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FRICRIVETING OF ALUMINUM 2024-T351 AND POLYCARBONATE: TEMPERATURE EVOLUTION, MICROSTRUCTURE AND MECHANICAL PERFORMANCE

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ABSTRACT

Friction Riveting (FricRiveting) is an innovative, fast and energy-efficient spot joining process used to join lightweight hybrid metal-polymer and metal-composite structures. In this process, a cylindrical metallic rivet is used to join one or more thermoplastic components by means of plasticizing and deforming the tip of a metallic rivet through frictional heating and pressure inside the polymeric parts. This work studies the feasibility of the FricRiveting technique for polycarbonate/aluminum 2024-T351 alloy spot joints by investigating the temperature development (measured by infrared thermography), microstructure (evaluated by optical microscopy) and mechanical properties (investigated by tensile testing) of the joints. The thermographic temperature investigation indicated that the average peak process temperatures were from 280-

LIST OF ABBREVIATIONS

AR Aspect Ratio
AZ Anchoring Zone
DOE Design of Experiments
JP Joining Pressure
JT Joining Time
MHAZ Metal Heat Affected Zone
MTMAZ Metal Thermomechanically Affected Zone
PC Polycarbonate
PEI Polyetherimide
PHAZ Polymer Heat-Affected Zone
PTMAZ Polymer Thermomechanically Affected Zone
RS Rotational Speed
UTF Ultimate Tensile Force
VR Volumetric Ratio

360°C, from 56% to 72% of the AA 2024 eutectic point and below the temperature range of extensive thermal degradation of polycarbonate (480-550°C). Furthermore, the typical deformed tip of the rivet – the anchoring zone - was attained for all joints investigated in this study, as induced by thermo-mechanical processing. The anchoring efficiency represented by the aspect ratio of the deformed rivet was evaluated by optical microscopy. Aspect ratio values were compared with the process temperatures and the tensile strengths of the joints. Increases in process heat input resulted in larger aspect ratios. High average values of ultimate tensile forces varying from 6659 ± 62 N to 8540 ± 182 N (68.4% to 87.8% of the ultimate tensile strength of the metallic rivet) were achieved, with final ductile fracture occurring in the metallic rivet for joints with aspect ratios of 0.88 ± 0.02 and in the polymeric base plate for joints with aspect ratios of 0.61 ± 0.03 and 0.68 ± 0.04. The volumetric ratio - a recent, more complex three dimensional approach for evaluating the mechanical performance of the joints - was also investigated, revealing similar interactions with process temperatures and tensile strengths as the aspect ratio. The results of this work proved that FricRiveting is a feasible method for use on the PC-AA 2024-T351 material combination, as it yields strong joints.

Keywords: polycarbonate, aluminum, joining process, Friction Riveting, hybrid materials, joining by forming

1. Introduction

The production of complex automotive engineering components by joining various dissimilar materials, such as polymers and light metal alloys, has required the development of new approaches in the field of welding and materials joining. Recently, Amancio-Filho and Dos Santos (2009 [‘a’]) observed limitations in the traditional joining techniques used to create polymer-metal hybrid joints, i.e., adhesive bonding, mechanical fastening, welding-based processes and hybrid joining methods (combinations of one or more different processes). These limitations include high operational costs related to pre- and post-joining procedures, long processing times, reduced mechanical properties and harmful environmental consequences due to chemical disposal. Thus, the study and development of new material joining methods has become an important subject in the field of materials engineering and processing.

The Friction Riveting technique (“FricRiveting”) was recently developed and patented by Helmholtz-

Zentrum Geesthacht (HZG) in Germany in 2007 (Amancio-Filho et al., 2007) as a method of joining hybrid metal-polymer structures. This method is based on the principles of mechanical fastening and friction welding, where a cylindrical rivet is used to join metallic and/or thermoplastic parts through frictional heat.

When compared to other manufacturing techniques used for hybrid joints, such as adhesive bonding, friction riveting does not require complex surface preparation or curing agents and requires a shorter process time. Regarding the use of rivets, this method eliminates the need for pre-drilling, reducing the number of process steps and reducing the stress concentration due to the presence of the notch effect related to through-holes. This technique allows for the manufacture of joints with high mechanical performance (Amancio-Filho et al. 2008 [‘b’]).

The friction riveting process can be performed for various joint configurations, such as lap joints using a metallic rivet or metallic inserts in polymer parts. The principles of this process can be better understood for the manufacture of metallic-insert joints in thermoplastics. Initially, the to-be-joined parts are fixed on the equipment over a backing plate. The next stage is the early joining stage, in which the rivet is rotated and pressed against the surface of the polymeric component (Figure 1A); the high rotation and applied axial force heat the polymer by friction, resulting in a thin molten/softened layer around the tip of the rivet (Figure 1B). As the rivet penetrates into the thermoplastic matrix, the molten/softened thermoplastic is expelled as flash outside the joint area. Due to the high temperature and low thermal conductivity of the thermoplastic, the local temperature at the tip of the rivet rises considerably, nearing the plasticizing temperature of the metal (between 60% and 95% of the melting temperature). At this time, the rivet’s rotational speed is decreased, and the axial force is increased; the rivet expels the remaining softened material towards the flash, encountering the resistance of the cold volume of the thermoplastic. The plasticized tip of the rivet is thereby deformed, assuming a larger diameter than the initial diameter (Figure 1C and 1D). After cooling under pressure, the joint is consolidated (Figure 1E).

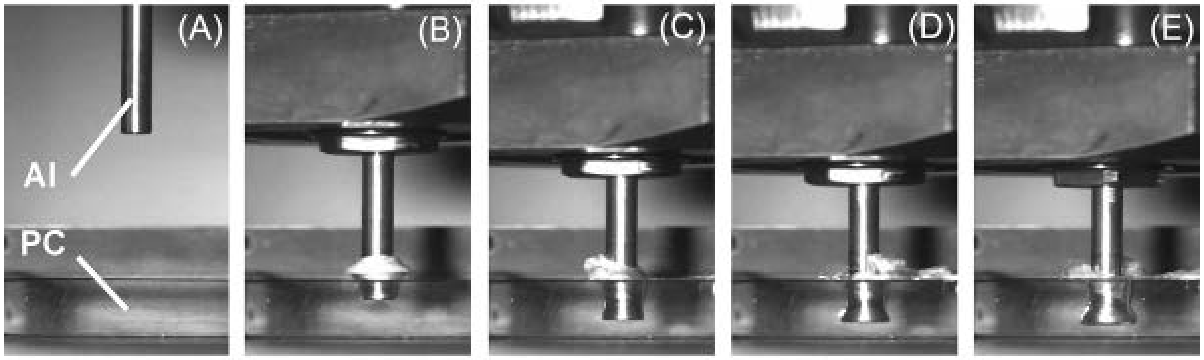

Fig. 1. Friction riveting process scheme as illustrated for metallic insert-type joints. (A) Positioning and clamping of joining partners. B) Rotational insertion of metallic rivet into the polymeric plate (C) Rotational braking followed by (D) rivet forging. (E) Cooling and joint consolidation.

The main process parameters that influence the thermal, mechanical and microstructural properties of joints manufactured by FricRiveting are: rotational speed (RS), joining time (JT) and joining pressure (JP). The effective combination of these parameters with the properties of the materials to be joined (thermal conductivity, thermal expansion, and melt viscosity, among others) determines the quality of anchoring of the metallic rivet following deformation in the thermoplastic matrix and hence the mechanical performance of the joints (Amancio-Filho and Dos Santos, 2008).

Amancio-Filho (2011) described the microstructural zones of joints between amorphous polymers and aluminum. He described the presence of four typical microstructural zones within the anchoring zone (AZ) of the deformed rivet tip: the polymer heat affected zone (PHAZ), the polymer thermo-mechanically affected zone (PTMAZ), the metal heat affected zone (MHAZ), the metal thermo-mechanically affected zone (MTMAZ). Figure 2 illustrates the various microstructural zones in a FricRiveting joint. These zones are influenced by the heat and high deformation rates imposed by the process, experiencing metallurgical (rivet) and physicochemical (polymer) transformations. This work provides a more detailed description of each zone.

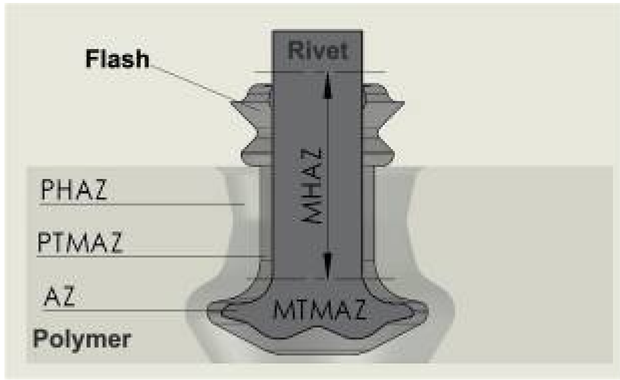

Fig. 2. Schematic representation of typical microstructural zones found in FricRiveting joints. Polymer heat-affected zone (PHAZ), polymer thermomechanically affected zone (PTMAZ), Metal heat-affected zone (MHAZ) and metal thermomechanically affected zone (MTMAZ).

There are currently a limited number of publications available regarding FricRiveting. Few studies conducted with PEI-AA2024-T351 joints showed tensile strength values near 93% of the maximum tensile strength of metallic rivets (Borges et al., 2012), with final fractures occurring outside the joint in the external area of the metallic rivet. Amancio-Filho et al. (2008 ['b']) reported five types of failure during tensile testing, as shown in Figure 3:

- *Through the rivet (Type I):* ductile fracture occurring in the metallic rivet outside of the joint. The maximum tensile strength of the joint is equivalent to that of the metallic rivet.

- *Rivet pull out with back plug (Type II):* a fracture in which the crack nucleates at the deformed tip of the rivet in the anchoring zone. The rivet is later pulled out from the polymer, leaving part of the anchoring zone (“the back plug”) embedded. The tensile strength is usually good but lower than that of the metallic rivet.

- *Full rivet pull out (Type III):* a fracture typically observed in joints with high ductility (e.g., polycarbonate), or in cases in which the tip of the rivet was only slightly deformed (low mechanical anchoring) during the forging process. In this type of fracture, the crack starts around the anchoring zone of the polymer, and the rivet is completely removed, leaving an orifice with a diameter similar to the deformed end of the rivet. The mechanical strength of joints exhibiting this type of fracture is generally less than the strength of the Type I and II joints.

- *Rivet pull out (Type IV):* a type of failure observed in joints with large deformations at the tip of the rivet but with small insertion depths, leaving the anchoring zone close to the surface of the polymer. In this type, the crack also nucleates in the polymer around the top of the anchoring zone and propagates toward the posterior surface of the polymer. A cone of polymer forms around the anchoring zone of the rivet detached from the joint.

- *Rivet pull out with secondary cracking (Type V):* a more complex type of failure under tensile strength that is not yet well understood. In this type of failure, nucleation is observed at multiple sites in the polymer around the anchoring zone. In the early stages of propagation, the crack seems to exhibit the same behavior as type IV failure, but the rivet is pulled out of the joint as observed in Type III failure. As with specimens failing by Type IV, specimens failing by Type V have medium to low tensile strengths.

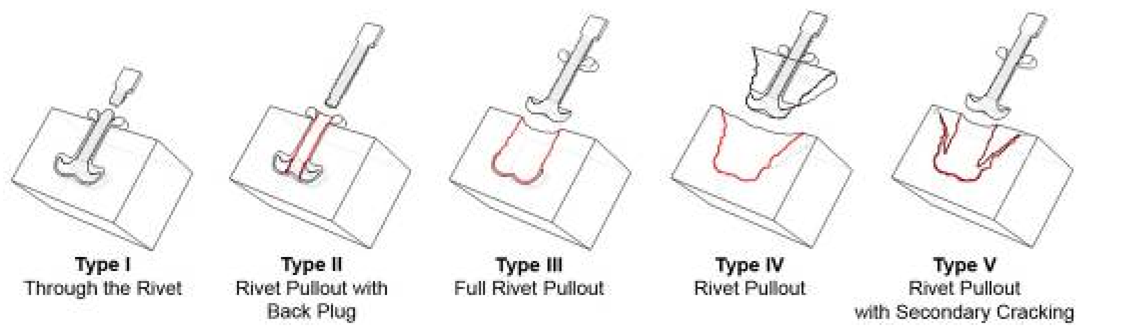

Fig. 3. Current description of failure modes under tensile loading in FricRiveting. The thicker red lines indicate the path of crack propagation upon final failure.

Amancio-Filho et al. (2008 'c') studied the anchoring performance of the deformed rivet in the polymer. They associated the heat input of the joint with the plasticizing of the rivet and its level of deformation, expressed by the so-called aspect ratio (AR) of the anchoring zone (AZ), defined in terms of the insertion depth (H) and the width of the deformed rivet (W) as AR = W/H. In another study (Amancio-Filho et al., 2009), the authors evaluated the influence of the rotational speed on the AR showing that the increase in heat input associated with higher rotational speeds enhanced rivet deformation, increasing the AR of the joint.

This technique has potential applications for a wide variety of materials and is currently under development for use in short fiber composites and carbon and fiberglass laminates joined together using titanium and aluminum rivets (Blaga et al., 2013).

The aim of the present study was to demonstrate the feasibility of using FricRiveting in producing metallic insert-type joints from AA 2024 T351 aluminum rivets and polycarbonate (PC) plates by evaluating their thermal, microstructural and mechanical properties. Joints with high tensile strength and reduced amount of defects were obtained. The achievement of good mechanical properties can be associated with microstructural changes and with the formation of the anchoring zone in the rivet, which, in turn, were correlated with the heat input and the rate of plastic deformation observed during the joining process.

2. Materials

Polycarbonate (PC) is an amorphous engineering thermoplastic with a main chain made up of phenyl rings, resulting in high rigidity, and flexible carbonate groups that contribute to its high impact strength. PC has a high impact strength in the temperature range from 100°C to 120°C (Wehrmann, 2001) high dimensional stability and heat resistance, excellent electrical and optical properties, and a high glass transition temperature (Tg) of 150°C (Staff and Andrew, 2008). PC is applied in a wide range of products including home appliances, shielding, vehicle panels and headlights, solar panels, medical supplies, and helmets. PC can be welded by different processes, such as solar energy welding (Stoynov et al., 2003) and focused microwave welding (Prasad and Chai, 1998)

The PC plates used in the manufacture of joints were obtained from 15-mm-thick extruded sheets (Makrolon Monoclear 099, Bayer Group). The sheets were machined to a 70 mm length and 70 mm width for test specimens used in the tensile test and to a 40 mm length and 25 mm width for the thermal and microstructural analysis. PC was chosen for the present study due to its transparency, facilitating visual evaluation of the anchoring zone of the rivet (non-destructive visual analysis), and due to its extensive use in the transportation industry.

The main alloying elements of aluminum 2024-T351 alloy are Cu and Mg ($AlCu_4Mg$). The heat treatment T351 consists of a solubilization step followed by cold hardening and, later, the relief of residual stress by deformation. Figure 4A shows the microstructure of the longitudinal section of the rivet formed by elongated grains oriented in the extrusion direction, where black dots inside the grains are secondary particles (AlMgCuC) and intermetallics (Al_2Cu-Ɵ) (ASM, 1996)

The aluminum 2024-T351 rivets used in this study were obtained through extrusion in the form of plain pins with a diameter of 5 mm and a length of 60 mm. The mean tensile strength of the rivets was 495.0 ± 3.0 MPa with a mean elongation at break of 7.9 ± 0.4% and microhardness values ranging between 151 and 169 HV along the extrusion direction (Figure 4B).

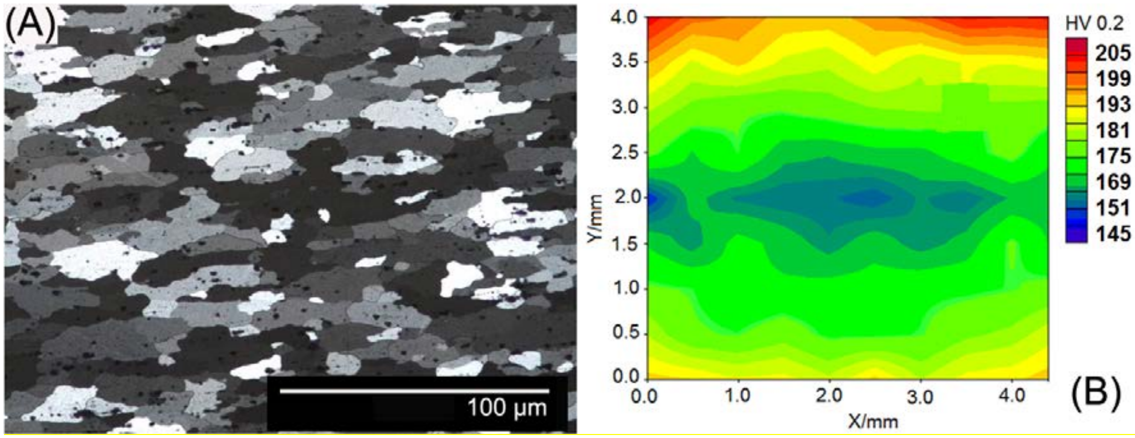

Fig. 4. Microstructure and microhardness distribution of a longitudinal section of the AA2024-T351 rivet. (A) Microstructure along the longitudinal section. (B) Vickers microhardness map.

Aluminum 2024 alloy exhibits excellent properties, such as good workability and surface finish, as well as high mechanical strength and moderate corrosion resistance. Therefore, these alloys are commonly applied in structural aircraft components and in the fuselage, suspension and hydraulic valve bodies of automobiles, screws and fasteners (Immarigeon et al., 1995).

3. Experimental Approach

3.1. Joining equipment and procedure

This study involved joining a series of metallic-insert type spot connections. A range of process parameters was considered (rotation speed between 18,000 and 21,000 rpm, joining time between 3 and 4 s, and joining pressure between 0.75 and 1.10 MPa) based on preliminary studies performed in PEI-AA 2024-T351 (Amancio-Filho, 2007) and PC-AA 6060-T66 (Mattos, 2010) systems, resulting in effective anchoring of the rivet in the polymeric matrix. A total of eight conditions were analyzed in a 2^k full factorial design of experiments, DOE (detailed results of the DOE analysis will be published in a separate manuscript). Table 1 shows the parameters used to produce the DOE conditions. Among these conditions, joints were selected to describe the results of this work. Joint production was carried out using commercial friction welding equipment, model RSM 400 produced by Harms and Wende GmbH Co. KG, Hamburg, Germany. During the joint manufacturing, a computer connected to the equipment allowed the monitoring of the main process parameters and variables using the RQ-Fuzzy software (Harms & Wende, Hamburg).

Table 1
Summary of the joining conditions used to produce 2^k full factorial specimens for this study.

Joining Condition	Rotational Speed [rpm]	Joining time [s]	Joining pressure [MPa]
1	18000	3	0.75
2	21000	3	0.75
3	18000	4	0.75
4	21000	4	0.75
5	18000	3	1.10
6	21000	3	1.10
7	18000	4	1.10
8	21000	4	1.10

3.2. Temperature Measurement

Process temperature was recorded using an infrared camera (High-End Camera Series ImageIR, Infratech GmbH, Germany) with a filter calibrated for the range of 200°C to 400°C. Aluminum rivets and PC plates were painted with black ink to minimize disturbances during measurements associated with the low emissivity of the aluminum alloy and the high transparency of PC. The joint area was not painted to avoid contamination of the joint. Data were collected from the volume of the softened polymer expelled as flash material outside the joint area, from a distance of 300 mm (distance between the temperature recording area and the center of the camera lens) at an incidence angle of approximately 15°, as shown in Figure 5A. Figure 5B shows an IR snapshot indicating the maximum temperature measured in a joint with the infrared system.

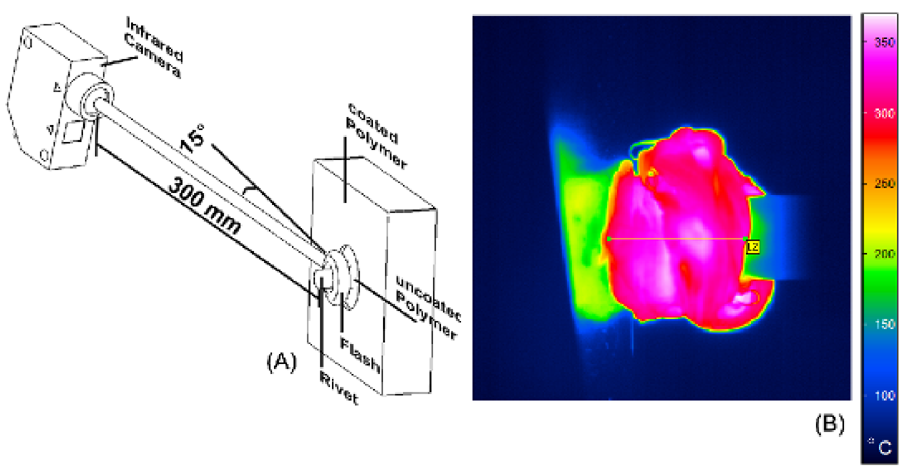

Fig. 5. (A) Schematic view of the infrared thermometry setup used in this work. (B) Thermogram (IR snapshot) showing the temperature of softened polymer flash material being pushed off to the surface (specimen was prepared at 21,000 rpm, 3 s, 1.10 MPa).

3.3. Anchoring Performance and Microstructural Analysis

The quality of the joints was evaluated in terms of the aspect ratio of the rivet anchoring as the ratio between the width of the deformed tip of the rivet and its insertion depth within the polymer (Amancio-Filho and Dos Santos, 2008). Cuttingt was performed in the mid-cross section of the joints (Figure 6A) using a low speed saw (Buehler Isomet Low-Speed Saw, Germany*)* to avoid any thermal changes in the joint area. Microstructural analysis was performed using photographs of the cross-section of the obtained samples with a stereo microscope (Leica DC 300). The insertion depth (H) of the tip of the rivet was measured by drawing a vertical line through the cross section of the thickness of the polymer plate. For measuring the width of deformation (W), a line was drawn horizontally between the extremities of the largest greatest deformation of the tip of the rivet (Figure 6B).

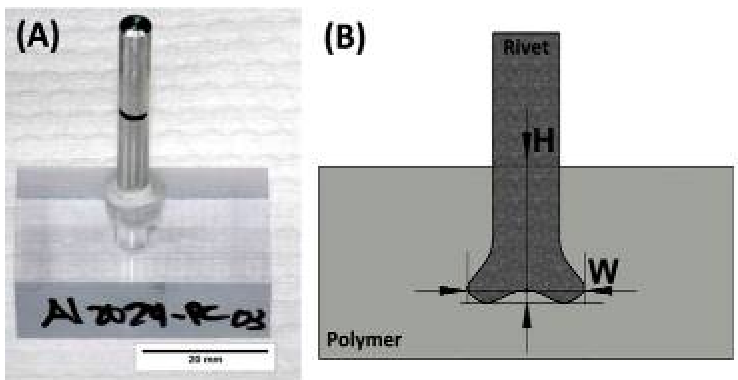

Fig. 6. (A) Joint produced with the FricRiveting technique for PC-AA 2024-T351 to measure the aspect ratio, AR. (B) Scheme of the cross-sectional view of a PC-AA 2024-T351 joint showing the measurement of the rivet insertion depth (H) and the width (W) of the tip deformation area.

Microstructural characterization was carried out by light optical microscopy (Leica Q550IW, Germany) of the cross-section of the joint before (to evaluate the polymeric partner) and after electrolytic etching in Baker's solution (200 mL of distilled water and 5g of 35% hydrofluoric acid) to reveal the metallurgical microstructural changes in the rivet (Amancio-Filho, 2007).

3.4. Local mechanical properties

The local mechanical properties were evaluated by microhardness testing performed on the base materials and on cross sections of the joints (polymeric and metallic regions). These measurements were performed using a Zwick/Roell ZHV microhardness testing equipment. In the region of the metallic rivet, measurements were performed by applying a load of HV 0.2 (200g) for 5 s with 500µm between indentations in accordance with ASTM E384-992e1 (ASTM, 2005). In the polymeric region, measurements were performed on the polymer-metal interface of the joints, located near the deformed tip of the rivet by applying a load of HV 0.05 (50g) for 15 s and a mean of 300µm between indentations, according to Calleja and Fakirov (2000).

3.5. Global mechanical properties

The global mechanical strength of the joints was analyzed by tensile testing using a universal testing machine (Zwick-Roell1484) equipped with a 200 kN load-cell. Tests were performed based on DIN EN 10002 (1999) at 2 mm/min at room temperature (21°C), in a type "T" spot joint configuration of 70 mm x 70 mm polycarbonate plates (Figure 7). Four tests were performed for each PC-AA 2024-T351 joint evaluated. Due to the sample configuration, a special specimen holder constructed in previous studies (Amancio-Filho, 2007) was used. Finally, the samples fractured during the test were photographed for analysis of fracture modes and their fractured surfaces were analyzed by light optical microscopy (Leica Q550IW, Germany).

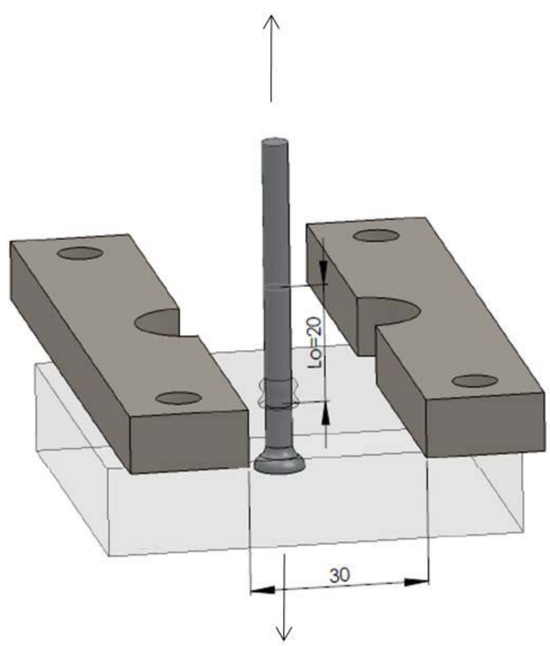

Fig. 7. (A) Scheme of T-Pull tensile testing in friction riveted joints.

4. Results and Discussion

4.1. Process Temperature

The mean processing temperature of the FricRiveting method is directly related to the conditions of friction and pressure that induce heat, material plasticizing and joining of the surfaces at the rubbing area (Amancio-Filho et al., 2008 [‘a’]).

In the present study, the average peak temperatures recorded by infrared thermography were measured on the softened polymer expelled as flash outside of the joint region. Figure 8A presents an example of temperature monitoring of a joint prepared at 18,000 rpm, 3 s and 1.10 MPa (Joining condition 5, Table 1). The graph shows the development of a peak temperature in the first three seconds of the joining process related to the high heating rates in the rubbing area. Next, the temperature decreases due to slow cooling rates in the consolidation step of the joint related to the low thermal conductivity of the polymer.

Figure 8B shows the average peak temperatures of the PC-AA 2024-T351 joints produced with different parameter combinations (Table 1, Section 3.1). The mean values of the maximum process temperatures were between 280°C and 360°C, a temperature range corresponding to approximately 56% to 72% of the lowest melting point temperature range of AA 2024-T351 rivets of 502-638°C (ASM, 1993) and sufficiently high to cause plasticizing and effective anchoring of the aluminum rivet inside the PC plates. Furthermore, the base material AA 2024-T351 most likely experiences metallurgical changes because of large shear rates and temperatures above 40% to 50% of the alloy’s melting point (Li and McClure, 1999), such as annealing, dynamic recovery and recrystallization (Gourdet and Montheillet, 2000), as reported by Amancio-Filho (2007) for the PEIAA 2024-T351 joints.

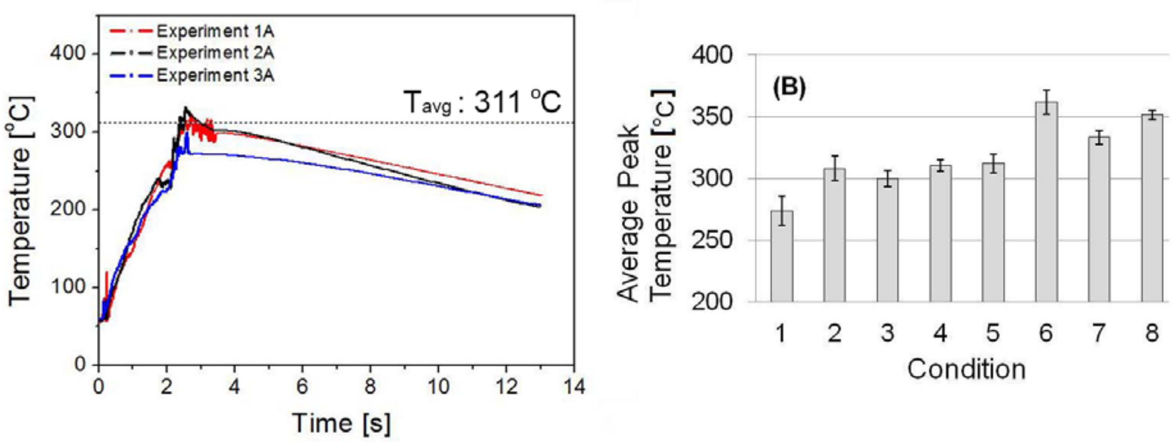

Fig. 8. (A) Example of the process temperature history of FricRiveting joints measured in polymeric flash material for three samples produced with 18000 rpm, 3 s and 1.10 MPa. (B) Average peak temperatures for PC/AA 2024-T351 joints studied in this work (Table 1, Section 3.1).

Several studies have focused on the process of thermal degradation of PC. Domininghaus (1998) reported that PC undergoes thermal degradation starting at 320°C by chain scission (CO_2 formation), where strongly degraded volumes are easily identified by changes in the color of the matrix. Jang and Wilkie (2004) evaluated the thermal decomposition of PC by thermogravimetric analysis and found that PC exhibits no weight loss up to 400 °C or 450 °C, respectively. They also observed that the decomposition occurs in a single stage, with a maximum degradation temperature of approximately 540°C. Finally, these authors were able to determine that the main range of thermal degradation by PC chain scission is between 480°C and 550°C. It is known that mechanisms of thermal degradation during thermal processing are significantly influenced not only by the applied temperature but also by the exposure time and heating rates. Thus, the PC in the region of the friction-riveted joint is not expected to undergo extensive thermal degradation because the processing temperatures (Figure 8B) were below or near the low end of the temperature range of polymer degradation, and the exposure times were relatively short (between 3 and 4 s). Further investigation of the thermal-mechanical changes in the PC joined material is in progress to confirm this assumption.

4.2. Microstructural analysis

The formation of the anchoring zone (AZ) was initially quantified by measuring the rivet aspect ratio (AR). Figure 9 shows the measurements of insertion depth (H) and width of deformation (W) of the tip of the rivet in the polymeric matrix performed on cross-sections of three joints produced with the following parameter combinations from Table 1: Condition 5 – 18,000 rpm, 3 s and 1.10 MPa; Condition 7 – 18,000 rpm, 4 s and 1.10 MPa; Condition 8 – 21,000 rpm, 3 s and 1.10 MPa. The average peak temperatures (T_{peak}) for these joining conditions are also provided in the figure. These conditions were selected based on their heat generation. Amancio-Filho (2007) studied the influence of the joining parameters on the heat input and temperature evolution of friction riveted PEI-AA 2024-T351 joints. He observed that the combined effect of rotational speed (shear deformation) and joining time has an important contribution to heat generation through viscous dissipation in the molten polymer, while the contributions of the joining pressure (axial displacement) are less important. For the PEI-AA 2024-T351 joints, increases in rotational speed and joining time resulted in higher heat inputs and process temperatures. As the rotational speed and joining time at constant joining pressures increase from Conditions 5 to 8, the heat input and the temperature of the analyzed joining conditions are also expected to increase.

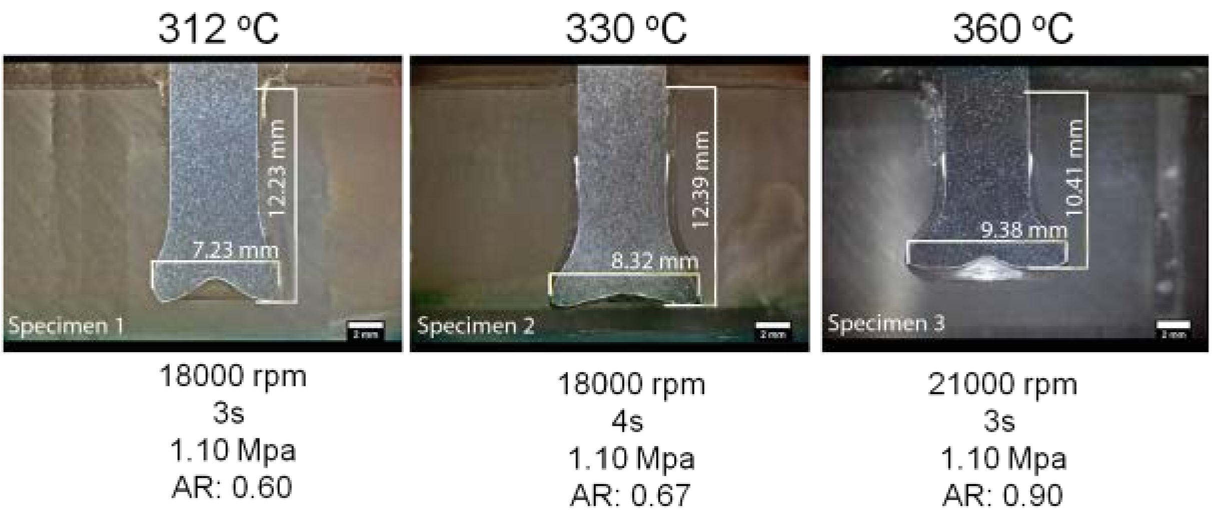

Fig. 9. Geometrical features of PC-AA2024-T351 joints at the mid-cross section. The image shows the anchoring zone area of the rivet into the polymer plate. Vertical lines represent the penetration depth, H, and horizontal lines represent the width of the deformed rivet tip used to calculate the aspect ratio.

Condition 8 had a mean processing temperature of 360°C, and the width of the rivet tip (9.4 mm) increased approximately two-fold compared to its original diameter (5 mm), resulting in a high aspect ratio ($AR_{cond\ 8} = 0.90$). Condition 5 and 7, with lower processing temperatures of 312°C and 330°C, respectively, exhibited minor dimensional changes in the rivet tip ($W_{cond\ 5} = 7.2$ and $W_{cond\ 7} = 8.3$ mm) and lower aspect ratios of anchoring ($AR_{cond\ 5} = 0.60$ and $AR_{cond\ 7} = 0.67$). This analysis of the process parameters of joint manufacture indicates that the increase in the value of the aspect ratio of the anchoring zone with increasing processing temperature is closely related to the heat input and the local plasticizing of the metal, as increases in rotational speed and joining time generated higher processing temperatures. Thus, the higher processing temperature of Condition 8 resulted in a greater volume of plasticized metal and hence greater deformation at the tip of the rivet (higher mechanical anchoring).

The microstructures of joints produced by FricRiveting are known to be significantly influenced by the high heating and deformation rates during the joining process. Metallographic analysis (Figure 10) performed in the region of the cross-section of a joint produced with 20,000 rpm, 3 s and 0.95 MPa identified the presence of metallurgical changes in different microstructural zones in the anchoring zone (AZ), i.e., the deformed tip of the rivet in the PC polymeric plate (Figure 10). In the thermo-mechanically affected zone of the metal (MTMAZ) (Figure 10B and 10C) , a realignment of grains was observed in the direction of the flow of forged and plasticized volumes. Partial grain refinement was also observed, characteristic of dynamic recrystallization in aluminum alloys, as reported for the PEI-AA 2024-T351 joint (Amancio-Filho, 2011) and other friction-based welding process. In the heat-affected zone of the metal (MHAZ) (Figure 10A), no visual microstructural changes, such as grain size variations, were observed compared to the base material (see Figure 4A, Section 2). However, the thermal influence in these areas may induce structural changes in the aluminum rivets that are only visible with the aid of electron microscopy, such as static recovery, solubilisation and/or coalescence of precipitates (an example of annealing processes) and re-precipitation (a local hardening mechanism) (Amancio-Filho, 2007).

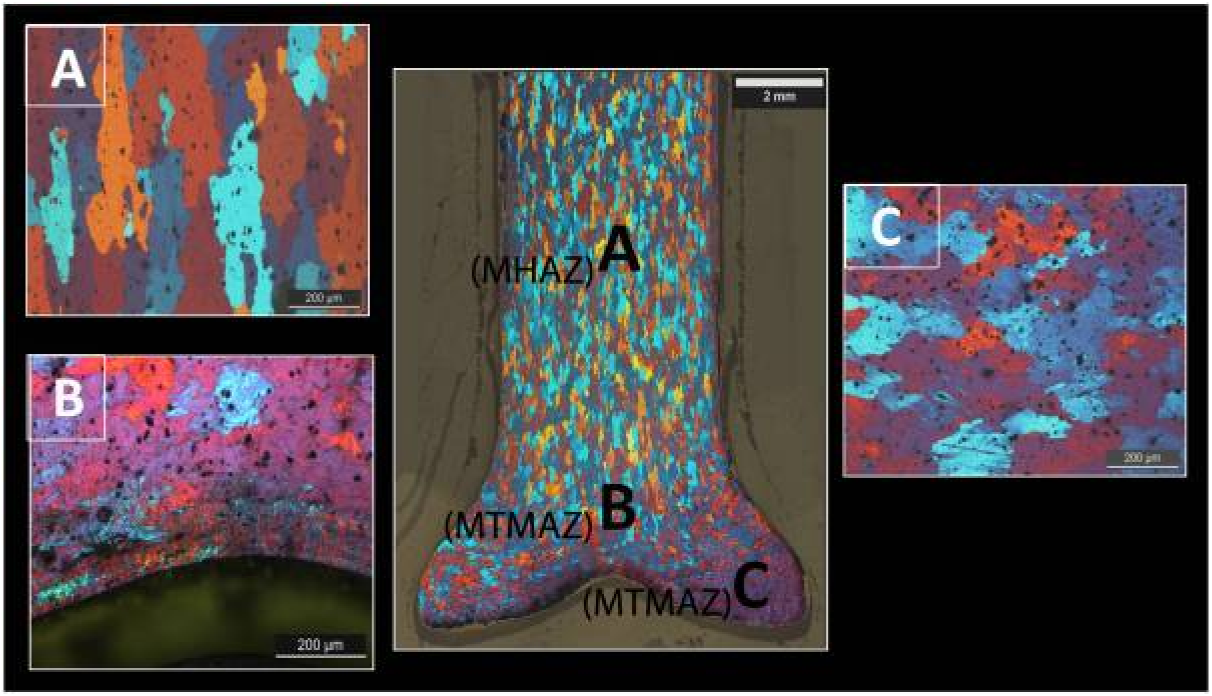

Fig. 10. Microstructural features of a FricRiveted PC-AA 2024-T351 joint (20,000 rpm, 3 s and 0.95 MPa). (A) Detail of the Heat Affected Zone of the metal, MHAZ. (B) The Thermo-Mechanically Affected Zone of the metal, MTMAZ, exhibits grain realignment in the direction of the material flow in the forged rivet tip. (C) View of region C in (A) showing the partially dynamically recrystallized grains in MTMAZ.

The microstructural and physicochemical transformations in the polymer caused by thermo-mechanical processing during FricRiveting were addressed by Amancio-Filho (2011) for PEI-AA 2024-T351 joints. The author observed that PEI did not exhibit any visible change because it is amorphous and transparent, as is the case for PC. This behavior was also observed for joints where the Heat Affected Zone (PHAZ) and the Thermo-Mechanically Affected (PTMAZ) Zones of the PC in the region of the polymer-polymer interface could not be identified by optical microscopy. No sharp change in color of the consolidated molten polymer was observed. Considering that the mean processing temperatures measured were not excessively high (280°C to 360°C), and considering the short exposure time of the molten polymer (between 3 and 4 s), minimal macromolecular changes are expected to have occurred in the PC. Further research on the microstructural changes of the PC joined plates is in progress to better understand the influence of FricRiveting on joint properties.

4.3. Evaluation of local mechanical properties by measuring microhardness

The determination of local mechanical properties through microhardness provides an important way of understanding the process-structure-properties relationship of FricRiveting joints, due to the relationship between hardness (H) and yielding stress (Y), ($H \approx 3*Y$) proposed by Tabor (1951). Figure 11A shows an example of microhardness mapping performed on a cross-section of the metallic region of a PC-AA 2024-T351 joint. The variation in microhardness values helps to support the assumptions of the above-mentioned microstructural changes related to thermo-mechanical processing.

Figure 11 shows a decrease in the hardness values of the microstructural heat and thermo-mechanically affected zones (MHAZ and MTMAZ) in comparison to the base material AA 2024-T351 (Figure 4A, Section 2). The MHAZ exhibited a decrease in microhardness, presenting values of approximately 88% compared to the mean hardness of the base material ($HV_{AA2024\text{-}T351}$ = 160 HV, HV_{MHAZ} = 141.5 HV); the greatest decreases were observed in MTMAZ, with mean hardnesses ranging from 59% to 69% of the base material (HV_{MTMAZ} = 95-110 HV). The decrease in the microhardness of the metallic rivet inserted into the PC helps to validate the occurrence of previously discussed annealing phenomena. It is known that in the MHAZ of the AA 2024-T351 rivet, metallurgical phenomena, such as static recovery (dislocation annihilation by climbing and cross-slipping) and precipitate coarsening (loss of coherence between the precipitate and the atomic matrix, reducing the dislocation pinning or Orowan (1958) mechanism), reduces the hardness. In MTMAZ, heating and high rates of deformation induce dynamic recovery and dynamic recrystallization (represented by the partial grain refinement that occurred in the rivet region near the deformed and rubbing surfaces). These phenomena markedly decrease the metal hardness by decreasing the density of the dislocation lines (Verhoeven, 1975).

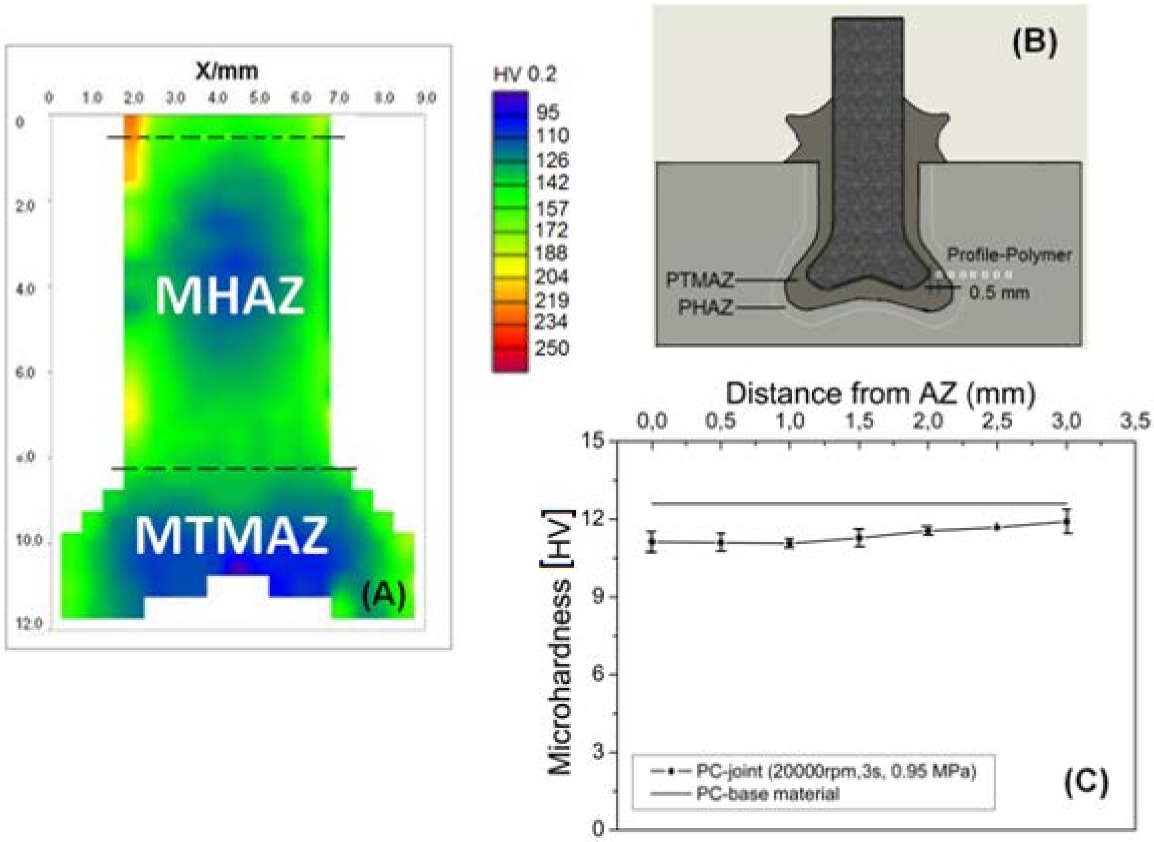

Fig. 11. (A) Vickers microhardness distribution of an AA 2024-T351 deformed rivet. (B) Schematic of the measurement locations (white dots) used to measure the microhardness in the polymer area. (C) Microhardness values at the joint polymer volume adjacent to the rivet anchoring zone in comparison to the polycarbonate base material.

The microhardness of the polymeric volume adjacent to the rivet anchoring zone, comprising the PHAZ and PTMAZ regions (Figure 11B), exhibited only a small decrease in hardness with an average value of 94% of the base PC material ($HV_{PC\text{-base material}}$ = 12.6 ± 0.4 HV; $HV_{PC\text{-joint}}$ = 11.9 ± 0.3 HV). The molecular weight of a polymer is known to be related to its hardness, with higher molecular weights generally resulting in polymers with higher hardness values (such relationships may be invalid for semicrystalline polymers) as expressed by Calleja and Fakirov (2000). Thermal degradation by chain scission (Grassie and Scott, 1985) usually leads to a reduction in molecular weight. Thus, the reduction of hardness in Figure 11C may indicate the onset of thermal degradation induced by the process. Further studies involving thermal analyses are needed to assess the thermo-mechanical influence of the process on the structural transformation of the polymer in the PC-AA 2024-T351 joints. However, these issues are outside the scope of the present study.

4.4. Evaluation of the global mechanical properties by tensile testing

The mechanical performance of joints produced by FricRiveting is influenced to a considerable degree by the geometry of the rivet anchoring zone in the polymeric matrix. The anchoring zone supports the majority of the load imposed on the joint through the mechanical interface with the polymeric matrix (Amancio and Dos Santos, 2009 ['b']). This geometry is heavily influenced by the frictional heat and by the deformation force applied to the rivet during the forging phase. Thus, determining the aspect ratio of anchoring zone is a good indicator of the mechanical anchoring of the metallic rivet and of the tensile strength of FricRiveting joints as well. Nevertheless, this is valid only if the values of the widths do not vary significantly, as it is the case for the joints in this work's combination of materials; in case of a significant variance in widths, a volumetric approach would me more appropriate.

The mechanical performance of the PC-AA 2024-T351 joints was assessed by tensile testing. The tested joints were manufactured by combining the parameters described in Section 4.2 (Figure 9) that resulted in effective anchoring of the aluminum metallic rivet in the polycarbonate matrix. Four replicates of each condition were produced for the tensile test. Table 2 presents the mean values of the ultimate tensile force (UTF) for the three tested joints and the AA 2024-T351 rivet, and expresses the tensile mechanical performance of the joints in comparison to the metallic AA 2024-T351 rivet.

Table 2
Average ultimate tensile force and tensile mechanical performance of PC-AA 2024-T351 joints in comparison to the rivet base material.

Condition	Average ultimate tensile force [N]	Standard deviation [N]	Tensile Mechanical Performance [%]
5	6659	62	68.4
7	8040	195	82.6
8	8540	182	87.8
Rivet	9730	70	-

The joints exhibited high values of ultimate tensile forces, ranging between 68.4% and 87.8% compared to the metallic rivet. The UTF values in this study are similar to those of the PEI-AA 2024-T351 joints reported by Amancio-Filho (2009 ['b']). For a better understanding of the mechanical behavior of the PC-AA 2024-T351 joints, the results of the tensile tests were analyzed along with the average aspect ratio (AR) values calculated from three replicates of each condition. UTF tends to increase with AR, as shown in Figure 12. Similar behavior was also reported for the PEI-AA 2024-T351 joints, indicating that AR appears to be directly related to UTF, at least for the cases where the H and W of the deformed rivet are not similar, which may invalidate the two-dimensional analysis used to calculate AR (Blaga et al., 2013).

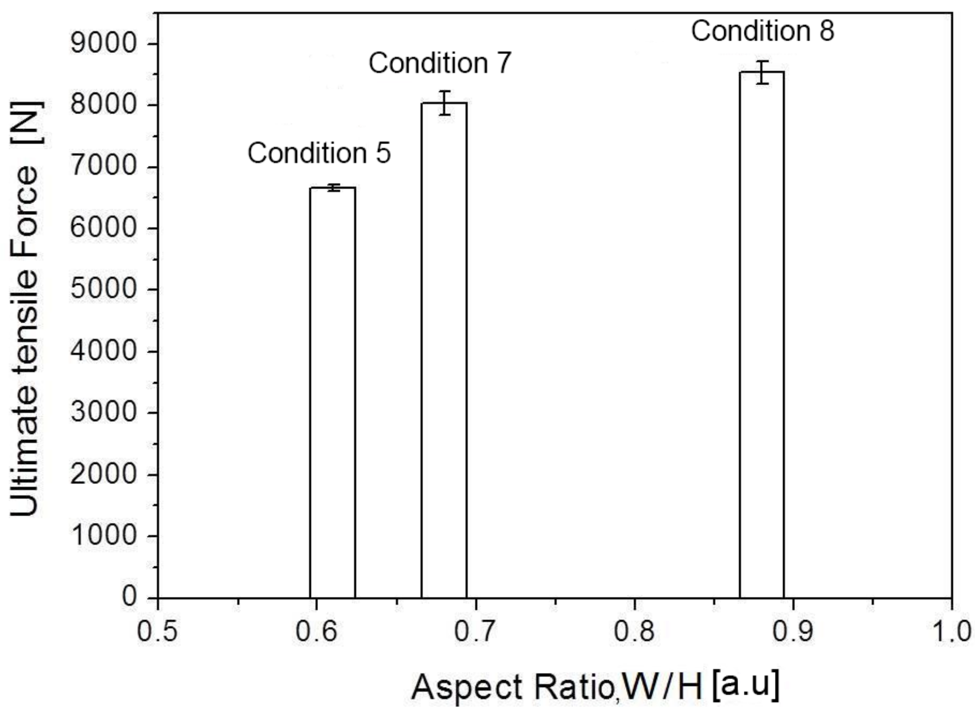

Fig. 12. Interaction between the aspect ratio and ultimate tensile force for PC-AA 2024-T351 specimens (Section 4.2 – Figure 9).

Blaga et al. (2013) proposed a more elaborated formulation describing the mechanical anchoring behavior of FricRiveting joints under tensile loading and validated their model for different friction-riveted material combinations. This formulation (Equation 1), defined as the volumetric ratio (VR), describes the mechanical anchoring of the rivet considering the interaction volumes (Figure 13) between the polymer and the metallic rivet, as calculated according to the dimensions of the rivet anchoring zone measured graphically on a central cross-section of the joint. This approach is a more complete formulation compared to AR, which treats the rivet anchoring in a simplified way in terms of volumetric interactions.

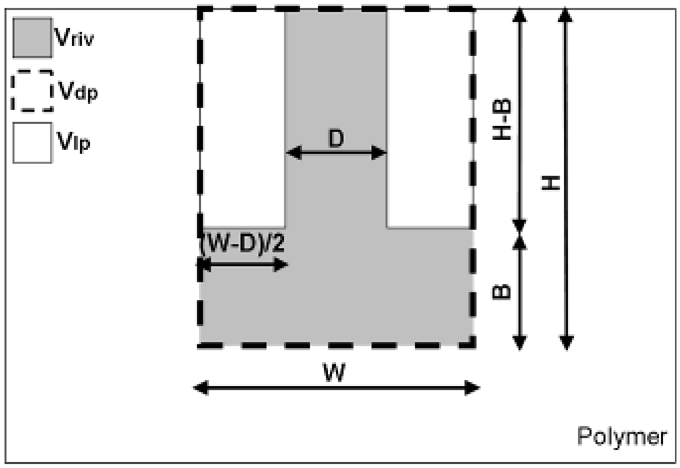

Fig. 13. Geometry of a simplified FricRiveting joint used to calculate the Volumetric Ratio in Equation 1 (V_{riv} = Volume of the metallic rivet anchored in the polymer base plate; V_{dp} = nominal volume of displaced polymer; V_{lp} = polymer volume interacting with the anchoring zone (Blaga, 2012).

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

, with H – Insertion depth

W - Width of the deformed rivet

D – Initial diameter of the rivet

B – Height of the deformed tip of the rivet

Equation 1 was also used to study the mechanical tensile behavior of PC-AA 2024-T351 joints. Table 3 and Figure 14 show the VR values calculated from the geometry of the joint anchoring zone in Figure 9 and compare the VR values to the mean UTF. These results indicate a trend of increasing UTF with VR, in agreement with the behavior of friction-riveted joints in PEI-AA 2024- T351 and glass fiber reinforced PEI-Ti gr. 2 (Blaga, 2012). Furthermore, VR was observed to follow the same behavior as AR (Figure 12), a result that validates the use of the two-dimensional AR approach for the evaluated range of parameters.

Table 3
Parameters used to calculate the Volumetric Ratio (VR) for the investigated joints and a comparison between VR and Ultimate Tensile Force (UTF) values.

Condition	W	H	H-B	B	D	VR	VR-Average	VR-STD [N]	UTF [N]	STAND. DEV [N]
5A	7,23	12,23	11.03	1.2	5	0.47	0.49	0.02	6659	62
5B	7,22	12,22	11.41	0.81	5	0.49				
5C	7,87	12,04	10.37	1.67	5	0.51				
7A	8.43	11.49	10.67	0.82	5	0.60	0.59	0.03	8040	195
7B	7.97	12.85	11.85	1.00	5	0.56				
7C	8.32	12.39	11.84	0.55	5	0.61				
8A	9.38	10.41	9.75	0.66	5	0.67	0.68	0.01	8540	182
8B	9.50	11.26	10.69	0.57	5	0.69				
8C	9.50	10.73	10.15	0.58	5	0.68				

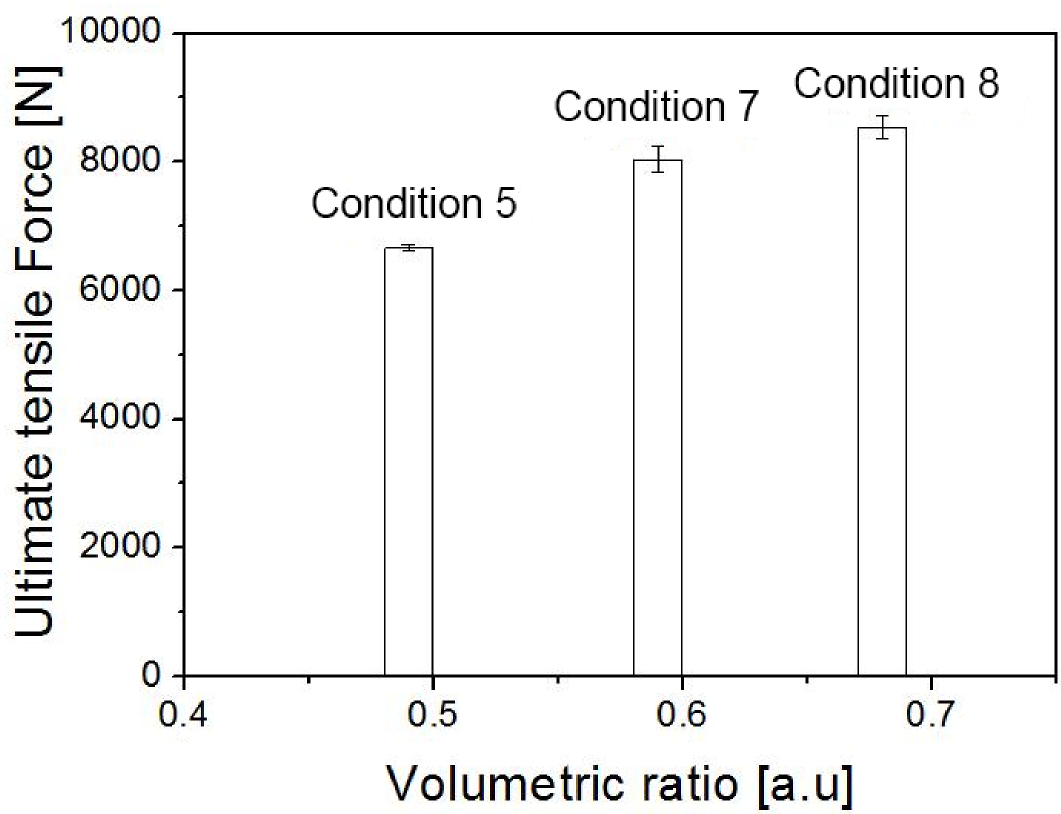

Fig. 14. Interaction of the volumetric ratio and the ultimate tensile force for PC-AA 2024 T351 samples.

Two types of fractures were observed in the PC-AA 2024-T351 joints tested in this experiment: Type I-Through the Rivet, and Type III-Full Rivet Pullout (Figure 3). The specimens of Conditions 5 and 7 had lower mean UTF values (6659 N ± 62N, 8040 N ± 195 N) and developed Type-III fractures in which the aluminum rivet was fully pulled out from inside the PC plate without any visible deformation in the AZ (Figure 15A and 15B). This type of fracture is common in structures with ductile polymers with low effective anchoring of the rivet in the polymeric matrix ($AR_{cond\ 5}$ = 0.61 ± 0.03, AR_{cond7} = 0.68 ± 0.04, $VR_{cond\ 5}$ = 0.49 ± 0.02 and $VR_{cond\ 7}$ = 0.59 ± 0.03). The reduced volume of polymer interaction (V_{lp}, Figure 13) in the anchoring zone resulted in the failure of the polymer by shearing - related to pulling of the rivet - resulting in full pullout of the rivet. Figure 15A shows the rivet completely removed from the polymer plate, and Figure 15B presents a cross-sectional view of the orifice formed in the plate, the diameter of which is similar to that of the deformed tip of the rivet.

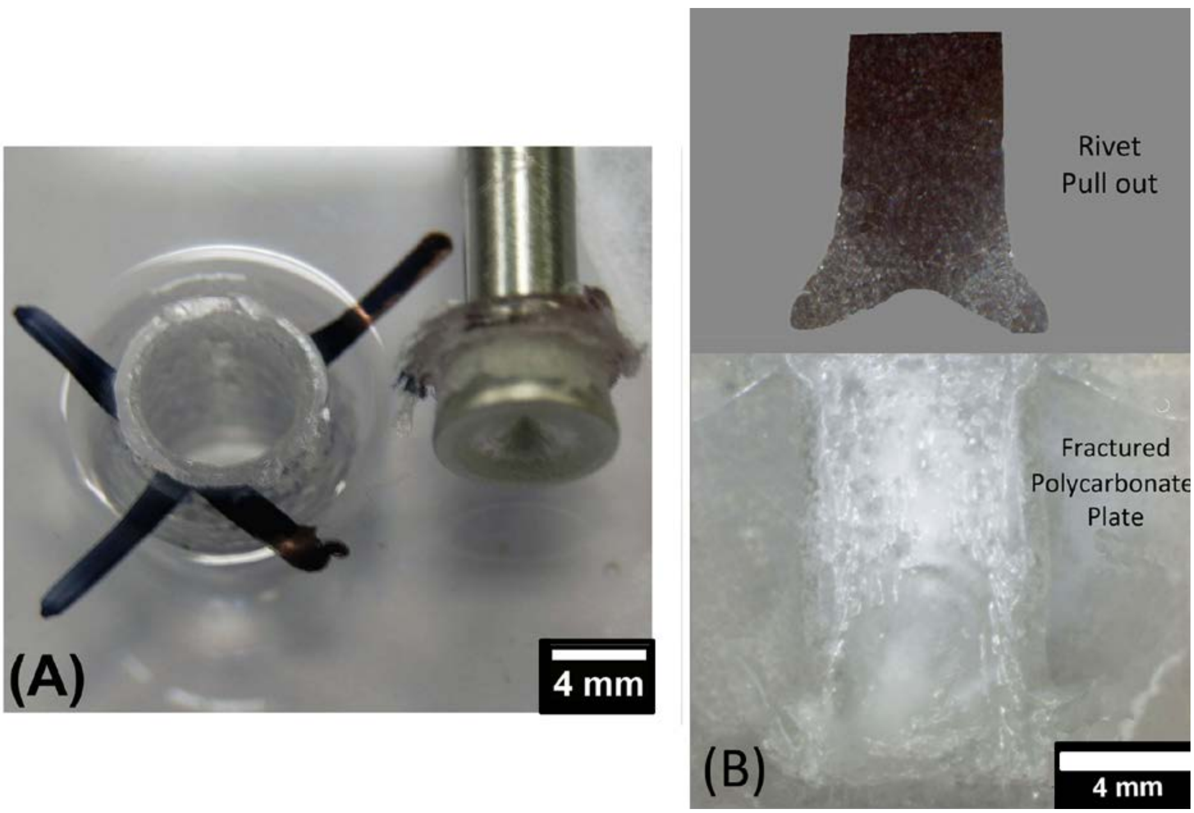

Fig. 15. Type-III fracture observed in joining Conditions 5 and 7. (A) Specimen after tensile T-Pull testing. (B) Cross-sectional view of the fractured specimen.

The joints of Condition 8 developed Type-I fractures with higher mean UTF values (8540 N ± 182 N). Type-I fracture results in a ductile-type final failure (cup/cone) in the region of the metallic rivet located externally to the PC matrix (Figure 16A). This type of fracture is desirable in friction-riveted structures under tensile loading and is justified by the effective anchoring of the rivet in the PC matrix ($AR_{cond\ 8} = 0.88 \pm 0.02$ and $VR_{cond\ 8} = 0.68 \pm 0.01$). Figure 16B shows a cross-section of the joint, including the portion of the rivet that has remained inside the PC plate.

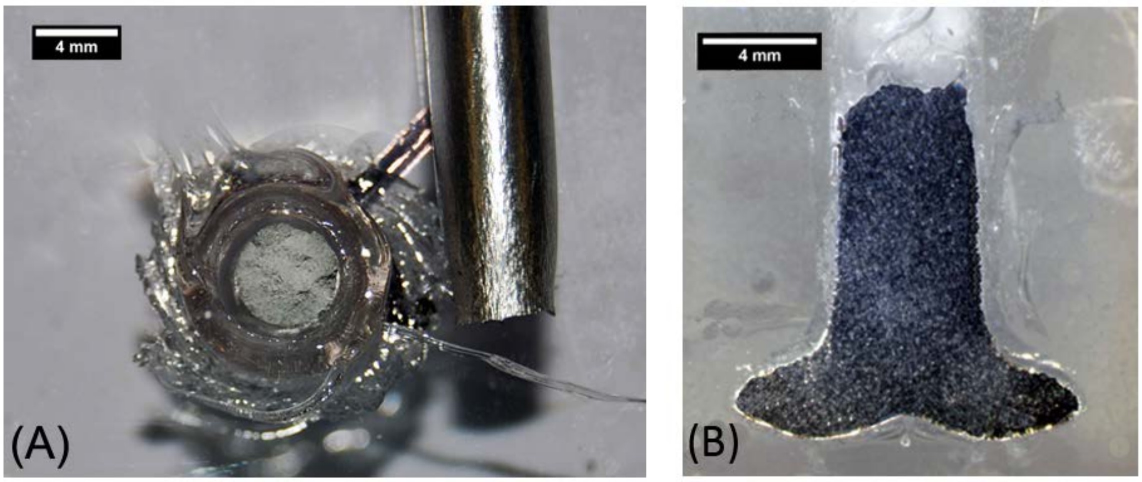

Fig. 16. Type-I fracture observed in joining Condition 8. (A) Specimen after tensile T-Pull testing. (B) Cross-sectional view of the fractured specimen.

5. Conclusions

This study demonstrated the feasibility of using FricRiveting on metallic-insert type joints of polycarbonate and AA2024-T351 rivets by analyzing their mechanical and microstructural properties and the evolution of the process temperature.

Joints were obtained with satisfactory mechanical performance due to the effective anchoring of the metallic rivet in the polymeric matrix. The mean maximum process temperature ranged between 280°C and 360°C, close to the temperature range where the rivet undergoes metallurgical transformations and approximately 56-72% of the lowest melting point of aluminum 2024-T351 rivets of 502°C. Thus, metallurgical phenomena, such as annealing and partial dynamic recrystallization, will occur in metal heat affected and metal thermo-mechanically affected zones as identified through microstructural analysis (grain partial refinement and plastic deformation) and microhardness (12% to 41% reduction in the microhardness of the joint in comparison to the metallic base material as a result of annealing phenomena).

Furthermore, the processing temperatures were below the range of PC thermal degradation by chain scission (480 and 550°C). Thus, the polycarbonate in the joint region is not expected to undergo extensive thermal degradation, although reduction in molecular weight by a certain percentage most likely occurred, as indicated by the small decrease in microhardness (6%) in the polymer consolidation zone located at the polymer-metal interface.

Process parameters exerted a strong influence on the heat generation and the deformation of the rivet tip. Increases in heat input from conditions 5 to 8 led to higher average process temperatures ($T_{peak\text{-}condition\ 5}$ = 312°C; $T_{peak\text{-}condition\ 7}$ = 330°C; $T_{peak\text{-}condition\ 8}$ = 360°C) and, consequently, to greater insertion depths and widths of the deformed rivet tip in the polymeric matrix. Thus, the aspect ratio of the rivet anchoring zone in the polymeric matrix also increased with the heat input ($AR_{cond\ 5}$ = 0.60; $AR_{cond\ 7}$ = 0.67; $AR_{cond\ 8}$ = 0.90). In addition to the aspect ratio, a simplified two-dimensional measure of the anchoring efficiency of the metallic rivet, the concept of Volumetric Ratio - a more elaborate approach that considers interaction volumes between the polymer and the anchoring zone - was used. The ultimate tensile force was correlated with the anchoring performance. Similar behavior was observed in both cases, with ultimate tensile force increasing with both aspect ratio and volumetric ratio. This finding indicates that the AR measurement, although simple, is valid for PC-AA 2024-T351 joints.

The PC-AA2024-T351 joints showed ultimate tensile force (UTF) values ranging between 6659 ± 62 N and 8540 ± 182 N with two types of fractures observed: ductile fracture in the rivet located outside the region of the PC matrix (Type I - Through the Rivet) and fracture with total removal of the rivet (Type V - Full Rivet Pullout). For structural design purposes, it is desirable that metallic insert type FricRiveting joints fail by mode I, thus avoiding the catastrophic failure of the joint. The present study demonstrates the potential of this new riveting technology in the joining of materials used in the automotive industry. More detailed studies are underway in the area of microstructural and mechanical properties that will help to better understand the process behavior and accelerate the transfer of this new technology to industrial applications.

Acknowledgments

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LIST OF SYMBOLS

T_{peak} Peak temperature

T_g Polymer glass transition temperature

H Rivet insertion depth

W Width of the rivet’s tip deformation

HV Vickers microhardness

LIST OF FIGURES

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