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Assessment of the interlaminar strength of resistance-welded PEI/carbon fibre composite

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ABSTRACT

This study has as its main objective to evaluate the effectiveness of the welding process by electrical resistance in a composite poly (ether-imide) matrix reinforced with continuous fibres of carbon, from the study of the thermal and mechanical properties of the welded joint. To evaluate the thermal properties of the welded material, samples were subjected to analysis by thermogravimetry and by thermomechanical analysis. With the intention to study the resulting weld interface, studies were made from the shear tests ILSS and Iosipescu, as well as end-notched flexure (ENF). The results of the thermal analysis in laminated non-welded PEI/carbon fibre show that the beginning of degradation for these composites is 460 °C, and it is also evident that the glass transition temperature of welded samples is about 15% higher than the results from samples not welded. The mechanical tests show that there was an increase of 32 and 20%, respectively, in interlaminar shear results for the ILSS- and Iosipescu-welded samples when they are compared to samples not welded. The ENF test results show satisfactory values of interlaminar fracture toughness in the composite welded from the values found in the literature.

KEYWORDS

Composites; electrical resistance welding; mechanical test; thermal analyses

1. Introduction

The polymer matrices currently available for advanced composites have gradually evolved as an alternative for the aeronautical industry, and in recent years various special, high-performance thermoplastic matrices have been investigated for use in the manufacture of structural composites [1].

In recent years, the number of metal components and structures replaced with polymer composites, not only in military aviation, but also in designs of civil aircraft has increased considerably. An example of this can be seen in the Airbus A380 aircraft, where 22% of its total weight consists of composites. Therefore application of composites is already a reality, especially in the aerospace industry.

On the other hand, one of the main problems in using thermoplastic composites in structural applications is efficient joining of them for integrating different components, owing to the occurrence of defects resulting from said joining, such as: stress concentrations caused by holes in the structure when riveted, the delay for the curing of adhesive systems consisting of thermosetting resins, deconsolidation for joining processes by co-consolidation [1,2].

Assessment of the feasibility of using the resistance welding process for joining thermoplastic laminates for aeronautical applications is a new question, especially in Brazil. Among the various welding techniques used at present for composites, the resistance welding technique stands out, mainly for the economy of material that it provides, as it does not require welding consumables or auxiliary means for joining, it dispenses with the use of rivets, screws, nuts, and additionally does not require machining operations, and can also be used for joining components with complex architecture [2,3].

Figure 1 is an illustration of a standard system for carrying out resistance welding of polymer composites. It can be seen that it is necessary to use a resistive element, connecting clamps for the passage of electric current, electric power supply, clamping fixtures, leads, voltmeter and ammeter. The temperatures that are developed in this process are measured by means of thermocouples [4].

Basically, this process consists of using resistive elements connected between the faying surfaces of the laminates to provide the heat necessary for joining by the Joule effect. An electric current is applied to the resistive element, causing its temperature to increase. The temperature of the resistive element increases considerably at the interface, melting the composite and consequently promoting welding of the laminate under the application of pressure [1,3].

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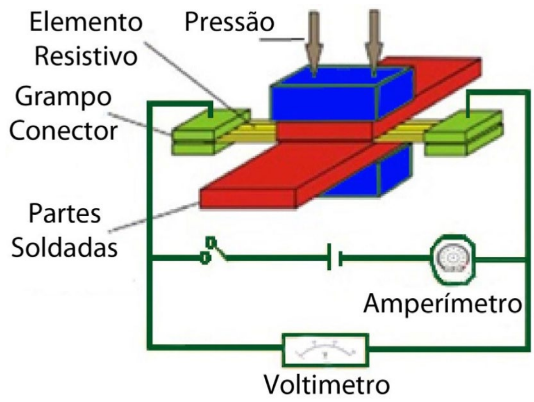

Figure 1. Illustration of a resistance welding system for polymer composites [2]. Elemento Resistivo = Resistive element; Pressão = Pressure; Grampo Conector = Connecting clamp; Partes Soldadas = Parts being welded; Amperímetro = Ammeter; Voltimetro = Voltmeter.

Welded joints are particularly interesting for joining advanced materials of high mechanical strength, as is the case for the PEI (poly(ether-imide)) polymer matrix composites used in this study [5]. PEI is considered to be an excellent candidate for use as the matrix in advanced composites, and has the following main advantages: good mechanical strength and rigidity at high temperatures; high heat resistance; good electrical properties and suitable chemical resistance [6,7].

However, the methods of welding inspection for composites for structural use have not kept up with the development of the technology itself. At present, the same methods that are used for testing conventional joining processes, such as the use of rivets, bolts and nuts, are used for assessing the strength and quality of the joints [8,9].

Some joining processes are available for joining structures of thermoplastic composites that require high levels of heating of the workpiece. Among these techniques, we should mention the process of co-consolidation. This method of joining is ideal for joining laminates, as no weight is added to the final structure of the laminate, no material is introduced in the fibre/matrix adhesion line, no surface preparation is required, and the bonding force is potentially equal to that of the original laminate. However, the entire process of joining by this method depends on the melting point of the laminate, and this generally means that complex and very expensive tools are required (different compared to welding processes) for maintaining the pressure throughout the material to prevent deconsolidation [10].

Because of the anisotropic properties of advanced polymer composites, it has become evident over the years that interlaminar fracture is potentially one of the main failure processes that limits the life of a given component, mainly owing to the absence of reinforcement orthogonal to the plane of the fibres. This becomes even more critical in welded composites [11,12].

Interlaminar fracture is usually called delamination, failure that is associated with the interface between the layers of a polymer composite. Accordingly, interlaminar fractures describe failure oriented between the layers, taking place in the plane of the laminate, fracturing mainly the matrix, with little or no fibre fracture [13,14].

The combined action of all these factors in the behaviour and durability of composites is quite a complex phenomenon, occurring at the molecular level. Investigation of this phenomenon and interpretation of the resultant behaviour are crucial tasks for determining the useful life and safety of structures made of composite material [15].

The aim of this work is to assess the efficiency of the resistance welding process, by determining the interlaminar strength in welded composites, consisting of a PEI matrix reinforced with carbon fibre. For this purpose, mechanical tests were carried out, involving interlaminar shearing by ILSS and Iosipescu, i.e. ENF tests (ENF: End-Notched test) for determining the G_{IIc} failure mode.

2. Materials and methods

2.1. Laminates

The laminates that underwent resistance welding were supplied by the Dutch company TenCate Advanced Composites. These laminates were manufactured with cloth in the 8 HS configuration, with nominal thickness of 2.0 mm. The PEI/carbon fibre laminate was manufactured with cloth in the 8 HS configuration with nominal thicknesses between 2 and 3.5 mm, and with $(0/90)_{5s}$ configuration, containing approximately 50 vol% of matrix.

2.2. Thermal properties

Thermogravimetric analysis (TGA) and thermomechanical analysis (TMA) were performed to determine the thermal properties of the welded laminates.

2.2.1. Thermogravimetric analysis (TGA)

Prior to welding, it was necessary to determine the safe temperature, i.e. the degradation temperature of the polymer matrix (PEI). For this purpose, thermogravimetric analysis (TGA) was carried out in a model TG-DTA 6200 analyser from SII Nanotechnology, using a dynamic method with heating from 35 to 1000 °C, with a heating rate of 10 °C/min and an atmosphere of synthetic air (flow of 100 ml/min).

2.2.2. Thermomechanical analysis (TMA)

TMA is a technique for studying the properties of materials as a function of the temperature variation. This process consists of measuring the dimensional variations of the specimen as a function of temperature, at the same time as the specimen is subjected to mechanical stress.

In the field of polymers, this technique is used essentially for determining the coefficient of thermal expansion and for measuring the glass transition temperature [16].

Thus, analysis involving TMA was carried out, to assess the glass transition temperature of the polymer matrix and analyse the effects of the behaviour of the coefficient of linear thermal expansion of the PEI/carbon fibre composite with respect to the welding process. To this end, analyses were carried out in TMA/SS 6100 equipment (TMA: Thermo Mechanical Analysis), made by SII Nanotechnology Inc. of Seiko. The analysis conditions used were: temperature range between 30 and 230 °C, with a heating rate of 3 °C/min and a nitrogen atmosphere (flow of 100 ml/min), according to standard ASTM E831. The specimens were cut in milling machines and ground to obtain reproducible dimensions of 8.0 mm × 8.0 mm × 2 mm (4 mm for the welded specimens) (length × width × thickness).

2.3. Welding

As the aim of this work is to develop a welding technique for laminates that are commercially available, it was not necessary to insert films of PEI in the assembled joint. Welding was carried out using a resistance welding machine for composites, manufactured by the company AUMEK in partnership with the Faculty of Engineering of Guaratinguetá (UNESP). Welding was carried out using metal mesh of stainless steel AISI 304 with 300 wires per inch, as the resistive element for the process. Figure 2 shows, representatively, the configuration of the metal mesh, with the positioning of the warp and weft of this material, which are indicated by arrows (1) and (2), respectively. The specimens were welded using the following parameters: Current: 50 A, Time: 80 s and Pressure: 0.7 MPa. These welding parameters established in the study were based on the literature [18,19], through the statistical model of factorial experimental design.

2.4. Mechanical properties

ILSS (Interlaminar Short Beam), Iosipescu and ENF (End-Notched Flexure) mechanical tests were performed to determine the interlaminar strength of the welded composites, against shearing stresses. Table 1 summarizes the mechanical tests with the dimensions of the PEI/carbon test specimens, welded and not welded.

2.4.1. ILSS (Interlaminar Short Beam) test

The ILSS (Interlaminar Short Beam) test was performed in this work in order to assess the interlaminar shear strength and compare this property with shearing in the welded region. The tests were carried out with a 10-kN load cell in a Shimadzu universal mechanical tester, model AG-X, according to standard ASTM D2344. For this purpose, 10 (ten) test specimens were tested for each case investigated.

2.4.2. Iosipescu

The Iosipescu shearing method was carried out on a rectangular test specimen with V notches. The dimensions of the test specimens and the test conditions were based on standard ASTM D5379. For this test, the notch has a standardized radius of 1.3 mm, with the aim of preventing interference in the results due to the presence of sharp edges.

2.4.3. ENF (End-Notched Flexure)

The ENF (End-Notched Flexure) test is carried out for the purpose of obtaining failure mode II of interlaminar

Table 1. Summary of the mechanical tests carried out in the study with the respective dimensions.

Tests	Dimensions (length × width × thickness)	
Materials	PEI/carbon, not welded	PEI/carbon, welded
ILSS	24 × 6.35 × 2 mm	24 × 6.35 × 4 mm
Iosipescu	76 × 20 × 2 mm	76 × 20 × 4 mm
ENF	Not done	125 × 25 × 4 mm

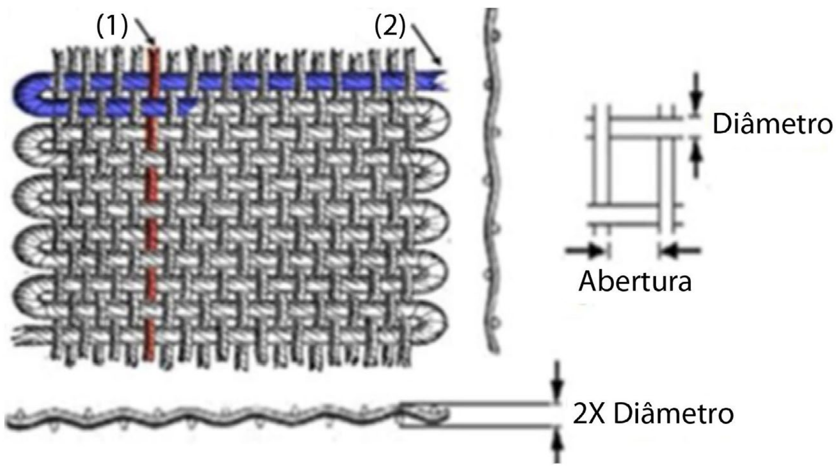

Figure 2. Schematic representation of the AI 304 mesh with 300 wires per inch used in the study [17]. Diâmetro = Diameter; Abertura = Aperture.

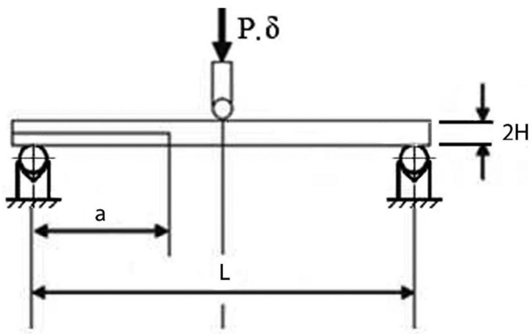

Figure 3. ENF test method for measuring the interlaminar fracture toughness of composites, where: a = crack length (m), P = force (N), δ = displacement (m), h = thickness of the test specimen, L = distance between the supports (m) [14].

fracture. Mode II corresponds to in-plane shear loading and causes 'slip' between the failure surfaces in opposite directions. When structures made of composites are subjected to mode II loading, the interlaminar layer is the first to fail. Interlaminar failures occur in planes parallel to those of the layers and their failure mechanisms and appearance tend to be dominated by fracture of the matrix and separation of the fibre from the matrix, causing one of the commonest failures in composites: delamination.

This failure may occur on account of the shearing stresses but also as a result of transverse stresses that arise in the interlaminar region, when the material is subjected to bending. Delamination often leads to loss of rigidity and strength, which may lead to problems of safety and reliability of a given structure.

The ENF test was performed on the basis of standard ASTM D7905, with the following dimensions of the test specimens: a = 45 mm, L = 120 mm, 2 h = 4 mm and width = 25 mm. Figure 3 illustrates the geometry of the test specimen for the ENF test. Visual monitoring was employed, with marks made on all the test specimens, and the interlaminar fracture toughness in mode II was calculated after obtaining the graph of load × displacement.

The ENF test was carried out in a Shimadzu universal tester, model AG-X, at a speed of 1 mm/min, using a 5-kN load cell. The rate of energy release in mode II fracture (G_{IIc}) was calculated from Equation (1).

$$G_{IIc} = \frac{9a^2 P\delta}{2B\left(2L^3 + 3a^3\right)} \tag{1}$$

The ENF test was performed on five-welded PEI/carbon fibre specimens, for determining the interlaminar fracture toughness in failure mode II, G_{IIc}. The ENF test carried out in this study is illustrated in Figure 4, showing photographs of details of the process of crack growth during the test until rupture of the welded material.

Figure 4(a) was taken from a photograph at the beginning of crack growth, when the crack had travelled 15 mm. Figure 4(b) illustrates the continuous growth of the crack, said growth being maintained in

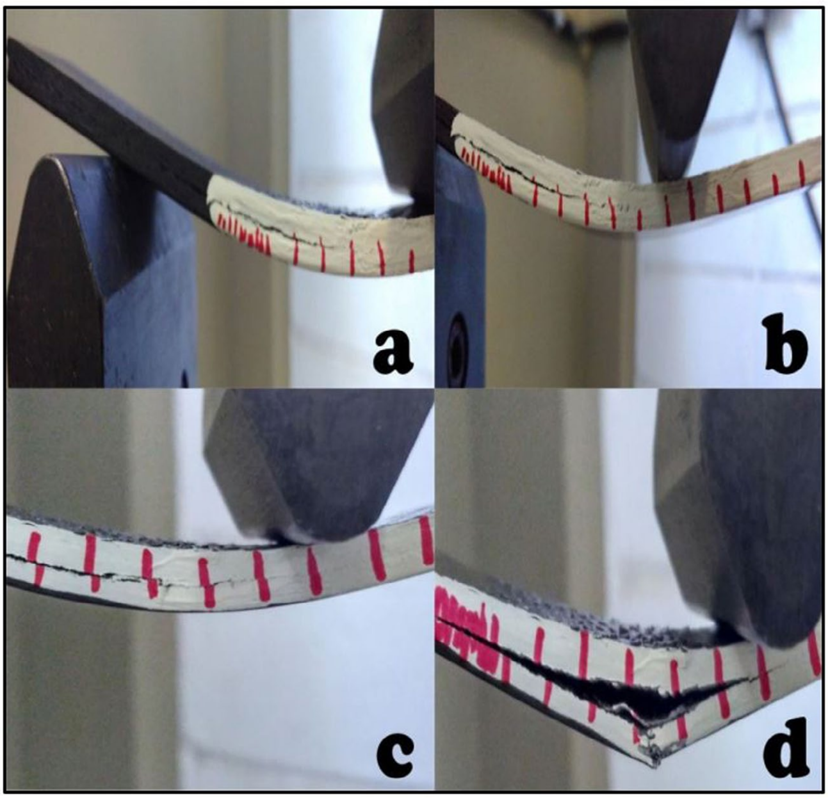

Figure 4. ENF test performed on PEI/carbon composite: (a) Initial crack growth; (b) Continuous growth of the crack causing rupture; (c) Close detail of the crack before rupture; (d) Rupture of the material.

the centre of the welded specimen (in the region where the laminates are joined together), with the crack travelling 6 mm. Figure 4(c) shows the crack prior to rupture of the material; the crack can be observed to have travelled about 25 mm. Finally, Figure 4(d) shows the moment when the material is subjected to the full load, and consequently rupture, the final length of the crack observed at the moment of failure reaching 35 mm. This test is essentially a three-point bending test, in which a specimen is positioned on two supports and a force is applied in the centre of the specimen [14].

2.5. Light microscopy

For characterization of the laminates, analyses were carried out by light microscopy using a Zeiss AXIO Imager Z2 m stereo microscope, by the technique of extended-focus light-field reconstruction, using an LD EC Epiplan-Neofluar 50x/0.55HD DIC M27 objective, available from the Imaging Laboratory of the FEG/UNESP.

3. Results and discussion

3.1. Assessment of the welding process

Determination of the window of the welding process, i.e. of the minimum and maximum temperatures that the polymer matrix must withstand, is an essential condition for the parts to form efficient joints with maximum bond strength. This temperature must be above that required for the matrix to 'soften' (glass transition temperature), but must not exceed values much above these, to avoid degradation of the material. According to the literature, for welding thermoplastic polymers, specifically those that are amorphous, which is the case with PEI, the temperature that must be maintained as a reference for the welding process is the glass transition temperature (*Tg*) (i.e. welding must take place at a temperature above the *Tg* of the material under investigation), taking care not to exceed the degradation temperature of the polymer in question [20].

To find the maximum temperature that may be reached during the welding process, and to ascertain the thermal degradation behaviour of the PEI matrix, the specimen was investigated by TGA. It can be seen from Figure 5, relating to the PEI/carbon fibre laminate, that thermal decomposition of the material begins at a temperature of 430 °C. As the analysis was carried out in synthetic air, thermal oxidation of the carbon fibre took place without leaving a final residue in the analysis.

Figure 6 presents the results of TMA for specimens of the PEI/carbon fibre laminate for the purpose of evaluating the glass transition temperature (*Tg*) and coefficient of linear thermal expansion of the laminate, welded and not welded. *Tg* was determined from the point of intersection between the curves relating to the vitreous zone and the zone where there is rubber-like behaviour. It can be seen from the results obtained that the PEI matrix has a *Tg* of 163 °C.

It can be seen in Figure 6 that the value of α (coefficient of linear expansion) found for the welded composite was 69.10^{-6}/°C, i.e. higher than that of the PEI/carbon fibre composite that was not welded (about 23%), but they are of the same order of magnitude. This shows that the metal mesh does not reduce the coefficient of

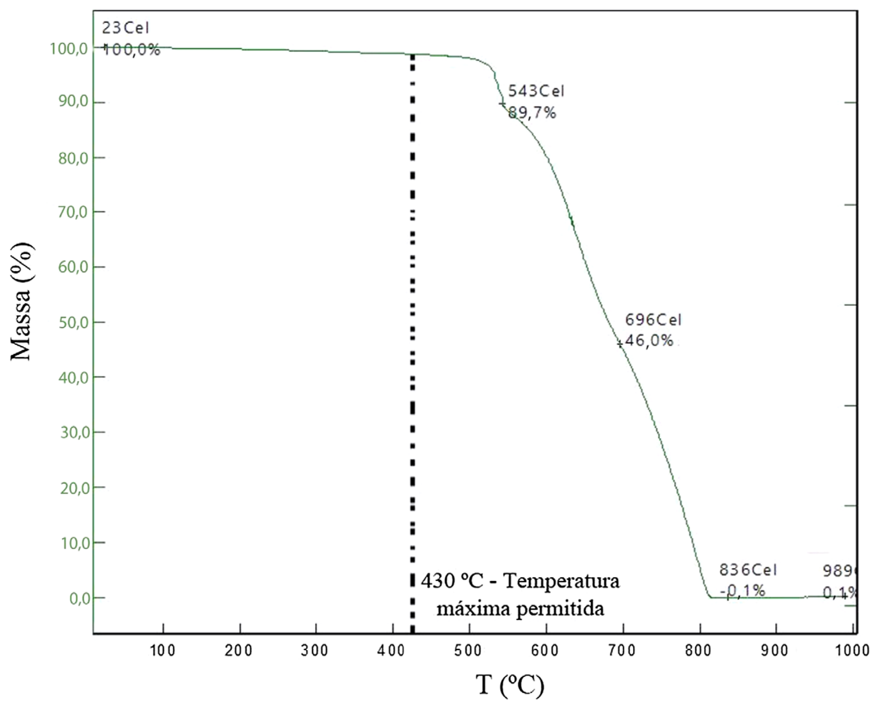

Figure 5. TGA graph obtained for the PEI/carbon fibre composite. Massa (%) = Weight (%); Temperatura máxima permitida = Maximum permitted temperature.

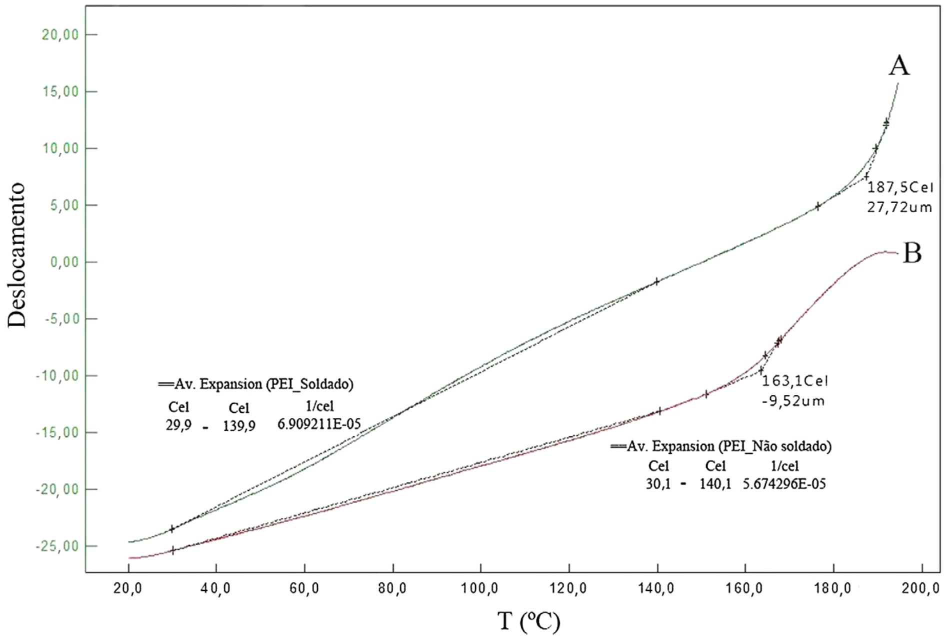

Figure 6. TMA graph obtained for the PEI/carbon fibre composite, welded (A) and not welded (B). Deslocamento = Displacement; (PEI_Soldado) = (PEI_Welded); (PEI_Não soldado) = (PEI_Not welded).

linear thermal expansion of the polymer composite as was expected, because of the presence of a metallic component (which has a lower value of the coefficient of linear thermal expansion) which, in its turn, has a lower value of α (stainless steel 11.7 × 10^{-6}/°C) [21,22].

Thus, it can be concluded from the results obtained that the window for welding this laminate is between 180 and 400 °C, taking into account a safety factor both with respect to the glass transition temperature and the degradation of this material. Thus, for determining the processing window for the materials studied in the present work, thermal analyses carried out by TMA and TGA were taken into account, and additionally an investigation on the welding machine, with observation in relation to degradation of the material.

The glass transition temperature obtained by TMA for the laminates with PEI polymer matrix without welding (163 °C) is lower than the values for the glass transition found in the literature for the PEI polymer (between 180 and 217 °C) [23]. According to the literature [20], for the welding of thermoplastic polymers, specifically those that are amorphous, as is the case with PEI, the temperature that is to be taken as the reference for the welding process is the glass transition temperature (*Tg*) (i.e. welding must take place at a temperature above the *Tg* of the material under investigation), taking care not to exceed the degradation temperature of the polymer in question. Starting from *Tg*, the polymer chains attain greater mobility, allowing mass transfer by diffusion across the interface.

The temperature is an important factor in the resistance welding process, as it has to reach a sufficient value for heating the parts. However, the temperature value must not greatly exceed the glass transition temperature of the polymer, to form joints without degradation of the material and with maximum bond strength [24].

Figure 7 presents the results from preliminary tests, showing the maximum temperature reached in the resistance welding process.

As can be seen in Figure 7, the maximum temperature reached in this case was 378 °C, while the initial degradation temperature observed for this laminate by the TGA technique was 430 °C. Thus, based on the result from the graph of preliminary measurement of the welding temperature, the laminate was welded without degradation, with the maximum temperature reached in the welding process remaining within the window of welding temperatures (163–430 °C) obtained by the thermal analyses.

After the welding process, the joint obtained was assessed by light microscopy (LM). Figure 8(a)–(d) show images of the transverse region of a welded PEI/carbon fibre test specimen, obtained by light microscopy.

The red arrows indicate the weld interface for PEI/carbon fibre, with the shiny points in the figures representing regions of the metal mesh used as the resistive element. It can be seen from these results that the welding process gave a homogeneous interface between the welded plates in relation to the region where there was no interference of local heating during the welding process. In addition, evidence of good interaction between the metal mesh and the PEI polymer matrix could be identified in the micrographs. Furthermore, it was possible to observe the appearance of pores in the material, indicated by the blue arrows in Figure 8, which may be assumed to have resulted from thermal degradation (evolution of gases) of the laminate or also through the presence of humidity in the air, wherein,

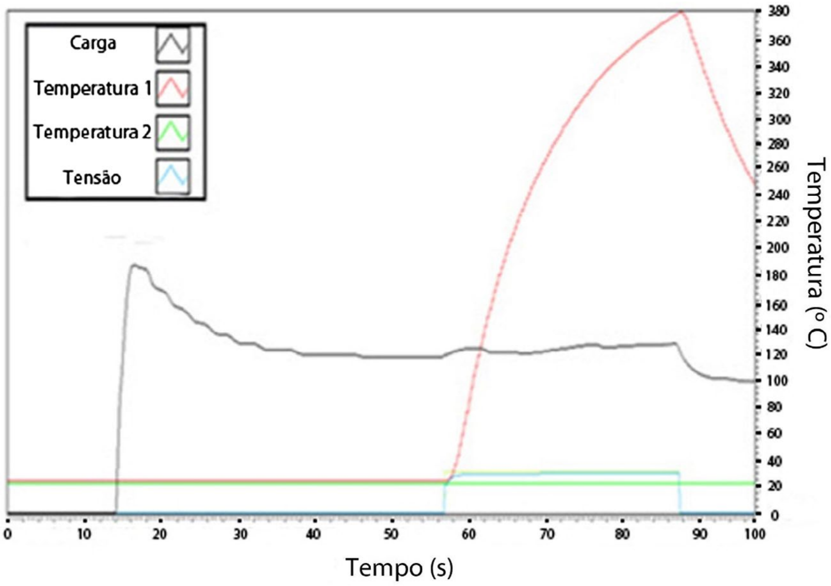

Figure 7. Results for the temperature reached in the resistance welding process for the PEI/carbon fibre composite, where temperature 1 is the temperature that is reached in the process and temperature 2 is the ambient temperature. Carga = Load; Temperatura = Temperature; Tensão = Voltage; Tempo (s) = Time (s).

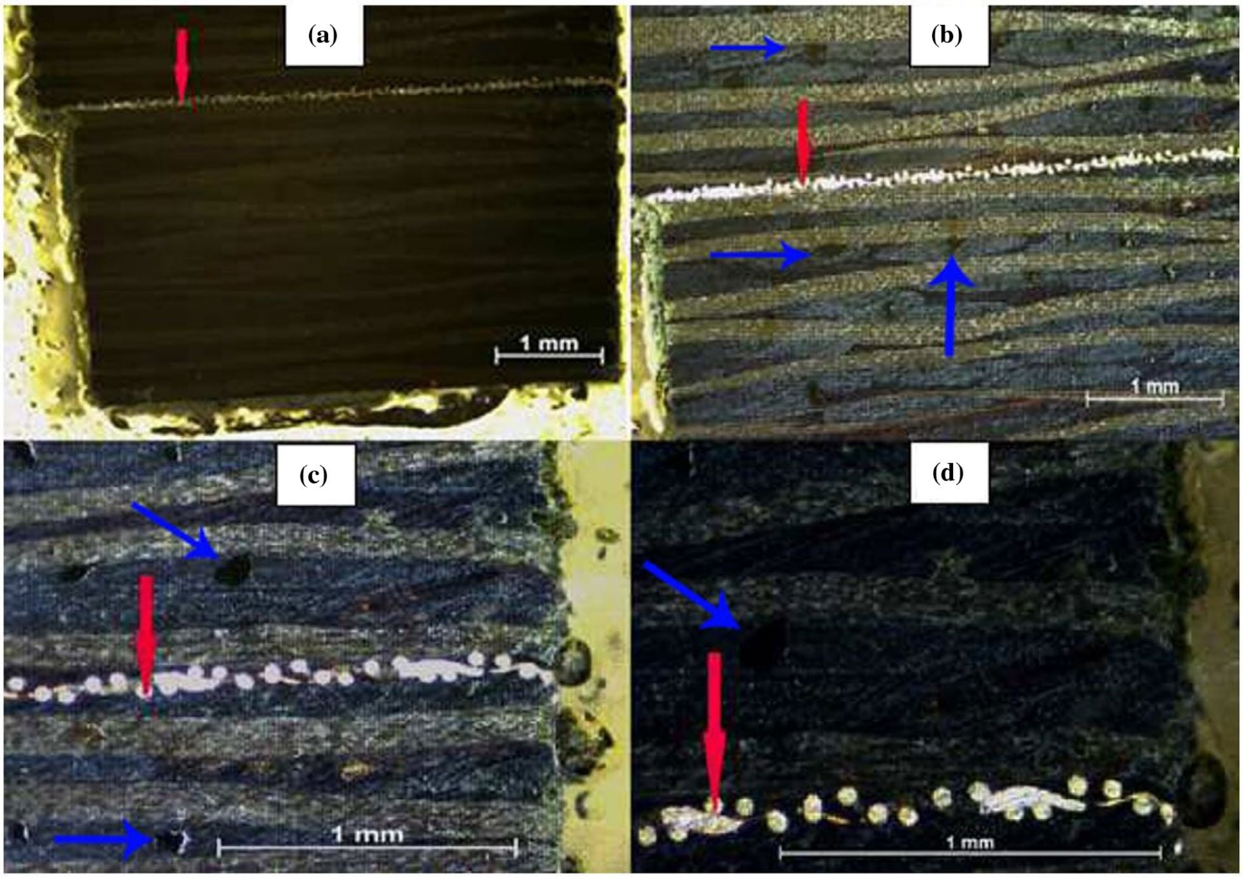

Figure 8. Microscopy of the transverse region of the welded PEI/carbon fibre specimen: (a) Magnification 6.5X; (b) Magnification 10X; (c) Magnification 20X; (d) Magnification 40X.

during solidification of the laminate, evaporation of the moisture dissolved in the resin of the PEI may have caused the porosity to appear [25].

3.2. Assessment of interlaminar shearing by ILSS and Iosipescu

The results obtained from mechanical analysis of the welded joint by ILSS and Iosipescu in comparison with the values of the material without welding in this study (PEI/carbon fibre laminate) are presented in Table 2.

The results obtained in the ILSS tests show that there was a significant increase in the interlaminar shear strength in the welded specimens, of up to 32%. This behaviour probably occurred because of the presence of the heating element (stainless steel), thus contributing to the improvement in this mechanical property of the laminate. However, the ILSS test did not provide a state of completely pure shear, but a state with combined stresses.

To confirm the effect of the heating element on the interlaminar shear strength, an analysis was performed by light microscopy with the aim of assessing the failure mode occurring in the ILSS tests for the materials under investigation. Figures 9 and 10 show the fracture of the welded and non-welded composites after mechanical testing, indicating the regions that were analysed by microscopy. It can be seen from the results given in Figures 9 and 10 that the PEI/carbon fibre laminate presents translaminar fracture when stressed with interlaminar shearing. However, when the metal mesh is present, fracture is interlaminar, altering the form of failure of this laminate. Accordingly, the presence of the metal mesh aids in the formation of cracks at the weld interface, which propagate throughout the test specimen. Therefore in the specimen with the weld, the crack is propagated to a region ahead of the weld, not being affected by where the resistive element is located (weld region), and consequently is not propagated to the upper part of the specimen, as shown by the circle in Figure 10(b). In addition, the laminate region, the region of crack propagation and the weld region are indicated by the arrows in Figure 10(b).

Table 2. Values of ILSS and Iosipescu shear strength of the PEI/carbon fibre laminate.

	ILSS		Iosipescu	
Composites	Shear strength (MPa)	Standard deviation	Shear strength (MPa)	Standard deviation
Welded	63.7	4.03	119.2	1.99
Not welded	48.1	2.03	100.4	0.4

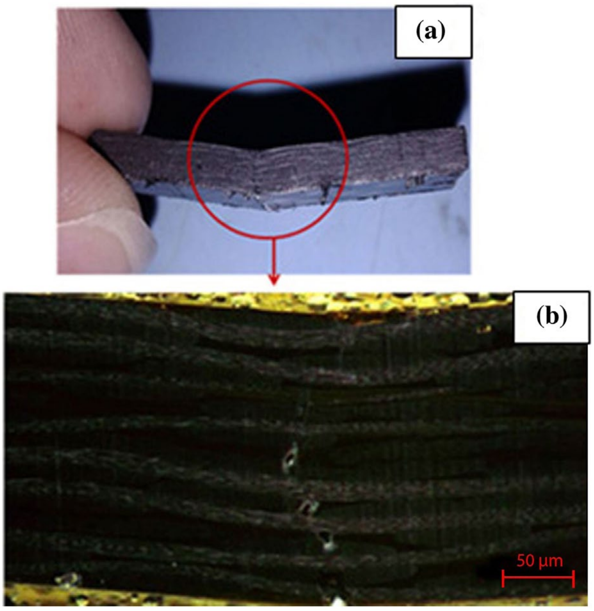

Figure 9. (a) PEI/carbon fibre composite without welding, after the ILSS test; (b) micrograph showing the start of fracture in the region fractured by the ILSS test of the PEI/carbon fibre laminate without welding.

Interlaminar fractures tend to be influenced by the fracture of the matrix and by fibre/matrix displacement. In general, the commonest conditions in which fibre/matrix displacement occurs are at the interface in mode I and mode II. Accordingly, interlaminar fractures describe failures oriented between the layers, occurring in the plane of the laminate, mainly fracturing the matrix, with little or no fibre fracture. Translaminar fractures are those that occur transversely to the plane of the laminate, causing significant rupture of the fibres. Normally there are components that display the three types of fracture simultaneously [26,27].

For the Iosipescu test, analysis of the interfacial failure mode was able to verify the quality of fibre/resin adhesion, which is an essential condition for explaining the interlaminar shear strength in this test method. This tendency for an increase in mechanical strength for the welded specimens was observed in the results obtained from the Iosipescu tests, since it had been demonstrated that welding altered the values of shearing stress, with an increase of approximately 20% in the shear strength in the Iosipescu test. This result is in agreement with those found from the ILSS shearing test and can be explained by the presence of the metal mesh, providing additional resistance to the shearing forces.

A fractographic analysis of the laminates that had undergone Iosipescu shearing was carried out in this work by light microscopy. Thus, the micrographs illustrated in Figures 11 and 12 show magnified images of the test specimens after they had been tested in the notch region shown in Figure 13.

It can be seen in Figures 11 and 12 that in both cases interlaminar and translaminar fractures occurred when stressed by Iosipescu shearing, showing that for this mechanical stressing, the presence of the metal mesh did not in principle cause marked interference in the fracture morphology. However, on deeper analysis, Figure 11 (non-welded laminate) shows a fracture

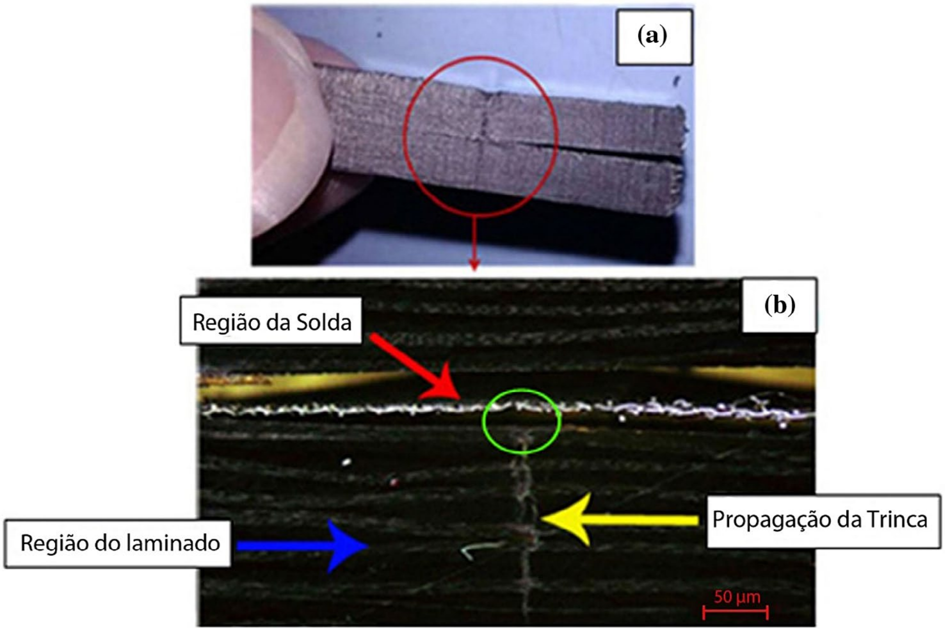

Figure 10. (a) Welded specimen of PEI/carbon fibre composite after the ILSS test; (b) Micrograph showing the start of fracture in the region fractured by the ILSS test of the welded PEI/carbon fibre laminate. Região da Solda = Weld region; Região do laminado = Laminate region; Propagação da Trinca = Crack propagation.

Figure 11. Light microscopy image of the non-welded laminate after the Iosipescu test, with magnification of × 8.

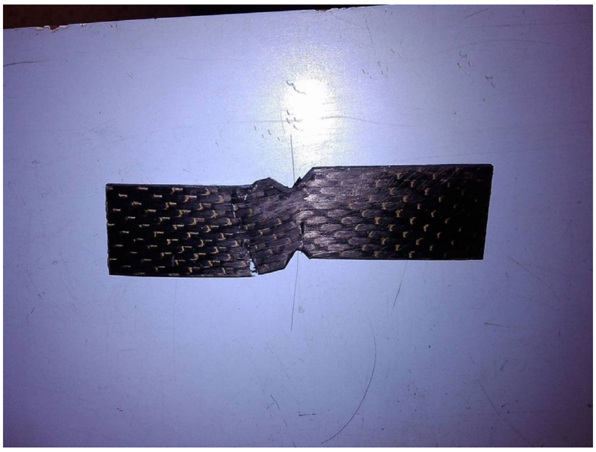

Figure 13. Specimen of the PEI/carbon fibre composite after testing.

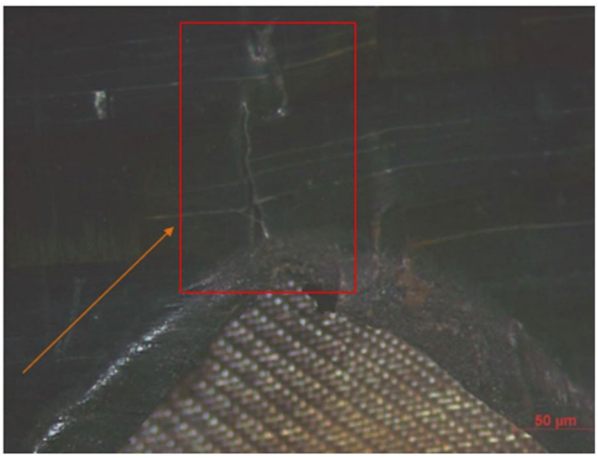

Figure 12. Light microscopy image of the welded laminate after the Iosipescu test, with magnification of × 8.

probably resulting from a process of microbuckling followed by translaminar fracture that is more intense than occurs in welded materials.

3.3. *Interlaminar fracture toughness G_{IIc}*

The resistance of composites to delamination may be well characterized by the resistance to interlaminar fracture (in-plane shearing), measured as the energy dissipated per unit area of crack growth [28]. One of the most important parameters in the application of fracture mechanics for composite structures is the rate of release of deformation energy (G). To determine the critical rate of release of deformation energy, it is necessary to conduct fracture experiments [29,30].

Table 3. Results obtained in the ENF test for the welded PEI/carbon fibre laminate.

Welded PEI/carbon	Interlaminar fracture toughness G_{IIc} (J/m^2)
1	1171
2	2089
3	1628
4	1610
5	1986
Mean value	1687
Standard deviation	333

Mode II of delamination has not been studied extensively for welded composites, which may be explained by some difficulties inherent in the experimental tests required for this purpose, however, the ENF (End-Notched Flexure) test is the most used for determining this mode of fracture [30,31]. Furthermore, in many real situations, delaminations are propagated primarily in mode II, as is the case with plates of composites under low-velocity impact [28,32]. Table 3 gives the values obtained from the ENF test on welded PEI/carbon laminate, showing the values of the force required to initiate crack propagation, consequently obtaining the value of the critical energy required for crack propagation in failure mode II, G_{IIc}. The mean value of G_{IIc} and the standard deviation are also given.

The mean value found in the present work for the fracture toughness in mode II is consistent with the values of this property reported in the literature (between 1159 and 1862 J/m^2) [33]. Figure 14 shows two curves of Force × Displacement of welded laminates, obtained in the ENF test. It can be seen from Figure 14(a) and (b) that even though the specimens were welded with the same parameters, the maximum load obtained in curve (a) is greater compared to that obtained in curve (b) (2000–1600 N, respectively). However, in curve (b) there was greater displacement than in curve (a) (10 mm and 6.8 mm, respectively). This is due to various problems inherent in the usual tests for characterizing mode II of interlaminar fracture, for example the propagation of unstable cracks [14].

As described in the literature [14,23,24], problems connected with unstable crack growth and monitoring thereof during propagation may increase the difficulty of rigorous measurement of the values of G_{IIc}. These difficulties of the test inherent in unstable crack growth might explain the difference in the value of interlaminar

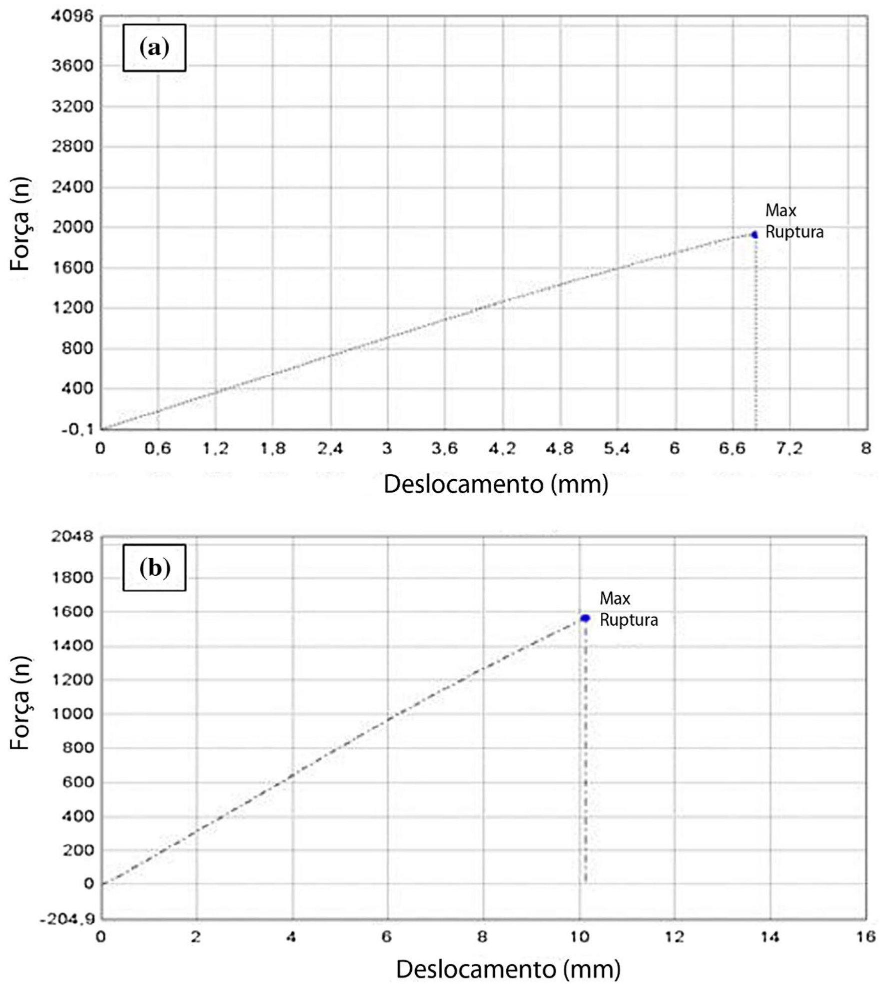

Figure 14. Load × Displacement curve of welded laminates: (a) Maximum load: 2062 N, Displacement: 6.8 mm; (b) Maximum load: 1567 N, Displacement: 10.1 mm. Força (n) = Force (N); Ruptura = Rupture; Deslocamento = Displacement

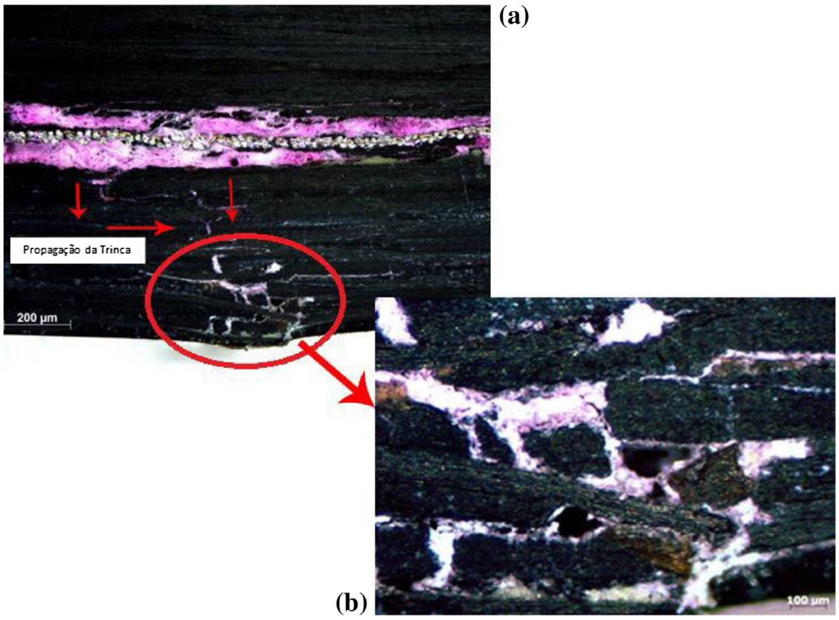

Figure 15. Crack propagation in the welded laminate at the moment of fracture: (a) magnification of 10×; (b) magnification of × 20. Propagação da Trinca = Crack propagation.

fracture toughness (Table 3) between specimen 1 of PEI/carbon (1171.4 J/mm^2) and specimen 2 (2089.8 J/mm^2).

Figure 15(a) and (b) show the moment when fracture occurs and the nature of crack propagation. Figure 15(a) shows, indicated by arrows, the course of the crack that occurs in the direction of the highest tensile force to which the material is subjected. Figure 15(b) shows delamination of the layers (interlaminar failure) of the welded laminates in response to this crack propagation, at greater magnification and in greater detail.

4. Conclusions

The temperature window that can be used in this welding process was established on the basis of the results obtained by the thermal analysis techniques employed in this work. In addition, it was observed that for the welded laminates there was an increase of approximately 15% in the glass transition temperature, resulting in higher processing temperatures.

Analysis of the interfacial shearing stress obtained from the Iosipescu and ILSS tests suggested that the resistance welding process was carried out successfully, since significant gains in this property were observed when welded specimens were compared with non-welded specimens.

The literature does not give many results obtained for interlaminar fracture toughness of mode II for welded laminates, whether for resistance welding or any other welding process. According to the results from the ENF test, the mean values of interlaminar fracture toughness of mode II (in-plane shearing) found in the study (1619.4 J/m^2) were also similar to values available in the literature (670-1862 J/m^2). The importance of this result for the welding process relates to verification of the quality of the welded joint, for assurance of the useful service life of this welded material in aeronautical structures. Determination of the energy does not in itself prevent joint failure. Maintaining this energy above minimum values may possibly prevent the failures usually encountered for this type of stressing of the material in service. In addition, morphological analysis of laminates fractured in the ENF test verified that the crack propagates in the direction of the plane of the joined laminates adjacent to the resistive element, which tends to deviate from the plane in favour of the maximum principal shearing stresses to which the material was subjected.

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