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ORIGINAL ARTICLE

Welding parameters process study of non-metallic expansion joints polymeric composite

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Abstract

Polymeric composite materials, presenting a practical solution for sealing non-metallic expansion joints under extreme conditions such as high temperatures and harsh chemical and physical abrasion, were investigated in this scientific study to discern the impact of welding parameters on their degradation and properties. The study entailed the bonding of polymeric composite blankets through hot plate pressing with a PTFE film, encompassing variations in temperature, duration, and load application. The findings elucidated that lower temperatures and shorter processing times failed to achieve optimal blanket adhesion, while higher temperatures led to material degradation, subsequently diminishing the mechanical strength of the welded joint. In contrast, extended processing times and the application of load during welding demonstrated a positive correlation, enhancing the mechanical strength of the joint by ameliorating interfacial adhesion. This research underscores the critical significance of carefully selecting welding parameters to ensure the peak performance and durability of polymeric composite structures.

Keywords: *polymeric composite, hot plate welding, composite, seal blanket.*

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1. Introduction

Non-metallic expansion joints are subject to specific requirements for their application, including withstanding high temperatures, resisting corrosive environments, and accommodating expansion, axial, and lateral movement[1]. Among the key components of a non-metallic expansion joint is the seal blanket, typically constructed from a polymer composite. Laminated seal blankets composed of fluorinated elastoplastic reinforced with fiberglass and aramid, and coated with PTFE (polytetrafluoroethylene), offer thermal stability, allowing continuous operation within a temperature range of approximately -40 °C to 260 °C. This makes them suitable for situations characterized by high thermal and chemical wear[2].

The mechanical and structural properties of these polymeric composites can be influenced by the welding parameters employed during the fabrication of welded joints. Therefore, understanding the characteristics of these materials entails studying their mechanical and thermal properties, such as Young's modulus and degradation[3].

Consequently, welding fluorinated elastoplastic reinforced with fiberglass and aramid polymeric composite coated with PTFE poses challenges in the production of non-metallic expansion joints. Incorrect execution of the welding process may lead to leaks during service, and degradation of the PTFE coating can result in cracks in the application of non-metallic joints.

Various polymer welding processes are currently employed, and with the increasing utilization of these materials, new techniques are continually being introduced[4]. Hot plate pressing welding is the most common method employed for joining fluorinated elastoplastic reinforced with fiberglass and aramid polymeric composite coated with PTFE. This technique involves heating the surfaces to be joined through direct contact with heated metal tools, applying compressive force to the mating surfaces. Subsequently, the interface cools and solidifies under controlled pressure, resulting in the welding of polymeric blankets[5-7].

While failures in polymeric composite materials have been analyzed in recent years[8-10], only a few studies have focused on their joining. For instance, Barbosa et al.[11] investigated resistance welding of composites composed of PPS and fiberglass, exploring microfractography for failure analysis and testing welding parameters to enhance joint mechanical properties and identify potential failure modes. Javaid et al.[12] examined welded joints of unidirectional fiberglass-carbon fiber composites used in wind turbines, studying joint geometries, finite element analysis, tensile testing, and fatigue testing. Du et al.[13] investigated the

tensile mechanical properties of integrated composite joints with the fuselage connected by fasteners and adhesives, using tensile testing and finite element modeling to predict joint behavior. Dissimilar joints represent another aspect of composite welding failures, as studied by Hu et al.[14], who examined bolted joints of unidirectional carbon fiber composites with polyester through interference, assessing the effects of temperature on joint tensile mechanical properties. Despite the limited literature available on composite welded joints, particularly involving thermal joint sealing materials like the commercially known Darlyn®, this study aims to enhance mechanical properties and prevent joint failures by varying welding parameters and assessing their mechanical and thermal properties.

The objective of this work is to determine the influence of hot plate pressing welding parameters on the degradation and mechanical resistance of fluorinated elastoplastic reinforced with fiberglass and aramid polymeric composite coated with PTFE. These parameters will be established to ensure the avoidance of future defects that may arise during service due to changes in the properties of the studied polymeric composite resulting from the welding process used to manufacture expansion joints.

2. Materials and Methods

Polymeric composite blankets (PCBs) made of fluorinated elastoplastic reinforced with fiberglass and aramid, and coated with PTFE, were used in this study. The PCBs were in the form of plates with dimensions of (150x220) mm. To join these blankets, a PTFE tape measuring 0.3 mm in thickness, 5.0 mm in width, and 220 mm in length was utilized. The schematic representation of this assembly is depicted in Figure 1a. Figure 1b demonstrates the overlapping of the polymer composite blankets, while Figure 1c illustrates the placement of the PTFE film between the blankets, clearly identifiable by its bright color in the corner of the blanket.

The welding process was performed using a Heat Sealer model 630 heat generator through the hot plate pressing method. The specific parameters employed in the welding process can be found in Table 1.

The tensile strength limit (s_r) of both the welded and non-welded materials was determined through a tensile test conducted in accordance with ASTM D412 standard[15]. The tests were performed in triplicate using an EMIC machine with a capacity of 150 kN, applying a crosshead speed of 4 mm/min. In order to assess the influence of the welding process on the material's resistance behavior, the welded region was strategically positioned within the functional area of the tested sample, as illustrated in Figure 2. Subsequently, the samples were precisely cut using a water jet. The fracture surfaces of the samples were analyzed using an Olympus model SZ61 stereoscopy equipped with a 5-megapixel image acquisition camera and Infinity Analyse® software.

Table 1. Parameters of the welding process.

Temperature °C (°F)	Pressing Load kgf
351 (655)	11.5
371 (700)	11.5
398.8 (750)	11.5
398.8 (750)	0.0

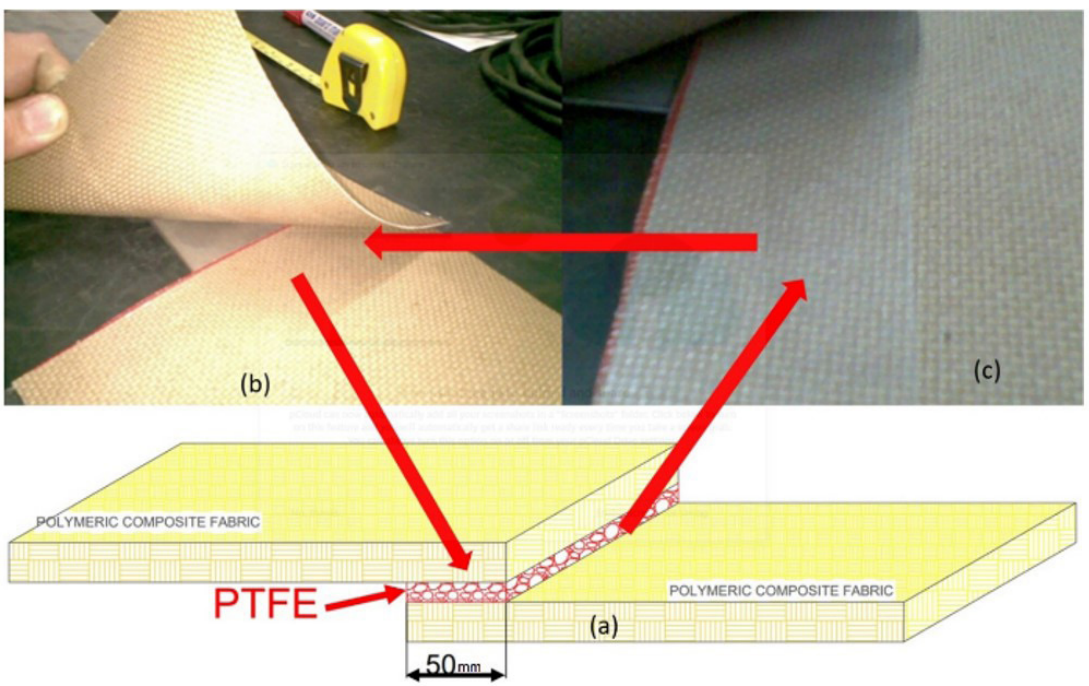

Figure 1. Polymeric composite blanket (a) illustrative scheme of the welded joint overlapping type, (b) overlapping of the polymer composite blankets and (c) positioning of the PTFE film between the blankets.

The chemical structural properties of the studied materials were determined using Fourier transform infrared spectroscopy (FTIR) on the PTFE film and PCB, both with and without the welding process. This analysis was conducted using a Spectrum 65 (Perkin Elmer) equipment in an ATR model. The absorption spectra were analyzed within the range of 4000 cm^{-1} to 600 cm^{-1} with a resolution of 4 cm-1 and 32 scans.

Thermogravimetric analysis (TGA) was performed to characterize the PCB, PCB welded, and PTFE film. This analysis was carried out using the TA Instruments model Discovery TGA 55 equipment. The samples, weighing 10 mg, were heated at a rate of 10 °C/min, starting from -25 °C and reaching 700 °C in an atmosphere of 100% nitrogen.

Furthermore, differential scanning calorimetry (DSC) was employed to analyze the thermal properties of the material. The TA Instruments Discovery DSC 25 equipment was utilized for this purpose. Samples weighing approximately 7 mg, enclosed in hermetically sealed aluminum holders, were subjected to the DSC analysis. The samples were cooled to -50 °C and then heated to 700 °C at a rate of 10 °C/min in a nitrogen atmosphere.

3. Results and Discussions

Figure 2 illustrates the surface appearance of the weld region on the PCB, showcasing variations in welding time (2, 4, 6, and 10 minutes) at a constant temperature of 398.8 °C (750 °F) and a load of 11.5 kgf. It can be observed that the material in contact with the hot tool and the PCB exhibits a darker appearance. Prolonged exposure to welding time intensifies the modification of the surface, indicating possible material degradation.

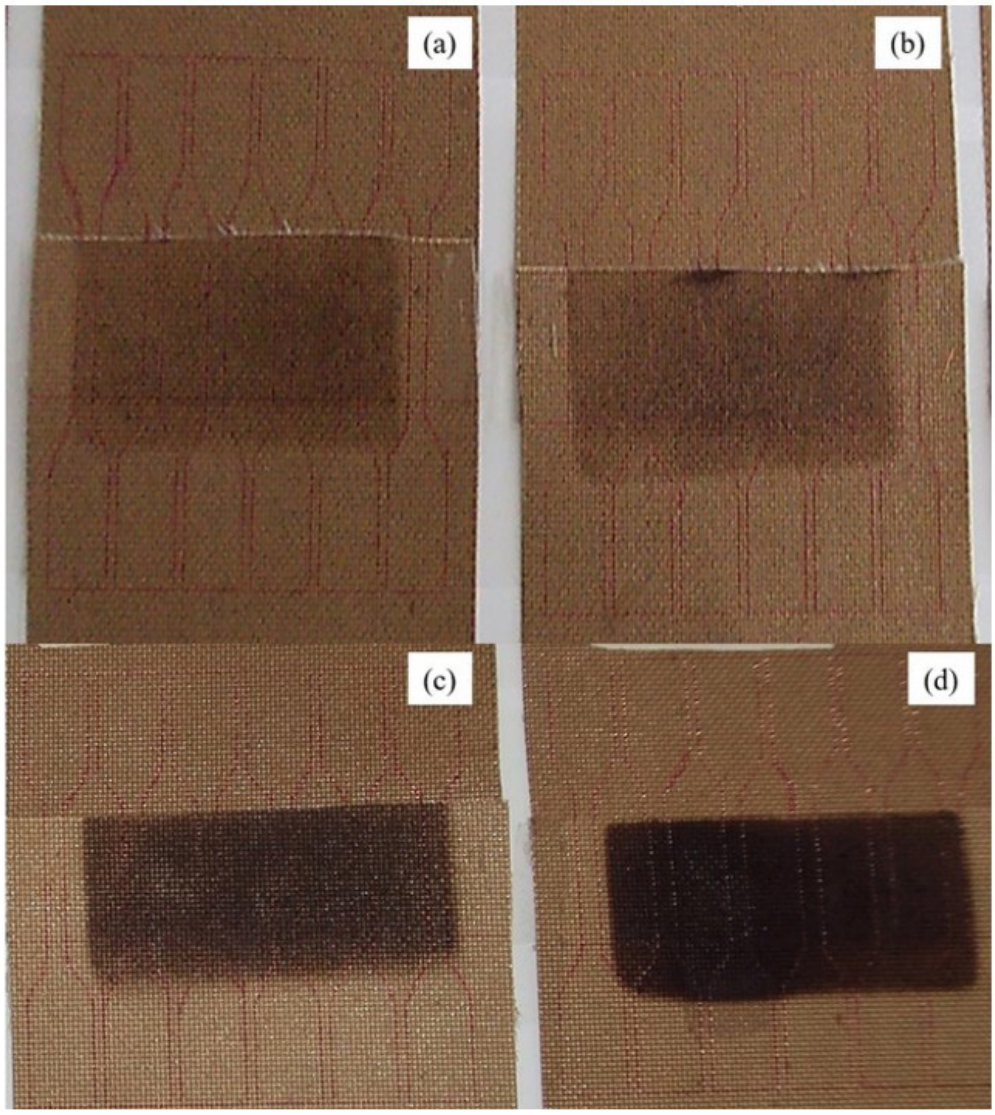

Figure 2. Surface aspect of the welded region of the polymeric composite blankets at 398.8 °C (750 °F) with a load of 11.5 kgf and a welding time of (a) 2 min, (b) 4 min, (c) 6 min, and (d) 10 min.

The qualitative degradation of PTFE, characterized by darkening and stiffening, becomes more pronounced with increased soldering time, particularly at 6 and 10 minutes. In contrast, welds created with processing times of 2 and 4 minutes maintain a preserved, non-brittle appearance with slight darkening, without producing soot-like particulate material post-welding. This suggests that shorter processing times contribute to the material's dissipative capacity and thermal resistivity, preventing significant degradation.

It is important to note that in applications involving non-metallic expansion joints exposed to abrasive chemical vapors and mechanical stress, PTFE degradation can lead to structural issues such as fiber exposure and accelerated damage. This is particularly concerning when it results in reduced mobility of the blanket due to composite stiffening, as observed in welds tested between 6 and 10 minutes.

Furthermore, temperature also influences the qualitative results in a similar manner to time. Increasing the weld temperature leads to darkening and stiffening of the material, intensifying the surface carbonization. Figure 3a presents the PTFE film over the fabric, showcasing the non-degraded qualitative visual aspect of the PCB (detailed in Figure 3b). The lighter parts seen in Figure 3a and 3b are a reflection of the light, so these figures show the PTFE film whole and not degraded. However, when the weld is performed at 398.8 °C (750 °F) for 6 and 10 minutes, Figure 3c illustrates the burn marks on the PTFE film, resulting in cracks on the surface coating (Figure 3d).

Non-metallic expansion joints display visible signs of damage that serve as indicators of potential structural failures. These signs include external cracking, bubbles, strains, delamination, exposure of reinforcing metal or fabric, separation of fabric layers, polymer deterioration, and leakage[16,17]. These failure modes can be attributed to various causes, such as excessive extension of the joint assembly[18], chemical attack, excessive pressure or vacuum, high temperatures, insufficient load on the joint union, and degradation of the polymeric material due to external agents[16].

It is important to highlight that PTFE, with a manufacturer-specified melting temperature of 326.8 °C (620.2 °F) as per Chemfab Corporation®, has a lower melting temperature compared to the temperature applied during the welding process. This ensures that the PTFE film melts and spreads over the fabric overlap in the weld. However, it is worth noting that the PTFE film may also undergo degradation as the thermal insulation properties of the polymer are surpassed by thermal conduction, primarily influenced by the duration of material exposure to the welding hot plates.

The results of the tensile test are presented in Figure 4. The efficiencies of the tested materials were determined by comparing the tensile strength of the welded specimens to that of the unwelded material. It can be observed that the highest efficiencies were achieved for welds performed at a temperature of 371 °C (700 °F) with a load of 11.5 kgf and times of 2 minutes and 4 minutes, resulting in efficiencies of 79.2% and 88.9%, respectively. The lowest tensile strength limit was observed in the welded material at 398 °C (750 °F) without load application, highlighting the necessity of load for ensuring good adhesion of the joint union.

Upon analyzing a processing time of 4 hours, the highest efficiency was observed at an intermediate temperature of 371 °C (700 °F). At a welding temperature of 398 °C (750 °F), the PTFE film melted and increased in fluidity, resulting in its flow over the welded region assisted by the applied load. However, degradation of the PTFE film also occurred, supporting the findings of Pugmire et al.[19].

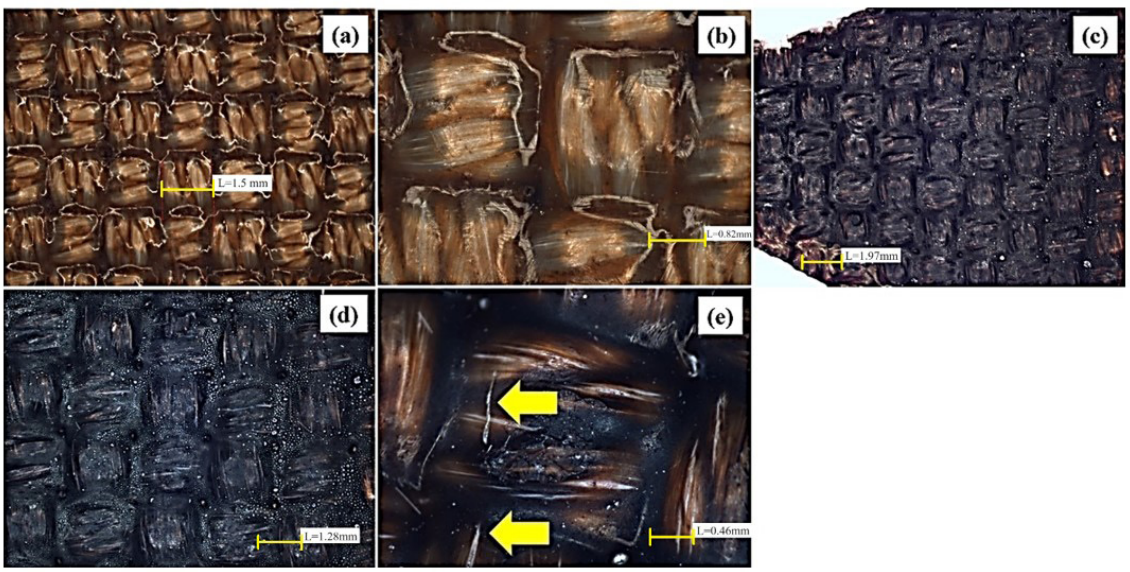

Figure 3. Surface of the polymeric composite blankets (a) front view of the fabric weaves without welding, (b) detail of the PTFE film on the fibers of the fabric without welding, (c) PTFE film in the welded region at 398.8 ºC (750 °F) for 6 min and application of a load of 11.5 kgf, (d) PTFE film in the welded region at 398.8 °C (750 °F) for 10 min and application of a load of 11.5 kgf, (e) surface cracks in the PTFE film for the welded region at 398.8 °C (750 °F) for 10 minutes and a load application of 11.5 kgf.

In contrast, the welding temperature of 371 °C (700 °F) yielded the highest tensile strength limit. This can be attributed to the effective melting of the PTFE film, which acts on the joint without causing burning of the composite in the welded region, unlike what happened at the welding temperature of 398.8 °C (750 °F).

The welding time is another crucial parameter that influences the tensile strength of the welded material as it affects the heat dissipation capacity necessary to melt the PTFE film applied to the fabric blankets. At a welding temperature of 351 °C (665 °F), which exceeds the polymer melting temperature, the PTFE film did not fully melt throughout the samples, indicating the need for a longer welding process time.

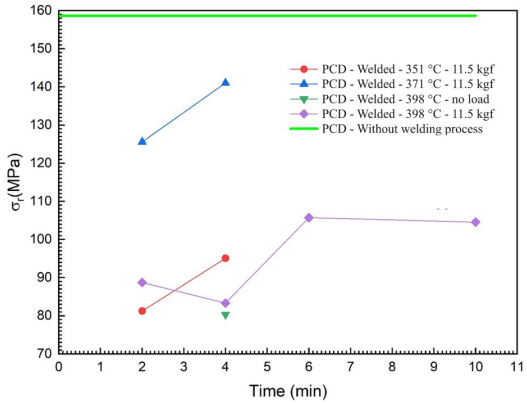

Figure 4. Tensile strength limit of the welded and unwelded materials at function of the processing time and temperature.

While the material welded at 398.8 °C (750 °F) exhibited a higher tensile strength limit for 6 min and 10 mi durations compared to 2 h and 4 h durations, the longer processing times led to thermal degradation of the material, as depicted in Figure 3e. The appearance of cracks in the welded film signifies the rupture of the polymeric chains, compromising the efficiency of the anchorage between the polymeric matrix and the non-polymeric filler in the PCB. This can negatively impact the material's performance in service. As the fabric is flexible, the cracks expose the fabric fibers due to movements occurring in non-metallic expansion joints, which can result in leaks and reduce the joints' lifespan.

In the absence of the welding process, the PCB exhibited a fracture that initiated in the PTFE and progressed to the fibers, as illustrated in Figure 5a. This offers a basis for comparison between a composite without heat influence and a degraded material caused by the welding process. In a non-degraded material, the interface between the polymer chains and the fibers prevails to the point of breaking one of the composite components, without pulling out the material fibers, which unravel during the application of tensile load.

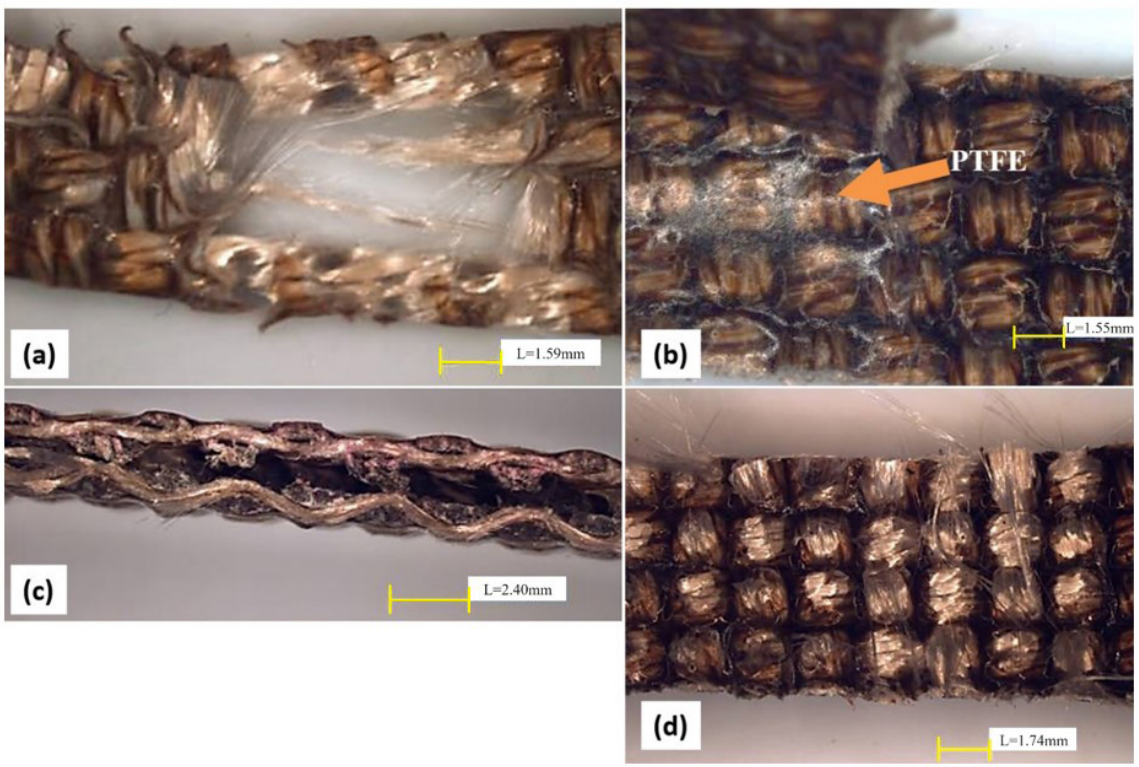

Figure 5. Fracture surface of the samples submitted to tensile test for (a) polymeric composite blankets without welding, (b) top view of the specimen welded at 398.8 °C (750 °F) for 4 minutes with no load applied, (c) side view of the specimen welded at 371 °C (700 °F) for 4 minutes with a load of 11.5 kgf and (d) observation of the exposed fibers of the specimen welded at 398.8 °C (750 °F) for 2 minutes with a load of 11.5 kgf.

However, when mechanically pulling a degraded material, a compromised interface leads to easy pullout of the polymer matrix fibers, as the chemical properties of the polymer are partially impaired[20].

Figure 5b illustrates the fracture region after the tensile test for the specimen welded at 398.8 °C (750 °F) for 4 minutes without load application. It is evident that this specimen exhibited fusion of the PTFE film, and the tension-induced fracture occurred due to the separation of the welded joint caused by the inadequate adhesion of the PTFE film with the fabric, as exemplified in Figure 5c. Importantly, the fabric fibers were not pulled out, highlighting the significance of the applied load during the welding process. The surface of the weld displays peeling of the PTFE film, exposing the fibers, as shown in Figure 5d, indicating an adhesion issue at the interface between the PTFE film and the fabric.

To ensure proper processing, the hot plate used in the welding process must maintain an ideal temperature. Deviating from the ideal temperature can lead to adhesion problems between fabrics or degradation of the interface material in the welded joint due to excessive heat[5]. Another parameter to consider is the pressing load applied to the welded joint, as it determines the crystallization rate in semicrystalline polymers, which can influence the mechanical and chemical properties of the welded joint[5,6,21].

The changes in the mechanical properties of the material can also be explained through physicochemical analysis using the spectra obtained by FTIR, which captures the molecular bonds present in the study material. This analysis allows for the observation of chemical changes that may occur due to thermal degradation. Figure 6 presents the infrared absorption spectra of the molecular bonds in the PTFE without processing, PCB without processing, and the effectively degraded PCB.

The spectrum obtained for the PTFE and PCB reveals several absorption bands. Two intense bands are present at 1198 cm^{-1} and 1146 cm^{-1}, attributed to the asymmetric and symmetrical stretching of the CF bonds in the CF_2 group[22]. Additionally, a less prominent peak can be observed at 639 cm^{-1}, indicating the angular deformation of the C-F bonds in the CF_2 group[23]. Finally, at 2924 cm^{-1} and 2853 cm^{-1}, there are absorption bands corresponding to the asymmetric and symmetrical stretching of the CH bonds in the -CH_2- group, respectively[24]. Although PTFE (C_2F_4) has no C-H bonds, these bonds were observed. However, it could be fiberglass residue in the samples.

Both the non-degraded and degraded PCB exhibit the same absorption bands observed in the PTFE sample. This similarity is due to the use of a PTFE and fluoroelastomer coating on the fiberglass fabric in the welding blanket[2]. However, in the FTIR spectrum of the degraded polymeric composite blankets, an enlarged peak at 900 cm^{-1} is observed, indicating changes in the polymeric chains caused by the temperature and time employed in the welding process.

The results of the thermogravimetric analysis are presented in Table 2. The thermal degradation of the PTFE film occurs in a single stage. The degradation process initiates at 491 °C and concludes at 549 °C, with the maximum degradation peak occurring at 518 °C. After the test, a small residue of approximately 0.3% of the initial mass is observed. These findings align with previously reported literature results[25,26].

In the thermogravimetric analysis of the non-degraded PCB, it was observed that thermal degradation commenced at 515 °C and concluded at 569 °C, with the maximum degradation peak occurring at 554 °C. At the end of the degradation process, the material exhibited approximately 60% residue, which could be attributed to the inorganic fraction present in the fabric along with a partially degraded polymeric fraction that may not have undergone complete degradation during the process.

For the degraded PCB, the thermal degradation process began at 509 °C and concluded at 568 °C, with the maximum degradation peak observed at 551 °C. At the end of the process, the material displayed approximately 77% residue, which can be associated with the inorganic component.

Comparing the results of the physicochemical analysis between the PTFE film and the non-degraded PCB, it is evident that the composite exhibits greater thermal stability than the PTFE film. This enhanced stability may be attributed to the favorable compatibility between the PTFE film and the composite, as the PTFE and glass fiber reinforcement synergistically contribute to a thermally more stable system.

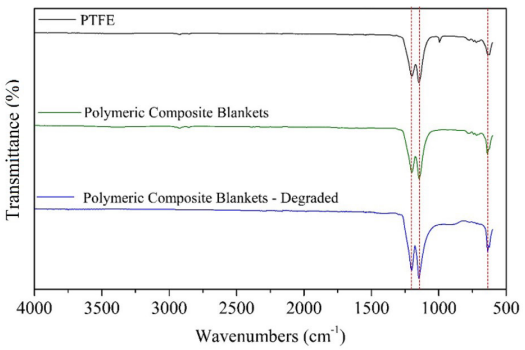

Figure 6. Molecular Bond Infrared Absorption Spectra FTIR analysis reveals molecular structures with distinct peaks at 1198 cm^{-1}, 1146 cm^{-1}, 990 cm^{-1}, and 627 cm^{-1}. Notably, the peak at 990 cm^{-1} demonstrates a significant loss in the case of degraded polymeric composite blankets.

Table 2. Temperature of start (T_{onset}), end (T_{endset}), and maximum (T_{max}) of the material degradation test.

	T_{onset}	T_{endset}	T_{max}	Residue
PTFE film	491 °C	549 °C	518 °C	0.3%
Not degraded polymeric composite blankets	515 °C	569 °C	554 °C	59.5%
Degraded polymeric composite blankets	509 °C	568 °C	551 °C	77.0%

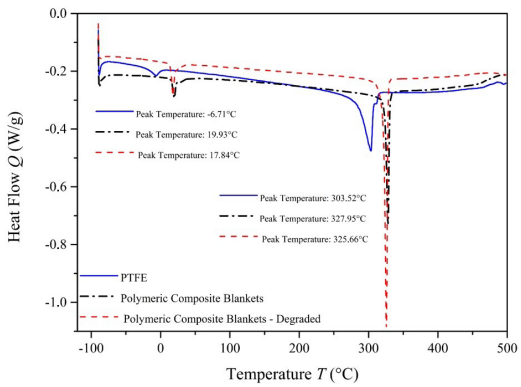

Figure 7. Differential calorimetric analysis for the PTFE film, not degraded polymeric composite blankets and the degraded polymeric composite blankets.

When comparing the results between the non-degraded PCB and the degraded PCB, it is observed that the non-degraded composite experienced greater mass loss. The degraded PCB retained traces of the polymeric phase, indicating that the previous welding process caused partial degradation of the PTFE phase present in the material, primarily affecting the surface region of the blanket while leaving the internal areas less affected by the degradation process.

Figure 7 illustrates the results of the differential scanning calorimetry (DSC) test, revealing the melting temperatures (peak) of different samples. The PTFE film exhibited a melting temperature of 303.5 °C, the non-degraded PCB had a melting temperature of 327.95 °C, and the degraded PCB had a melting temperature of 325.66 °C. It can be observed that the non-degraded PCB demonstrates an interaction between the matrix and fiber systems, resulting in a slight increase in the melting temperature of the polymeric phase within the fabric. The low-temperature phase transitions occurring around -6 to 19 °C may be associated with conformational changes in the solid phase of the material, considering its high degree of crystallinity[27].

4. Conclusions

Welding plays a crucial role in the production of non-metallic expansion joints using polymeric composite fabrics for structural sealing. The fabrication of polymeric composite blankets involves welding the fabrics together using PTFE (polytetrafluoroethylene) as the bonding element. Therefore, it is essential to study and determine appropriate welding parameters to ensure optimal structural efficiency.

Although the tensile strength of the welded composite is lower compared to the material without the welding process, employing suitable welding parameters allows for the production of polymeric composite blankets with desirable properties while utilizing lower temperatures than the conventional practice of 398.8 °C (750 °F). By welding the polymeric composite blankets at 371 °C (700 °F), an efficiency of 82% was achieved compared to the non-welded material. Additionally, increasing the welding process time from 2 to 4 minutes improved the tensile strength limit of the produced blankets. However, prolonging the welding time to 6 and 10 minutes at 398.8 °C (750 °F) resulted in severe material degradation, as indicated by the presence of cracks that could facilitate the penetration of corrosive fluids. Such degradation processes can negatively impact the lifespan of the structure. Welding temperatures lower than 371 °C (700 °F), such as 351 °C (665 °F), did not yield satisfactory adhesion of the welded parts, leading to a lower tensile strength limit. The lowest tensile strength limit was observed in the welded system without the application of load pressure, emphasizing the significance of this parameter for achieving robust adhesion of the welded material.

Thermal and chemical analyses conducted on the polymeric composite blankets before and after the welding process demonstrated that appropriate time, temperature, and load application during welding resulted in superficial thermal degradation of the studied material. However, the structural integrity of the polymeric phase was maintained even after exposure to temperatures above the melting point of the polymer.

In summary, when assessing the influence of welding parameters for producing non-metallic expansion joints using polymeric composite blankets and PTFE as the bonding element, it is evident that temperature, time, and load application during the welding process significantly impact the behavior of the system.

5. Author's Contribution

- **Conceptualization** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino; Eduardo de Campos Leite; Rafael Roberto Pavani; Lucas Camargo Soares Carvalho da Silva.
- **Data curation** – NA.
- **Formal analysis** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino; Eduardo de Campos Leite; Henrique Boschetti Pereira; Rafael Roberto Pavani; Lucas Camargo Soares Carvalho da Silva.
- **Funding acquisition** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino.
- **Investigation** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino; Eduardo de Campos Leite; Rafael Roberto Pavani; Lucas Camargo Soares Carvalho da Silva.
- **Methodology** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino; Eduardo de Campos Leite; Rafael Roberto Pavani; Lucas Camargo Soares Carvalho da Silva.
- **Project administration** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino.
- **Resources** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino.
- **Software** – NA.
- **Supervision** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino.

- **Validation** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino; Eduardo de Campos Leite; Rafael Roberto Pavani; Lucas Camargo Soares Carvalho da Silva.
- **Visualization** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino; Eduardo de Campos Leite; Henrique Boschetti Pereira; Rafael Roberto Pavani; Lucas Camargo Soares Carvalho da Silva.
- **Writing – original draft** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino; Eduardo de Campos Leite; Henrique Boschetti Pereira; Rafael Roberto Pavani; Lucas Camargo Soares Carvalho da Silva.
- **Writing – review & editing** – Marcos Dorigão Manfrinato; Luciana Sgarbi Rossino; Eduardo de Campos Leite; Henrique Boschetti Pereira; Rafael Roberto Pavani; Lucas Camargo Soares Carvalho da Silva.

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