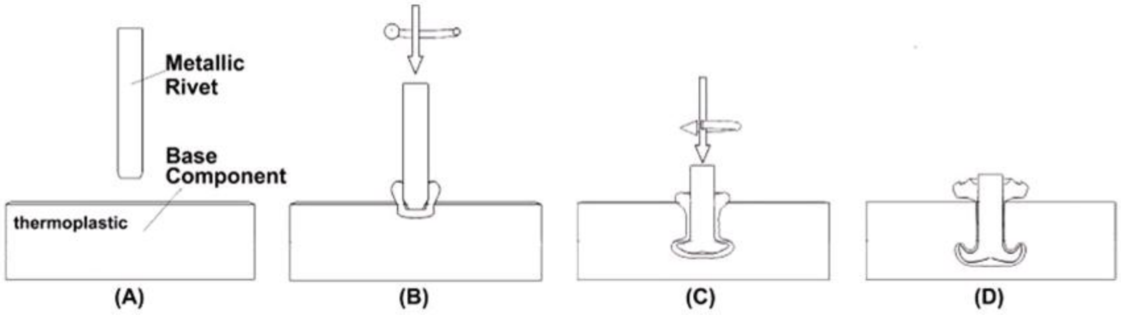

Figure 1 – Schematic view of the FricRiveting process in metallic-insert joints. (A) Positioning of the joining partners, (B) Feeding of the rivet into the polymer (Friction), (C) Rivet forging, (D) Joint consolidation.

Figure 2

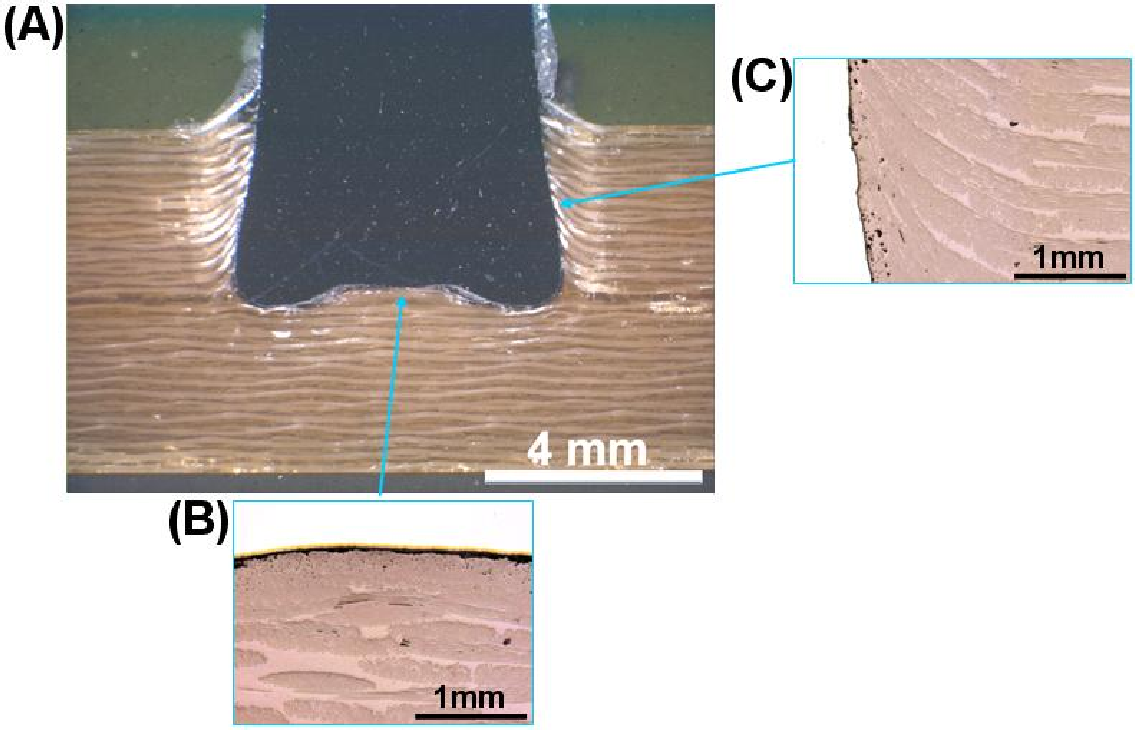

Figure 2 – (A) Example of a cross-sectional view of a friction-riveted PEI-GF/Ti gr.2 joint; (B) and (C) details of the volumetric thermal flaws around the rivet.

Figure 3

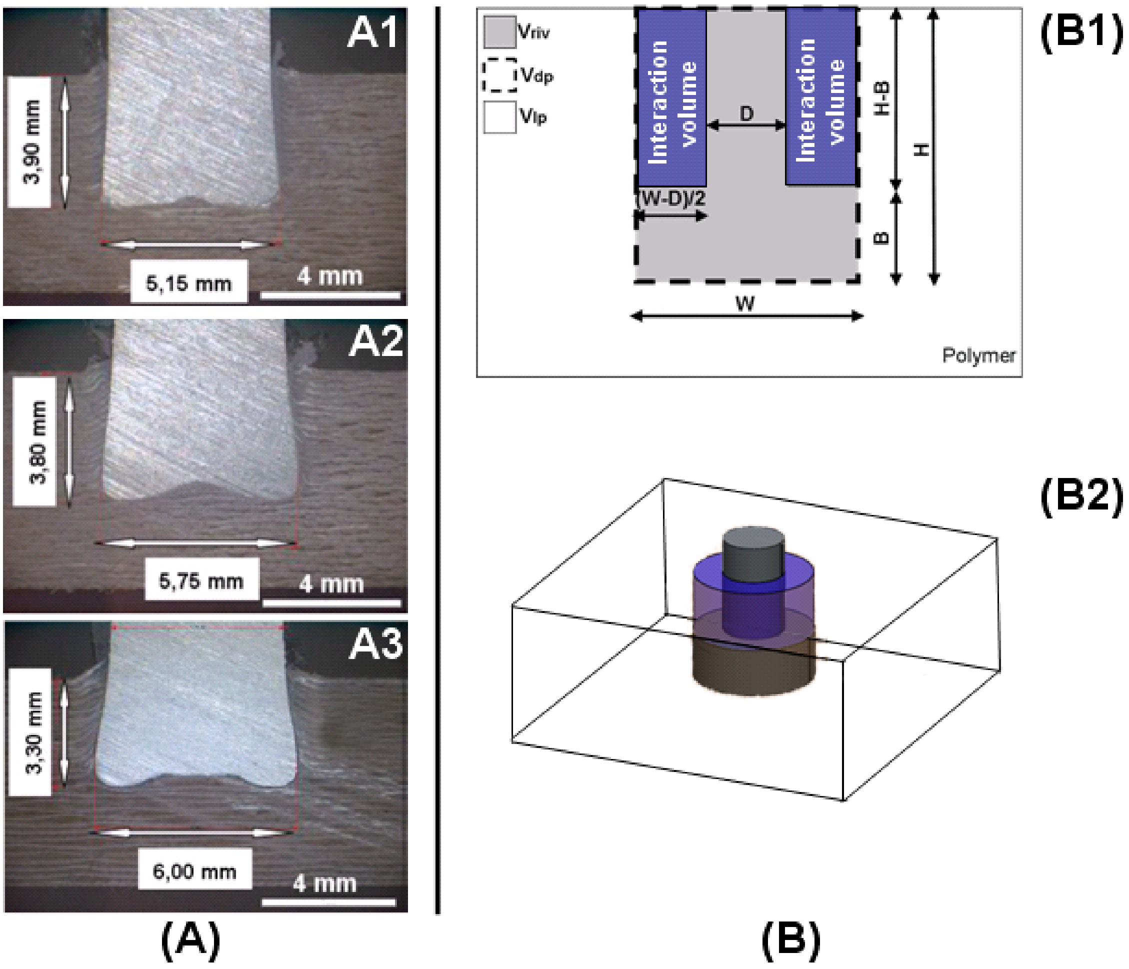

Figure 3 – (A) Cross-sectional views of the selected PEI-GF/Ti gr. 2 joints (Specimens A1, A2 and A3); (B) geometrical simplifications of the anchoring zone (1) and a simplified 3D model (2) depicting the polymeric volume of interaction.

Figure 4

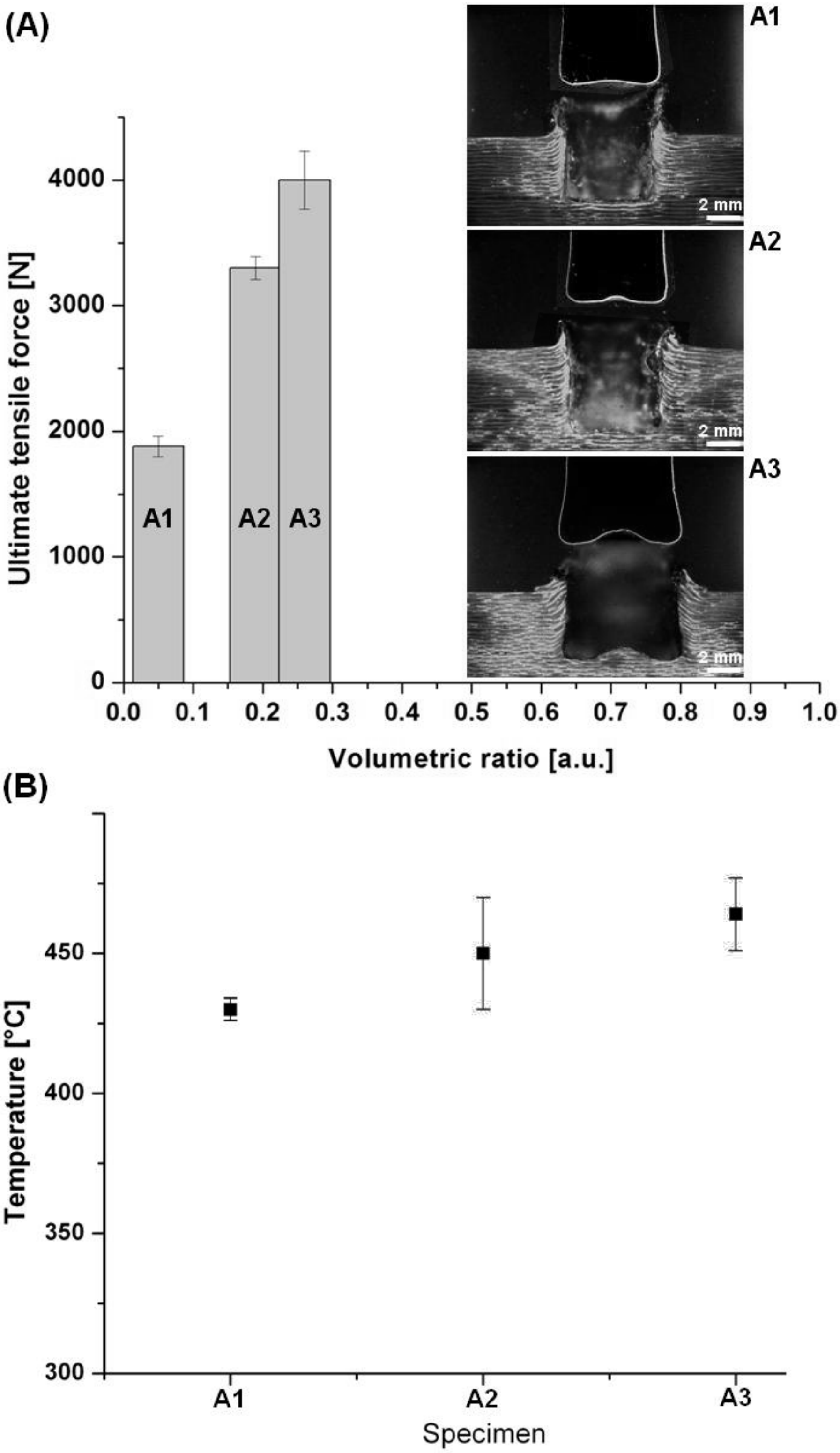

Figure 4 – (A) Interaction of the volumetric ratio with the ultimate tensile force for PEI-GF/Ti gr.2 specimens and cross-sectional views showing the tested specimens.(B) Peak process temperatures (average of three specimens for tensile and three for termography).