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Original Article

Friction riveting of FR4 substrates for printed circuit boards: Influence of process parameters on process temperature development and joint properties

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ABSTRACT

This work investigates the influence of Friction Riveting processing conditions on FR4-PCB substrate/AA2024 rivet joints in terms of process temperature evolution, joint formation, and joint physical-chemical and mechanical properties. The joints were manufactured using 4 mm diameter AA-2024-T3 rivets and FR4 laminates of 1.5 mm thickness with single or double copper-clad layers. The evolution of process temperature evolution was recorded on the FR4 substrate surface and correlated with the resulting joint formation. Most joints obtained with double copper clad layers developed process temperatures above 300 °C, whereas joints produced with a single copper clad presented slightly lower temperatures, but still above 250 °C. Rivet anchoring was achieved for both FR4 material combinations in the configuration of a single-base laminate, as well as two and even three overlapped laminates. Thermogravimetric analyses revealed that above 300 °C intensive thermal degradation occurs on FR4 materials (with 30% mass change), followed by decomposition, resulting in non-uniform heat distribution throughout the thickness. The joint ultimate tensile force was higher for double copper-clad layers and the joints achieved within more than one laminate, showing higher anchoring efficiency.

1. Introduction

The global printed circuit board (PCB) market exceeded 82 billion USD in 2022, and a compound annual growth rate of over 5% is expected between 2022 and 2030 [1]. These predictions are sustained by the growing demand for PCB for consumer electronic products and smart devices, as well as serving as a base for vast electronic components utilized in various industries such as communication, automotive, aerospace, and home applications [2]. Regarding the design and manufacturing of PCBs, the methods of attaching components to the board can directly influence the cost, functionality, ease of assembly, and availability of components.

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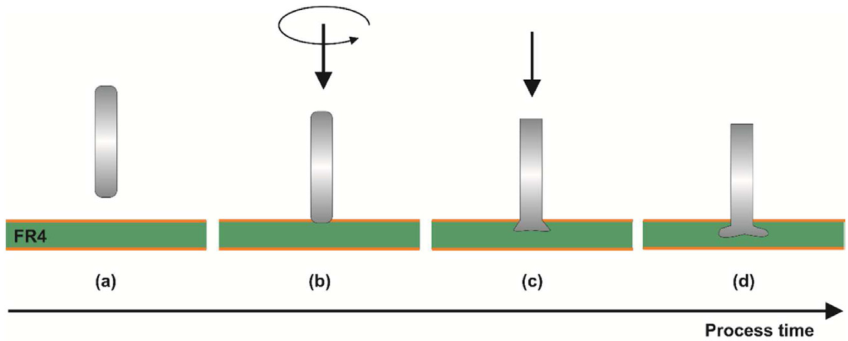

Fig. 1 – Schematic description of the Friction Riveting process steps applied on PCB: (a) positioning of the parts to be joined, (b) friction phase (plunging of the rotating rivet through the PCB upper part), (c) forging phase (plastic deformation of the rivet), and (d) joint consolidation.

The most commonly used methods are through-hole, through-hole mixed with one-sided surface-mount, one-sided surface-mount, double-sided surface-mount, and double-sided surface-mount combined with through-holes [3]. Among these methods, through-holes are the most commonly used, where the components are inserted into drilled holes on PCBs using manual or reflow soldering or press fit to hold leads/terminals in place as well as connect them to the board's conductive path [4].

The through-hole method by pressing, known as press-fit technology, has been applied to a wide range of PCB structural designs. The benefits of press-fit over soldering include fast processing [5], low temperatures (thus avoiding thermal treatment of the PCB), limited pre-processing steps, and reduced defects, such as bridges, flux residuals, etc [6]. However, press-fit has some limitations, such as the number of process steps and the need for pre-drilled holes on both sides of the plate [7].

[8] addressed friction-based joining processes as advanced techniques for joining metal-composite structures. The main principle of these processes is based on the significant thermomechanical deformation of metals achieved by friction, thus creating mechanical interlocking at the macro and/or microscopic scales. Among the listed friction-based processes that could be considered for PCB point-on-plate joints are friction-stir interlocking [9], friction self-riveting [10,11], friction riveting [12], and friction-based filling stacking [13]. The latter technique was developed relatively recently aiming to overcome the limitations of stacking by ingeniously filling the joining area with a polymeric stud [14]. Nonetheless, there have been no studies on composite materials or thermosetting composites, such as those used in most PCBs. In this regard, in this study, the Friction Riveting process is proposed as an alternative to press-fit fasteners to overcome limitations such as hole drilling by using one-step processing with components mounted on the same side of the PCB.

Fig. 1 schematically shows the different steps in the Friction Riveting process [15]. The technique is based on frictional heating, resulting from the rotation of the rivet and its insertion into the polymeric or composite parts, as shown in Fig. 1(b). A forging force is applied when the metallic rivet tip is plasticized, deformed, and consequently anchored (Fig. 1(c)), resulting in a consolidated joint, as shown in Fig. 1(d).

The process closest to Friction Riveting for PCBs is drilling. The principles governing other joining methods differ significantly mainly due to the absence of rotational friction [16]. Investigated the drilling process for PCBs in terms of temperature evolution and its effects on the boards. The study concluded that rotational speed had the highest impact on the resulting temperature. For micro-drilling, rotational speeds of 160.000–350.000 rpm have been applied, which exceed the usual rotational speeds of Friction Riveting by a factor of 10 and beyond [17]. Thus, Friction Riveting is distinct from drilling, although the former also involves friction.

The feasibility of Friction Riveting has been proven for various applications and material combinations, where previous studies have focused mostly on joint formation [18], process temperature evolution, mechanical behavior, and microstructural changes, see for an overview [19]. The thinnest composite material joined by Friction Riveting so far was reported by Ref. [20]; where 4.34 mm thick carbon fiber reinforced PEEK thermoplastic laminates were joined with 5 mm diameter Ti6Al4V rivets. This is also the first known publication on Friction Riveting, where the thickness-to-diameter ratio briefly fell below 1:1. With regard to friction-riveted thermosetting matrix composites [21], investigated the first material combination, consisting of 10 mm thick glass fiber reinforced polyester (with phenolic additive as a flame retardant) and 5 mm diameter Ti6Al4V rivets. Despite the occurrence of thermal flaws, sufficient mechanical anchoring was achieved [22]. Recently conducted a feasibility study on Friction Riveting, showing promising results regarding the mechanical anchoring efficiency of AA2024 rivets in FR4 laminates (material used as substrate in PCBs). However, process-induced changes in the physical-chemical properties of FR4 need to be investigated, especially their effect on the joint anchoring efficiency.

In this regard, this study investigates Friction Riveting on PCB copper-clad substrate materials using aluminum rivets with 4 mm diameter. The influence of different process parameters, i.e. rotational speed, friction force, and displacement at friction, on the produced joints was analyzed in terms of

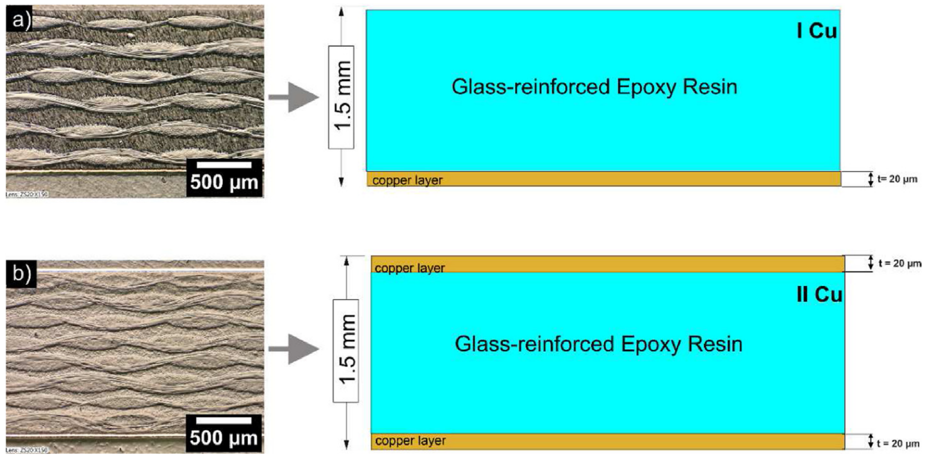

Fig. 2 – Microstructure of the glass-fiber-reinforced epoxy laminates (FR4 substrate for PCB) identified as (a) single (FR4-I Cu) and (b) double (FR4-II Cu) copper layers in tandem with the schematic distribution of the copper layers along the thickness of the FR4 laminates.

process temperature evolution, joint formation, material physical-chemical, and mechanical properties. The main challenges in terms of Friction Riveting related to the material utilized in the present study were its reduced thickness and thickness-to-diameter ratio, in addition to the presence of copper layers.

2. Materials and methods

Glass-reinforced epoxy resin laminates (FR4) are preferred as substrates in PCBs [23], because of their superior mechanical and chemical properties, such as a good

Table 1 – Friction Riveting investigated configurations with different process parameters. RS: rotational speed; DaF: displacement at friction; FF: friction force and material configuration (i.e. single, I, or double copper layer, II).

Condition	Rotational speed, RS [RSM]	Displacement at friction, DaF [mm]	Friction force, FF [N]	FR4 Material configuration
1	3000	3.00	3000	II Cu
2	7000	3.00	3000	I Cu
3	3000	3.00	3000	I Cu
4	7000	2.40	3000	II Cu
5	3000	2.70	4000	I Cu
6	5000	2.70	3000	I Cu
7	5000	2.40	4000	II Cu
8	5000	3.00	4000	II Cu
9	5000	2.40	4000	I Cu
10	5000	3.00	4000	I Cu
11	3000	2.70	4000	II Cu
12	7000	2.70	4000	II Cu
13	5000	2.40	2000	I Cu
14	3000	2.40	3000	II Cu
15	7000	2.70	2000	I Cu
16	3000	2.70	2000	I Cu
17	7000	2.70	2000	II Cu
18	5000	2.40	2000	II Cu
19	5000	2.70	3000	I Cu
20	5000	2.70	3000	I Cu
21	7000	3.00	3000	II Cu
22	7000	2.70	4000	I Cu
23	7000	2.40	3000	I Cu
24	3000	2.40	3000	I Cu
25	5000	3.00	2000	II Cu
26	5000	2.70	3000	II Cu
27	5000	2.70	3000	II Cu
28	3000	2.70	2000	II Cu
29	5000	2.70	3000	II Cu
30	5000	3.00	2000	I Cu

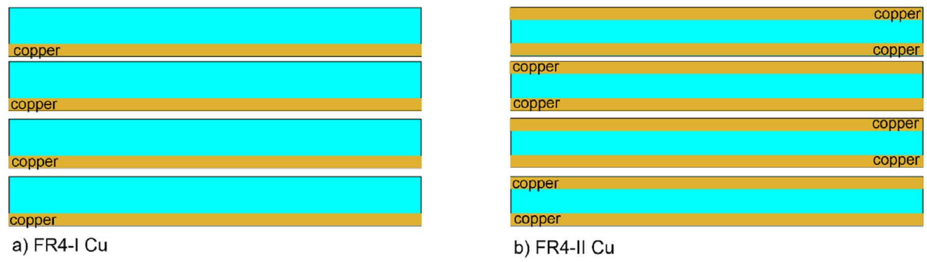

Fig. 3 – FR4 overlap configuration setup for joining. (a) FR4-I Cu (with a copper layer positioned on the bottom) and (b) FR4-II Cu laminates.

resistance-weight ratio, high mechanical strength, and good insulating properties in humid environments [24]. These laminates are designated FR4 by NEMA (National Electrical Manufacturers Association, USA), where 'FR' stands for 'flame retardant' material. FR4 consists of prepreg materials, which are woven glass fiber impregnated with epoxy resin [24]. It was supplied as a rectangular sheet with a nominal thickness of 1.50 mm, cladded with a 20 μm thick copper layer, either on one side (single copper layer, named in the following FR4-I Cu) or on both sides (double copper layer, FR4-II Cu), see Fig. 2. FR4s are the most common, affordable, and widely used type of substrate in the electronic industry. Fig. 2 also illustrates the microstructures of FR4-I Cu and FR4-II Cu together with their respective thicknesses and number of copper layers. To study Friction Riveting for PCB boards, an FR4 substrate material without printed circuits or electronic assemblies was adopted in this work, to allow the identification of the joining mechanisms, avoiding possible unknown effects of these additions. The FR4 materials used in this study were produced by Shenkai Electronics (Shenzhen, CN).

Extruded rivets of aluminum alloy AA2024-T351 with a diameter of 4 mm and length of 40 mm were employed. In addition to Al, the main chemical elements in AA2024 are Cu and Mg. Temper stage T351 indicates that this alloy has underwent solution heat treatment and residual stress relief.

The joints were produced with dedicated Friction Riveting laboratory equipment (Loitz Robotic, Germany), employing a friction welding spindle RSM410 (Harms & Wende GmbH, Germany). A sample holder with a pneumatic clamping system (DZF-50-25-P-A-FESTO, Islandia, NY, USA) was used to fix the overlapped FR4 laminate.

The process parameters of rotational speed (RS), displacement at friction (DaF), and friction force (FF) were systematically varied between three levels, following the Box-Behnken design (BBD). Consequently, 30 joining conditions were investigated with three center points (replicated conditions), see Table 1. Two categorical factors were designed as material configurations (FR4-I Cu and FR4-II Cu) and three sample replicates were prepared for each joining condition.

Considering the thickness of each individual FR4 laminate, a stack of four laminates was placed within the clamping system as shown in Fig. 3. However, the joining process is intended to produce only overlap joints of two laminates. The additional two laminates were only placed underneath to avoid welding the rivet to the working table of the equipment in case of full perforation. Fig. 3 shows the overlap configurations set up for joining (a) FR4-I Cu (copper layer positioned on the bottom side) and (b) FR4-II Cu laminates.

The process temperature was recorded using an infrared thermography camera (High-End Camera Series Image IR, Infratech GmbH, Germany), using IRBIS-3 software. A temperature filter calibrated within the range of 150 °C – 700 °C and a 20 Hz frame rate were applied. The measurements were recorded from the FR4 substrate surface area, with a focal distance of 1 m at an incidence angle of approximately 30°. The peak temperature recorded for each measurement was considered as the maximum joining process temperature. The average peak temperature (T_{peak}) was calculated from the three peak temperatures recorded for each studied condition. Furthermore, the geometry and quality of the joints obtained were assessed using digital optical microscopy (VHX-6000 series from KEYENCE America) and scanning electron microscopy (SEM, Quanta FEG 650).

The physical-chemical properties of the FR4 matrix were analyzed using a thermogravimetric analyzer (TG 209 F3 Tarsus, NETZSCH). Therefore, possible degradation, which might have occurred in FR4 during the joining process, was investigated. The measurements were performed on samples extracted from the FR4 base material (FR4-I Cu and FR4-II Cu), with sample weights between 8 mg and 16 mg. During testing, the samples were placed in an open aluminum pan and heated at 20 °C min^{-1} from 25 °C to 500 °C under a N_2 atmosphere (flow rate 50 $ml\ min^{-1}$). Four samples were analyzed for each type of FR4 laminate.

The global mechanical properties of the joints were evaluated through ultimate tensile force (UTF) measured via a pullout test. The pullout test was conducted in an universal testing machine (Zwick Roell 1484, Germany) equipped with a 100 kN load cell, with respect to the grip distance and a crosshead speed of 40 mm and 1 mm min^{-1}, respectively, at room temperature. A specially designed specimen holder was used for the pullout test, as shown in Fig. 4.

To evaluate the mechanical behavior of the joints further, the average volumetric ratio (VR) [19] is evaluated additionally, which is calculated as follows

$$VR = \frac{D_p \bullet (W^2 - D^2)}{H \bullet W^2}, \quad (1)$$

where H is the rivet penetration depth, W is the rivet tip width, D_p is the anchoring depth, and D is the rivet diameter. VR describes the anchoring efficiency of the deformed rivet by considering the interaction volumes between the polymeric material and the metallic rivet [25].

3. Results and discussion

In this section, the influence of the Friction Riveting processing conditions on joint formation was correlated with the process temperature evolution. Additionally, the measured temperatures are correlated with the physical-chemical properties of the FR4 substrate material to determine if substantial degradation was likely to occur, the mechanical behavior in terms of pullout testing is assessed, and its dependence on the above-mentioned process variables is discussed.

3.1. *Process temperature evolution and joint formation*

The evolution of temperature is an important response related to the occurrence of friction, which is responsible for heat generation, rivet tip deformation, and the final joint formation achieved by Friction Riveting. Fig. 5 shows the measured peak temperatures for the 30 joining conditions obtained using the two material configurations (FR4-I Cu and FR4-II Cu) according to the BBD, see Table 1.

In addition to the different process parameters, the FR4 material configuration plays a crucial role in determining the resulting process temperature. Most of the joints produced with FR4-II Cu exhibited peak temperatures above 300 °C. The joints produced with FR4-I Cu experienced slightly lower temperatures, some just above 250 °C. Joints produced with FR4-II Cu showed up to 26% higher process temperatures than those obtained with FR4-I Cu, particularly those produced at rotational speed of 3000 rpm, see Table 2. This behavior is probably due to the initial contact surface, where the rivet initially penetrates the copper layer directly in case of FR4-II Cu, see Fig. 3(b), which enhances the thermal conductivity and friction with the aluminum rivet. Copper[1] is a harder material with a much higher thermal conductivity [26] than epoxy.[2] In this regard, the additional Cu layer on FR4-II Cu might accelerate heat generation and the consequent vertical heat transfer through the epoxy matrix during the process, thus increasing the overall joint temperature.

Additionally, statistical analyses show that RS and type of the FR4 laminate have the highest influence on the process temperature and, consequently, the heat generation during Friction Riveting, see Fig. 6. The combined effects of DaF and FF are insignificant in this respect. For thermoplastics [27], showed that the heat generated during the Friction Riveting process is mainly generated through viscous dissipation in the sheared molten/softened polymer. Nonetheless, viscous dissipation is limited for thermosets, because no changes in the material viscosity occur when its temperature increases [28]. Thus, in the present study, the heat generated was mainly solid-state friction [19] between the metallic rivet and laminate substrate (epoxy, fiber component, and copper layer).

Representative joint geometries obtained with AA-2024-T3 rivets and FR4 laminates in relation to the observed maximum temperature ranges reached during the process are shown in Figs. 7 and 8. If the maximum process temperature reaches 250 °C, which can be regarded as a low process temperature,[3] independent of the FR4 material configuration, the rivet tip was only able to penetrate one laminate without generating sizeable deformation and anchoring, see Fig. 7(a) and 8 (a). If the process temperature was in the range of 260 °C and 340 °C, it was possible to plasticize and anchor the rivet into two overlapping laminates of FR4-I Cu, Fig. 7(b). Similar results were obtained for FR4-II Cu joints, but between 360 °C and 400 °C, Fig. 8(b). Above 360 °C, although there was penetration, the deformation of the rivet developed mostly on the surface into the laminate for FR4–I Cu, Fig. 7(c). In terms of FR4–II Cu, some rivets penetrated and deformed into three FR4 overlapped laminates, Fig. 8(c). If the temperature was even higher than 370 °C, most joints failed to anchor into FR4-I Cu and FR4-II Cu laminates. Irrespective of the specific FR4 laminate, the production of joints via Friction Riveting is challenging if the process temperature exceeds 300 °C. Similarly [21], observed unstable process conditions for Friction Riveting of thermosetting-based composites at high temperatures, even within a much thicker material.[4]

3.2. *Thermal properties of FR4 laminates*

The challenges faced in producing joints of FR4 laminates via Friction Riveting may also be related to the thermal properties of FR4. Fig. 9 shows the thermogravimetric (TG) analyses of both FR4 laminate base materials. The results suggest that, at 270 °C, both FR4 laminates started to suffer slow-rate thermal degradation, where up to 2% mass loss was observed. Between 300 °C and 400 °C, up to 30% mass change was observed, i.e. the resin system started to decompose into a primary carbonaceous char through the rupture of chemical bonds and loss of volatile components [29]. Finally, char oxidation occurs beyond 400 °C, which is characterized by higher residual char [23]. These intensive physical-chemical changes in FR4 at elevated temperatures result in non-uniform heat distribution throughout the thickness of inhomogeneous laminates during Friction Riveting, affecting joint formation in unpredictable ways.

Fig. 10(a) shows a micrograph of the FR4-II Cu part of a joint that presents insufficient anchoring, i.e. it is considered a failed-joining condition (RS: 7000 rpm, DaF: 2.70 mm FF: 2000 N). This joint exhibited a maximum process temperature of 480 °C, where severely charred FR4 is present, see Fig. 10(b). Consequently, only a small amount of resin remained within FR4, which impaired the joining anchoring. To better observe the degraded area, SEM micrographs (top view) were taken from the lower part of the failed FR4-II Cu joint, where rivet

[1] Thermal conductivity of copper 385 W/mK.
[2] Thermal conductivity of epoxy 0.25 W/mK.

[3] below 40% of the alloy's melting temperature is usually insufficient for plastic deformation of the metal in friction-based processes.
[4] about factor 8x compared to the present work.

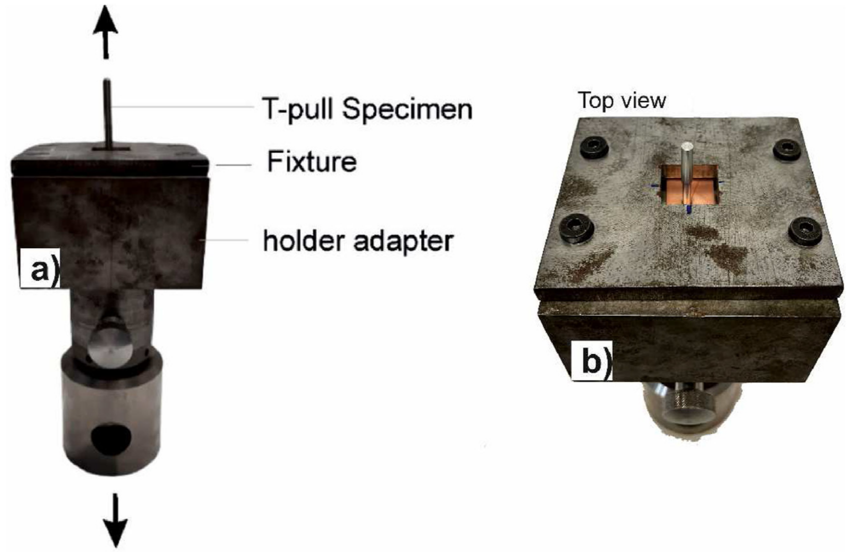

Fig. 4 – a) Pullout tensile testing holder adapter used for the evaluation of the ultimate tensile force of joints produced by Friction Riveting, including the top view (b).

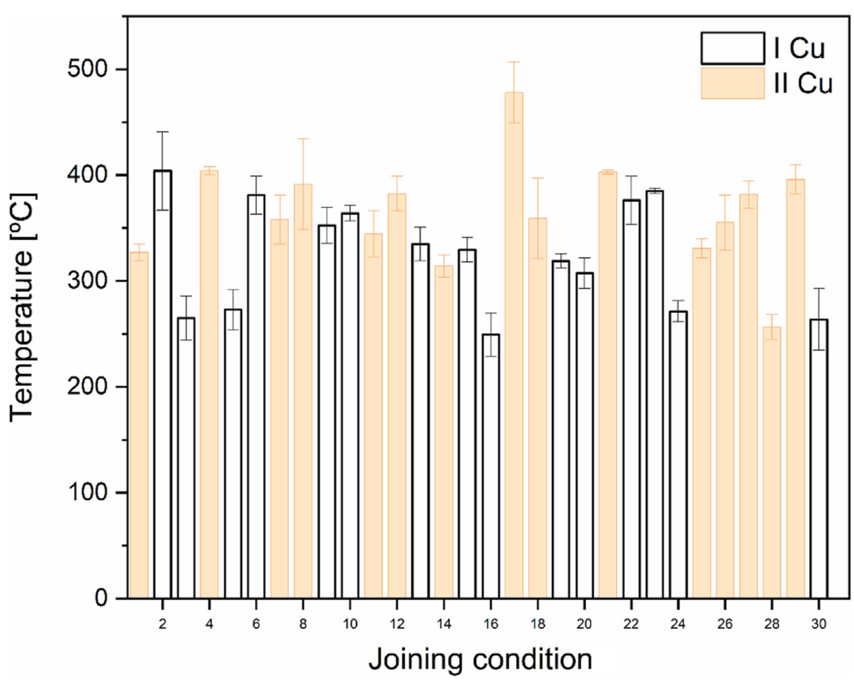

Fig. 5 – Peak process temperatures of 30 joining conditions used to produce joints of AA-2024-T3 rivet and different FR4 material configurations (I Cu and II Cu) according to BBD, see Table 1.

Table 2 – Comparison of average peak temperature (T_{peak}) for joints produced with FR4-I Cu and FR4-II Cu at 3000 rpm rotational speed (RS) and different displacements at friction (DaF) and friction force (FF).

Conditions	FR4-I Cu T_{peak} [°C]	FR4-II Cu T_{peak} [°C]
RS: 3000 rpm: DaF: 3.00 mm FF: 3000 N	265 ± 21	327 ± 8
RS: 3000 rpm: DaF: 2.70 mm FF: 4000 N	273 ± 19	344 ± 22
RS: 3000 rpm: DaF: 2.40 mm FF: 3000 N	271 ± 10	314 ± 10

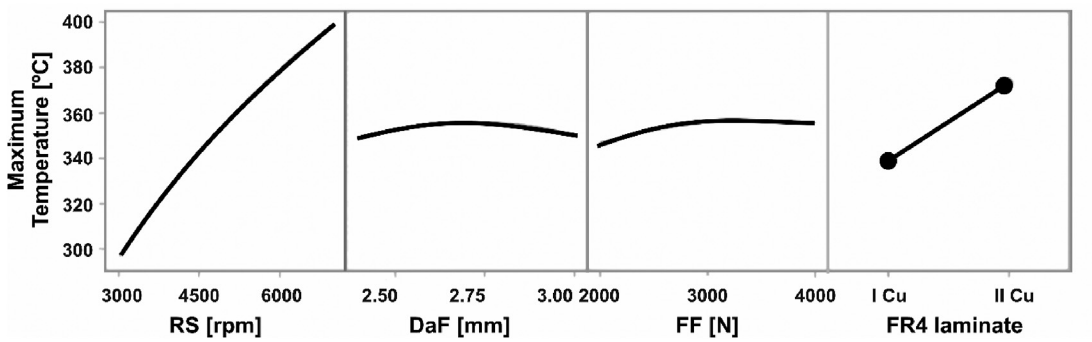

Fig. 6 – Effect of process parameters (Rotational speed, RS, different displacement at friction, DaF, friction force, FF) on maximum process temperature.

anchoring failed, as shown in Fig. 10(c) after rivet extraction. Remnants of epoxy resin and glass fiber fragments can be identified in this area, see Fig. 10(d). Fig. 10(e) shows the charred area in detail, where carbonized epoxy can be seen, as well as broken fibers. Fig. 10(f) clearly illustrates the aspect of fiber breakage owing to shear forces from surface friction. The remaining fragments of charred epoxy indicate a worn surface. This observation is in agreement with [21] for Friction Riveting of thermosetting glass fiber-reinforced polyester, whereby the process temperature also surpassed the onset of thermal degradation of the investigated polymer.

As shown in Fig. 10, as well as in the macrographs in Fig. 7, the composite-metal interface of the friction-riveted joints is largely affected and presents various thermal flaws that were generated from the thermoset degradation process. Furthermore, the Al–Cu contact is likely to induce a reaction that resulted in metallurgical bonding and intermetallic compounds (IMCs). Future research will have to assess these features, as addressed recently by Ref. [30] for friction-stir-welded AA2024 and copper joints. Combined XRD and EDS analyses identified Al_2Cu and Al_4Cu_9 intermetallics and it was argued that the thickness of the IMCs formed at the interface influences the mechanical properties of the joints. Nonetheless, in the case of Friction Riveting, up to the present study, the main contribution to the joint strength was related to the anchoring efficiency. As the anchoring efficiency in the current case appears to be relatively low, see following discussion, it is possible that the formation of IMCs and Al–Cu bonding could be more significant to the mechanical properties than previously considered and should therefore be studied further in the future.

3.3. *Mechanical properties of the joints*

The joints obtained with one or more FR4 laminates, see Figs. 7(b)–(c) and 8 (b)–(c), were selected and analyzed in terms of UTF, determined by pullout testing. Table 3 presents the mean values of UTF, together with the measured VR and maximum process temperature.

For the FR4-I Cu joints obtained at 329 °C, it was possible to plasticize and anchor the rivet within two overlapped laminates, resulting in rivet anchoring of 0.3 (VR) and an average

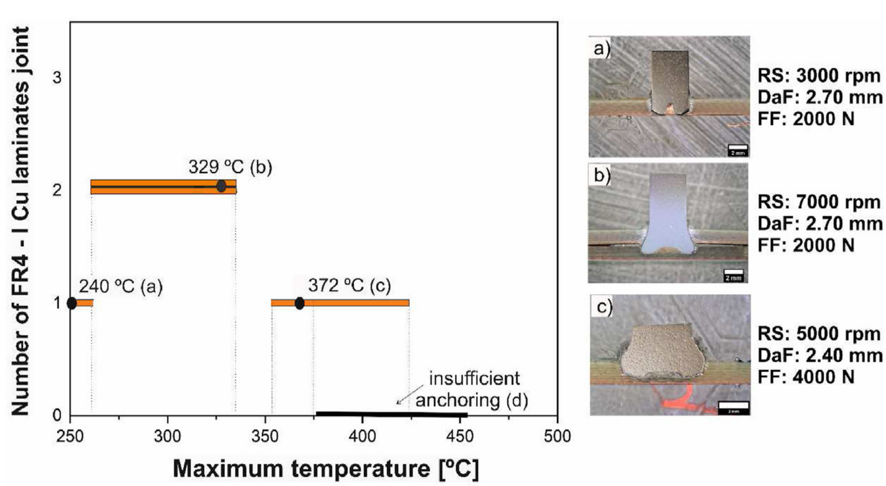

Fig. 7 – Representative geometries obtained for AA-2024-T3 rivets and FR4-I Cu within the temperature range reached during the process. Depending on the process conditions, the rivet penetrates different number of FR4- I Cu laminates.

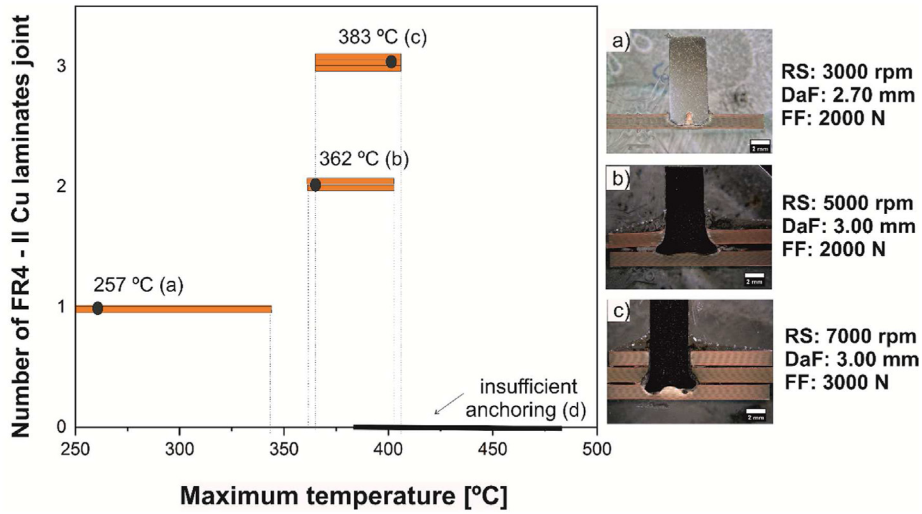

Fig. 8 – Representative geometries obtained for AA-2024-T3 rivets and FR4 – II Cu within the temperature range reached during the process. Depending on the process conditions, the rivet penetrated different number of FR4-II Cu laminates.

UTF of 813 N (Condition 15, Table 1). At a higher process temperature (352 °C), the insertion of the rivet tip into the FR4-I Cu laminate was incomplete and developed mainly on the laminated surface (VR = 0). The large deformation at the rivet tip coupled with the small insertion depth of these joints results in rivet pullout failure [31], where the rivet is easily removed from the laminate because of weak anchoring forces, resulting in a low UTF (17 N, Condition 9, Table 1).

For FR4–II Cu joints achieved at temperatures between 360 °C and 400 °C, within two or even three overlapped laminates, as shown in Fig. 8(b), VR varies between 0.4 and 0.5. The corresponding UTFs of 523 N (Condition 21, Table 1) and 686 N (Condition 25, Table 1) were obtained. These results are in agreement with previous publications on Friction Riveting

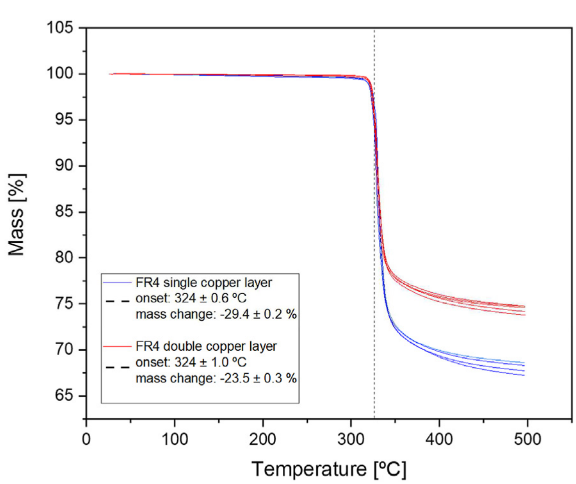

Fig. 9 – TG curves of FR4-I Cu (blue line) and FR4-II Cu (red line) in N_2 atmosphere at a heating rate of 20 °C min^{-1}.

[19], where the anchoring efficiency was identified as the main factor affecting the mechanical properties, i.e. the higher the anchoring, defined by both deformation depth and width, the higher the UTF [31]. However, because of the reduced thickness of the joints, it is possible that IMCs contributed to some portion of the mechanical properties.

Fig. 11 shows the influence of the individual process parameters and FR4 laminates (FR4-I Cu and FR4-II Cu) on the UTF. It can be noticed that the effect of RS and FF on UTF are similar and more significant than the influence of DaF. Increases in both RS and FF will result in a higher UTF for FR4-II Cu but a significantly lower UTF for FR4-I Cu. This behavior is directly related to the thermal degradation of FR4, the rivet anchoring efficiency, and the number of FR4 laminates that the rivet penetrates. Higher process temperatures led to improved deformation and anchoring of the metallic rivet within the polymeric material. However, the thermosetting matrix can have a negative impact on the mechanical properties if the onset of thermal degradation is achieved [32].

Another important factor, besides the anchoring efficiency, expressed by VR, is the thickness-to-diameter ratio, as this work presents the lowest ratio achieved so far in Friction Riveting. In this regard, future work need to address the optimal rivet geometry for a given plate thickness. As for the joint optimization, to reduce potential gaps between the rivet and the composite due to differential thermal contractions of the two materials, a different process control might be introduced, as applied by Ref. [33] by extending consolidation time after the actual joint formation. Finally, the response of the actual PCB stacking sequence to the friction riveting process must be addressed. As proven in this work, along with the results from Ref. [22]; the more composite anchoring material available, the better the mechanical properties of the friction-riveted PCB joints, which is in agreement with other studies

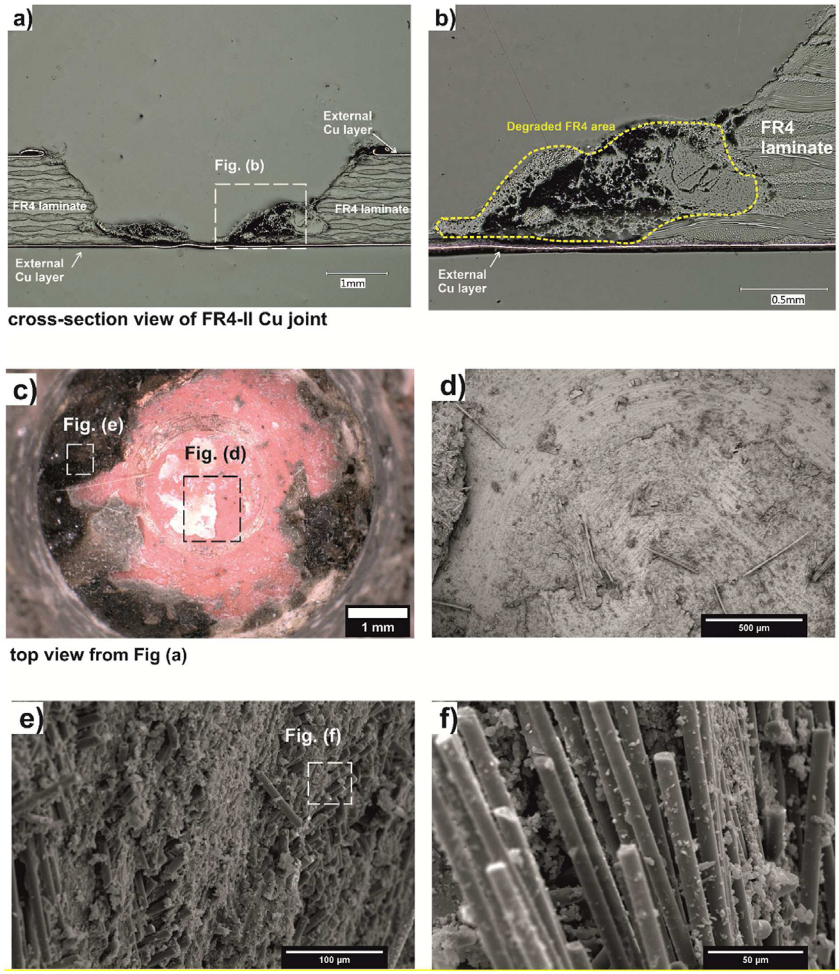

Fig. 10 – a) Micrograph of joint within the FR4-II Cu area after rivet extraction, where rivet anchoring failed (RS: 7000 rpm, DaF: 2.70 mm FF: 2000 N). b) Details of remaining carbonized epoxy (charred area). c) Top view of the degraded FR4 area from where SEM micrographs were taken, showing details of (d) remaining epoxy and fiber fragments, (e) carbonized epoxy and broken fibers and (f) high-magnification image of broken fibers.

Table 3 – The investigated joining conditions, their process temperature, UTF and VR values.

FR4 Laminate	Condition	Temperature [°C]	UTF [N]	VR
FR4 – I Cu	C15: RS: 7000 rpm: DaF: 2.70 mm FF: 2000 N	329 ± 11	813 ± 117	0.3 ± 0.1
	C9: RS: 5000 rpm: DaF: 2.40 mm FF: 4000 N	352 ± 16	17 ± 6	0
FR4 – II Cu	C25: RS: 5000 rpm: DaF: 3.00 mm FF: 2000 N	362 ± 40	686 ± 43	0.5 ± 0.1
	C21: RS: 7000 rpm: DaF: 3.00 mm FF: 3000 N	383 ± 17	523 ± 13	0.4 ± 0.0

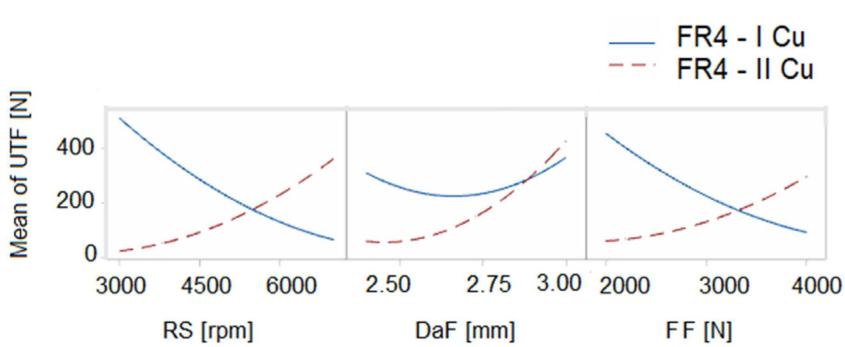

Fig. 11 – Interaction plots showing the effect of individual process parameters (RS, DaF, and FF) and materials (FR4-I Cu and FR4-II Cu) on UTF.

on Friction Riveting in various configurations and applications. As the PCB thicknesses can be even lower than the current investigated 1.5 mm, one solution for optimization the anchoring could be the reduction of the rivet diameter to match the thickness-to-diameter ratio of the joints with high mechanical properties achieved in stacked PCBs. This is not trivial, as the current best joining conditions would imply loads exceeding the critical buckling load for reduced rivet diameters. However, the downscaling of Friction Riveting is beyond the scope of the present study and will be addressed in the future. Furthermore, as the feasibility of joining FR4 PCB substrates has been proven, future studies should focus on actual PCB plates and various relevant substrates and solder masks for electronic applications to explore the full potential of Friction Riveting.

4. Conclusion

In this study, the influence of Friction Riveting processing conditions on FR4-PCB substrate/AA2024 rivet joints was investigated in terms of process temperature evolution, joint formation, physical-chemical and mechanical properties. Joints were manufactured using 4 mm diameter AA-2024-T3 rivets, FR4 laminates of 1.5 mm-thickness with single (FR4-I Cu) and double copper clad layers (FR4-II Cu) under different processing conditions.

Plastic deformation and consequent anchoring of the AA2024 rivets were successfully achieved with process temperatures within the range or beyond the onset of thermal degradation of the composites. The joints produced with FR4-II Cu exhibited up to 26% higher process temperatures than those obtained with FR4-I Cu, particularly those produced at a low rotational speed (3000 rpm). The existence of copper layers on both surfaces of FR4-II Cu enhanced the thermal conductivity and friction with the aluminum rivet, leading to higher process temperatures. Friction Riveting processing temperatures above 300 °C exhibit the risk of intensive thermal degradation (with 30% mass change) occurring in the FR4 laminate within the rivet anchoring zone.

Rivet anchoring was achieved for both FR4 material combinations in the configuration of one single base laminate, as well as two and even three overlapped laminates. The effects of rotational speed and friction force significantly influence rivet anchoring and consequent joint mechanical properties. Finally, the feasibility of Friction Riveting in producing joints on FR4 PCB substrate materials with good mechanical properties was proven, bearing in mind the reduced thickness of the substrate material and size of electronic components. However, special attention is required to avoid extensive thermal degradation related to high processing temperatures, which leads to deterioration of the joint quality.

Credit authorship contribution statement

C.F. Rodrigues: Investigation, Validation, Formal analysis, Visualization, writing – original draft preparation. **L. Blaga**: Visualization, Supervision, Writing –review & Editing. **B. Klusemann**: Supervision, Writing –review & Editing.

Data availability

Data will be available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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