Studying the *"induction welding"* process applied to thermoplastic-matrix composites

In recent years the number of applications requiring the use of thermoplastic-matrix composites has increased enormously and so has the emphasis on the assembling techniques of these materials. In particular, alternatives to traditional mechanical fasteners or bonding are of great interest to industry. The present work is a study of a welding process, called "induction welding", of a composite material made of polyphenylene sulfide reinforced with woven carbon fiber. Process parameters such as temperature, pressure, residence time and presence of susceptor elements at the weld interface were considered. The number of tests to be conducted has been optimized by using DOE (Design of Experiment) techniques. The quality of the weld was evaluated with ultrasound and non-destructive mechanical testing

Flavio Caretto

Studio del processo di saldatura *induction welding* applicato a compositi a matrice termoplastica

Negli ultimi anni il numero di applicazioni che prevedono l'utilizzo di compositi a matrice termoplastica è aumentato enormemente e di conseguenza anche l'attenzione verso le tecniche di assemblaggio di questi materiali. In particolare, sistemi alternativi alle classiche giunzioni meccaniche o all'incollaggio sono di grosso interesse per l'industria. Il presente lavoro consiste nello studio di un processo di saldatura, denominato "induction welding" di un materiale composito costituito da polifenilensolfuro rinforzato con tessuti in fibra di carbonio. Parametri di processo quali temperatura, pressione, tempo di residenza e presenza di elementi suscettori all'interfaccia di saldatura sono stati considerati. Il numero delle prove da effettuare è stato ottimizzato per mezzo di tecniche DOE (Design of Experiment). La qualità della saldatura è stata valutata con controlli non distruttivi agli ultrasuoni e test meccanici

Introduction

The development of ever more light and resistant structures, at lower costs, is a key factor in the transportation industry, particularly as to the aerospace industry.

Given their remarkable specific properties, composite materials allow to build 25% lighter structures, if compared to equivalent conventional metallic materials.

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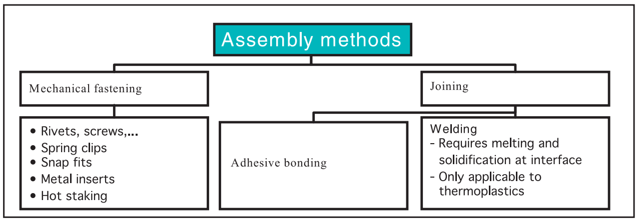


FIGURE 1 Assembly techniques of TPCs
Source: ENEA

Thermoplastic composites (TPCs) of more recent development are made of continuous fibers (glass, carbon, Kevlar, etc..) immersed in matrices consisting of specially designed polymers such as: PEEK, PEI, PEKEKK, PPS.
TPCs able to achieve mechanical properties comparable to those of thermoset composites, compared to these, have advantages in terms of: impact resistance, resistance to environmental stresses (moisture, temperature, aggressive media), deformation capacity, shelf-life and rapid-cycle process.
On the other hand they have: high-temperature process, not fully implemented processability, low availability and high cost of materials [1].
The construction of a structure must inevitably take into account such factors as: transport, inspectionability, accessibility, repairs to components, that make the use of joints inevitable. For TPCs, joints are even more frequently used because of their low deformability, which limits their use to simple geometries.
The junction of the various components is a critical step because it introduces a number of irregularities in the structure that are potential points of weakness and an inevitable source of added weight [2].
Mechanical joining techniques are used for TPCs, but with the limit of introducing important points of stress concentration, due to galvanic corrosion, infiltration of liquids, delamination of the composite during drilling, with a significant increase in weight and work to apply them.
The use of adhesive joints creating continuous connections avoids the presence of stress concentration points and therefore they are more advantageous than mechanical fasteners. For this technique to be applied, however, hard work is necessary to prepare the surfaces to be bonded and so are long cure times of adhesives [3].
Additionally, the success of TPCs is also due to their easy recyclability, and therefore the use of adhesives, epoxy in particular, is a solution that manufacturers try to avoid as much as possible since it limits the recyclability of the components [4].
The present work is aimed at evaluating the actual potential of the welding process of thermoplastic polymer matrix composites for aerospace known as "*induction welding*".
It has been verified that process temperature, compacting pressure, residence time, and type of weld interface affect the quality of the joint.
The experimental work was planned by implementing a "Design of Experiments" in order to reduce the impact of the trial, in terms of time and costs, still maintaining good levels of effectiveness and significance.
The material on which the welding tests were carried out is a semi-crystalline thermoplastic composite in polyphenylene sulfide (PPS), reinforced with high-resistance carbon fiber fabric (T300 3k 5HS), known as *CETEX® PPS* and produced by *Bryte Technologies Inc*.
Along with the experimental welding, the welded specimens are examined with ultrasound and mechanically characterized.
The interlaminar shear strength values, obtained by welding, are well above those of the testing specimens bonded with acrylic structural adhesive, specifically designed for plastics, known as *3M™ Scotch-Weld™ DP 8005*.
The activities have been fully developed at the Laboratory for Polymers, at the ENEA Research Centre of Brindisi.

Induction welding

In recent years, the technique of induction heating – which for a century has been widely used for metallic materials – has also been proposed for thermoplastic matrix composites (TPCs). The technology has proved particularly advantageous especially for welding applications, where the absence of contact between the workpiece and the heat source has significant advantages by reducing process times, increasing the versatility and the types of weldable materials [5] [6] [7].
Induction welding is a process by which the work-

FIGURE 2 Experimental set-up
Source: ENEA

piece is brought to temperature by using the principle of electromagnetic induction.
The welding system consists of a generator of electrical energy that powers a high frequency induction coil (Fig. 2). The coil is designed to generate high-frequency electromagnetic field (EMF) (hence the name *High Frequency Induction Welding*).
At this point, if an electrically conductive material and/or magnetically susceptible is surrounded by EMF, it will circulate the eddy currents with a frequency equal to that of the EMF. These currents will, in turn, bring the piece to heat up by Joule effect. In the case of TPCs, the procedure consists of a reinforced carbon fiber closed loop, into which the eddy currents to circulate are the very reinforcement fabrics.

Materials

The welded material is a composite semi-crystalline thermoplastic polyphenylene sulfide (PPS) reinforced with high-resistance carbon fiber fabric (T300 3k 5HS), called *CETEX® PPS* and produced by Brite Technologies Inc.

Thermal Characterization of TPCs using Simultaneous Thermal Analysis (TGA-DTA)

To assess the oxidative problems of *CETEX® PPS* associated with induction welding, thermogravimetric analyses (TGA) have been used, carried out in static air, acquired simultaneously with the measurement of the difference of temperature (DTA). The purpose is to identify changes in the degree of degradation of TPCs, as a function of time and temperature. The equipment used is the Simultaneous Thermal Analyzer STA 429 NETZSCH GmbH. The tests were performed on both the pre-preg and the laminate *CETEX® PPS.*
In both cases, the TGA curve is stable up to 400 °C and higher temperatures, which indicates the beginning of the process of thermal decomposition associated with a change in weight by about 20%. On the pre-preg DTA curve there was a first exothermic peak at 121 °C (Tpeak), probably associated with phenomena of crystallization and crystal grain refinement and a second endothermic peak at 279 °C (Tpeak) characteristic of the fusion phenomenon. At higher temperatures, namely at 512 and 588 °C peak temperatures, the decomposition process of the resin occurs. For the laminate, the DTA curve is identical to that of pre-preg, except for the absence of exothermic peak at 125 °C. This evidence is probably justified by the fact that, during rolling, the material has been cooling by quenching the molten state.

Experimental set-up

To perform the tests a high frequency induction generator FELMI mod. EGMA 6R with inductor 180x241mm has been used for heating overlooking. The machine has a supply voltage of 400V, a maximum output power of 6kW and a working frequency of 150 kHz to 250, varied by inverter and controlled by an automatic coupling system called "*autotuning system*" that it calibrates based on the type of coil fitted.
The temperature was kept under control by means of an infrared camera ThermaCAMS60 FLIR Systems Company.

Welding of specimens

For testing, 50x48mm welding specimens were used in *CETEX® PPS*. The size of the specimens to be welded is chosen so that each one of them could get three specimens for determination of apparent interlaminar shear strength by short beam, according to UNI EN ISO 14130. The analysis of the results obtained from preliminary heating tests showed that by using a distance piece-inducer of 8 mm and a power setting of 1.8 kW (62% of available power), it is possible to reach temperatures useful for welding in an acceptable time (47 sec).

The equipment provided in previous tests of heating has been implemented so that a series of concrete slabs, immune to EMF, were placed on the samples to be welded to exert adequate pressure.

Setup of process parameters

The factors that most influence the quality of welding are: temperature (T), compaction pressure (P) and residence time (t).
DTA analysis showed that the melting temperature of the PPS is 275 °C. Therefore, in the welding tests carried out, temperature has been varied in the neighborhood of this value. The residence time was set on different values varying by the order of minutes, in order to have acceptable timing for the purposes of any industrial process, the same applying to the pressure values varied by about 130 kPa.
Each of the three factors differs on three levels, as reported in Table 1, in order to assess the presence of any non-linearity in the correlation between the three factors and the quality of the junction in terms of values of ILSS.
The influence of these three parameters was examined by planning the number of tests using DOE (Design Of Experiment) techniques. *The number of test combinations has been restricted by using a reduced orthogonal matrix of the* $L_9(3^3)$ *type. Each test condition was repeated twice. The experimental campaign also planned to use, with the same combinations of factors (T, P, T), three different types of welding interface: 1) no interface element, 2) prepreg CETEX® PPS, 3) metallic mesh.*

Characterization of specimens welded by non-destructive ultrasonic technique

The objective of ultrasonic characterization is the definition of methodological criteria for the quality control samples welded by induction welding.
The analysis has allowed to obtain the mapping of each sample in order to perform an analytical evaluation of weld quality and its mechanical coupling composite/composite. Furthermore, a database was made of possible defects in this type of welds (discontinuity of adhesion between the two laminates and assessment of the weld compared to the process of life itself) as a function of different welding parameters.
The C-scan system used is composed of: Handler Micro-Controle Newport XYZ, Newport Motion controller MM4006, Ultrasonic Tool Panametrics P/R 5601°, Oscilloscope LeCroy LC574A 1GHz PC with card NI PCI-GPIB and LabWiev 7.1, Ultrasonic Probe 5 MHz focused for immersion.

Factors and levels

Factors	T [°C]	P [kPa]	t [min]
Level 1	260	100	1
Level 2	275	130	5
Level 3	285	160	8

TABLE 1 Description of variability levels of selected parameters
Source: ENEA

Mechanical tests to determine ILSS

In this research, the values of the interlaminar shear strength (ILSS) – measured by the test described in EN ISO 14130 "Determination of apparent interlaminar shear strength by short beam" – have been chosen as an indicator of the quality of the welding process. The determination of the ILSS values for specimens welded in different process conditions has allowed to study the relationship between process parameters and weld quality.
For all tests, we used a test machine MTS Alliance RT/50 equipped with a 50 kN load cell.

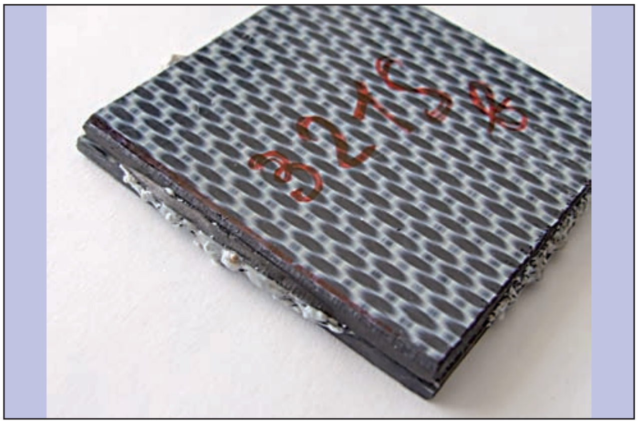


FIGURE 3 Pictures of a welded speciment. As a result of pressure and temperature, it is the *squeeze-out* of the matrix
Source: ENEA

Analysis of the effects of process parameters on the interlaminar shear strength

The following is a proposed study to determine how process parameters affect the quality of welds carried out, in terms of ILSS values.
The research of the most influential process parameters and the determination of criteria for performance optimization are approached by using the statistical method of Taguchi.
ILSS values are measured experimentally by means of mechanical tests performed on specimens made of those specific levels of process parameters, set as provided by the DOE procedure. By evaluating the mean values of ILSS at various levels of parameters, it has been identified how the interlaminar strength of these levels varies. The same operation was performed with standard deviation values. It was thus possible to identify combinations of levels that maximize the quality of the weld and that minimize the instability of the welding process.
In Table 2, Table 3 and Table 4, the patterns of analysis programs are shown, respectively for the specimens: without insert, with pre-preg and with metallic mesh as inserts interface. In each row, and then for each combination of process parameters, the mean values of interlaminar shear strength ILSS values and their standard deviation are reported.
In case of specimens without insert interface, the parameter that most affects the value of shear strength is temperature, followed by the applied pressure and residence time. Among other things, the oscillations due to the latter parameter, are contained in the experimental error. By setting the process parameters to the values "212" there is the maximum ILSS. Even by the standard deviation, the most influential parameter is temperature, followed by pressure and time. The combination of levels minimizes the standard deviation and the "111" setting that would create a more stable welding process at the expense of the resistance of the junction.
Using the statistical Taguchi an estimate of the values of apparent interlaminar shear strength has been made, even for the process conditions not covered in the adopted experimental matrix. It was confirmed that in the case of welding without insert, the combination of levels optimizing the ILSS is the "212" (T = 275 °C, P = 100 kPa, t = 5 min), a combination that is one of those verified experimentally and can reach a value of ILSS equal to 55 MPa.

Interlaminar shear strength for specimens without insert

	Level			Results	
Run order	T	P	t	ILSS average [MPa]	St Dev [MPa]
1	1	1	1	46.86	2.1
2	1	2	2	46.59	2.9
3	1	3	3	47.61	2.9
4	2	1	2	55.07	4.0
5	2	2	3	47.64	6.6
6	2	3	1	54.63	4.2
7	3	1	3	54.14	5.4
8	3	2	1	46.82	5.6
9	3	3	2	52.58	5.2

Level	T	P	t
1	47.02	52.03	49.44
2	52.45	47.02	51.42
3	51.18	51.61	49.80
Delta	5.43	5.01	1.98
Rank	1	2	3

DevSt ILSS	T	P	t
1	2.66	3.88	4.02
2	5.01	5.09	4.08
3	5.47	4.17	5.04
Delta	2.81	1.20	1.02
Rank	1	2	3

TABLE 2 Table response to DOE's analysis ILSS test results on specimens without insert
Source: ENEA

Figure 4 shows a C-scan image of the specimen "212Sa". As can be seen, the welding is uniform and the ultrasound signal reflected from the interface particularly weak, indicating a good joint. Comparison of this image with those of other specimens is a further confirmation of how, if not using any insert to the interface, the combination of process parameters "212" is the one that effectively optimizes the quality of the weld.
Also in the case of specimens with pre-preg insert interface, the parameter that most affects the value

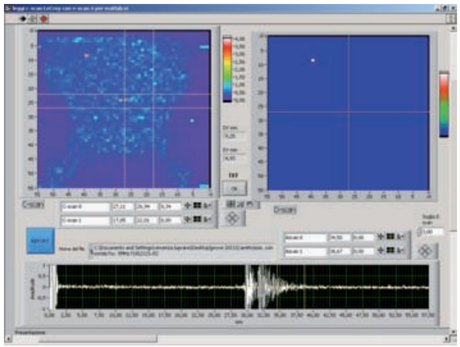


FIGURE 4 C-Scan image of the 212Sa specimen
Source: ENEA

of shear strength is temperature, followed by the residence time and applied pressure. Among other things, the oscillations due to the latter parameter, are contained in the experimental error. By setting the process parameters to the values "313" there is the maximum ILSS value.
Even by the standard deviation, temperature is the most influential parameter, followed by time and pressure. The combination of levels minimizes the standard deviation and the "121" setting that would create a more stable welding process at the expense of the resistance of the junction.
By using the statistical Taguchi, the values of apparent interlaminar shear strength have been estimated, even for the process conditions not covered in the adopted experimental matrix. It was confirmed that the combination of levels optimizing the ILSS is the "313" (T = 285 ° C, P = 100 kPa, t = 8 min), a combination that is one of those verified experimentally and can reach a value of ILSS equal to 47MPa.
Figure 5 shows a C-scan image of the specimen "313Pa". Although welding is sufficiently uniform, there are small areas where there is a strong reflection of the ultrasound signal from the interface, denoting non-welded areas. This agrees with ILSS values lower than those of specimens welded without insert interface.
Comparison of this image with those of other specimens is a further confirmation of how, if using *pre-preg CETEX® PPS* insert at the interface, the combination of process parameters "313" is the one that effectively optimizes the quality of the weld.

Interlaminar shear strength for specimens with pre-preg insert

	Level			Results	
Run order	T	P	t	ILSS $_{average}$ [MPa]	St Dev [MPa]
1	1	1	1	38.12	1.1
2	1	2	2	39.29	1.7
3	1	3	3	37.52	0.9
4	2	1	2	40.46	1.9
5	2	2	3	40.71	1.9
6	2	3	1	40.89	1.2
7	3	1	3	46.99	3.6
8	3	2	1	40.76	2.3
9	3	3	2	43.64	4.8

Level	T	P	t
1	38.31	41.86	39.93
2	40.69	40.26	41.14
3	43.80	40.69	41.75
Delta	5.49	1.60	1.82
Rank	1	3	2

DevSt ILSS	T	P	t
1	1.25	2.23	1.57
2	1.70	2.02	2.87
3	3.62	2.32	2.13
Delta	2.38	0.30	1.30
Rank	1	3	2

TABLE 3 Table response to DOE's analysis ILSS test results on specimens with pre-preg insert
Source: ENEA

Using a metal mesh as a susceptor, the parameter that most affects the value of shear strength is the applied pressure, followed by the residence time and temperature. It should be noted that the standard deviation values recorded are higher than those in previous methods of welding. *In the case of metal mesh, the process is less stable and changes in the value of ILSS, related to changes of the three process parameters, within experimental error.*
For the standard deviation, the most influential parameter is pressure, followed by time and temperature. The combination of levels minimizes the standard deviation and the "122". By using the statisti-

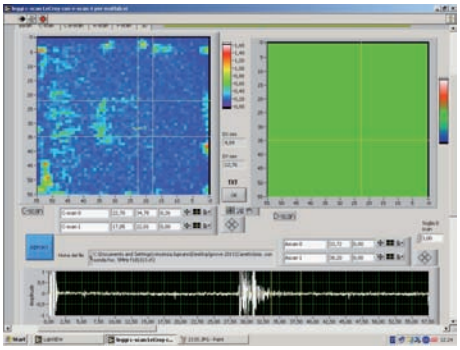


FIGURE 5 C-Scan image of the 313Pa specimen
Source: ENEA

cal Taguchi, the values of apparent interlaminar shear strength have been estimated, even for the process conditions not covered in the adopted experimental matrix. It was found that the combination of levels optimizing the ILSS is the "312" (T = 285 °C, P = 100 kPa, t = 5 min), through which it is expected to reach a value of ILSS of 41 MPa.
Figure 6 shows a C-scan image of the specimen "313Mb", specimen welded with process conditions closer to "312", best evaluated by statistical analysis. Welding is uniform at the edges, but in its central part an ultrasound signal reflected from the interface, denoting non-welded areas. This agrees with ILSS values lower than those obtained with the above types of welding interface.
By comparing this image with those of other specimens, it was found that if using a metal mesh as a susceptor interface, the combination "313" is the one that gave a better welding. Considering that the combination of process parameters "313" is the closest to the theoretical "312", this confirms the predictions obtained by statistical analysis.

Results of flexural tests

To have a basis of comparison of the ILSS (apparent interlaminar shear strength by short beam) results obtained, tests were performed on specimens bonded for the purpose and an acrylic structural adhesive was used, specifically designed for plastics, known as *3M™ Scotch-Weld™ DP 8005.*
Grafic 1 shows the different stress-strain curves for

Interlaminar shear strength for specimens with metallic mesh insert

	Level			Results	
Run order	T	P	t	ILSS $_{average}$ [MPa]	St Dev [MPa]
1	1	1	1		
2	1	2	2	34.76	2.1
3	1	3	3	39.62	6.5
4	2	1	2	40.22	6.7
5	2	2	3	35.08	2.7
6	2	3	1	35.33	4.6
7	3	1	3	39.03	6.3
8	3	2	1	37.19	3.7
9	3	3	2	39.86	3.7

Level	T	P	t
1	37.19	39.63	36.27
2	36.88	35.68	38.28
3	38.70	38.27	37.91
Delta	1.82	3.95	1.03
Rank	3	1	2

DevSt ILSS	T	P	t
1	4.28	6.50	4.13
2	4.68	2.85	4.16
3	4.55	4.91	5.17
Delta	0.41	3.65	1.03
Rank	3	1	2

TABLE 4 Table response to DOE's analysis ILSS test results on specimens with metallic mesh insert
Source: ENEA

each junction interface. Because the stress-strain curves vary with the setting of process parameters, in the case of this graph the curves of the specimens are welded under optimum conditions.
The curve "unwelded" shows the behavior of specimens not bonded in any way.
The curve "adhesive" shows the behavior of the specimens bonded with adhesive, where the "tooth", which is around 3500 N, represents the point at which the adherence soldered. As can be seen, the curve of the interface after the break "adhesive" follows the same trend of the curve "unwelded".

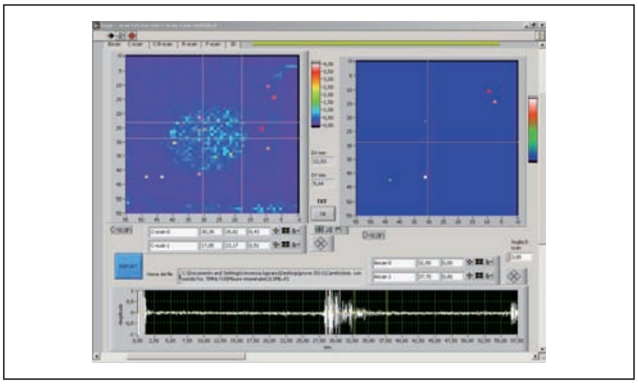
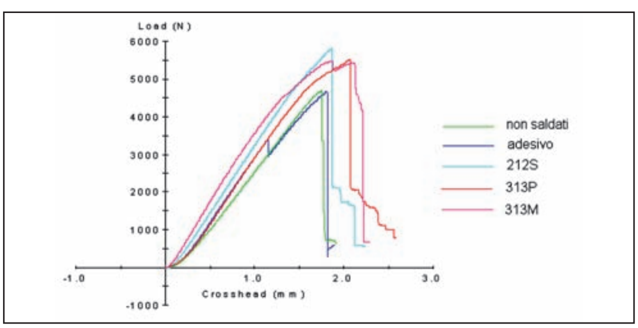


FIGURE 6 C-Scan image of the 313Mb specimen
Source: ENEA

The curves of the specimens welded with the optimal process parameters, in general show a higher stiffness than specimens bonded with significantly higher maximum stresses.
The curve "313M" shows a progressive failure, a behavior also observed on other specimens using metal mesh. The samples that do not use inserts or make use of pre-preg show, however, an unexpected failure, indicating a brittle-type fracture.
As seen in the previous paragraphs, through statistical analysis of Taguchi ILSS values were extrapolated for all possible combinations of the three process parameters, even for those not tested. This allowed to identify, for each interface type, the conditions that optimize the quality of the weld.



GRAF. 1 Stress-strain curve for specimens:
1) unwelded, 2) adhesive 3) welded without inserts,
4) welded with pre-preg insert,
5) welded with metallic mesh as susceptor insert.
Source: ENEA

At optimal conditions, the ILSS values obtained are equal to:

- 55 MPa with T=275 °C, P=100 kPa, t=5min, no insert interface;
- 47 MPa with T=285 °C, P=100 kPa, t=8min, *pre-preg CETEX® PPS* insert interface;
- 41 MPa with T=285 °C, P=100 kPa, t=5min, metallic mesh insert interface.

ILSS values, obtained by welding, are well above those of the testing specimens bonded with acrylic structural adhesive, specifically designed for plastics, known as 3M™ Scotch-Weld™ DP 8005, which recorded a mean value of 18 ILSS MPa, in line with 20MPa reported in literature, for bonded joints [8] [9].

Conclusions

The present work was aimed at an experimental study of the welding process called "induction welding" of thermoplastic composites for aerospace. Activities have been fully developed at the Laboratory for Polymers, at the ENEA Research Centre of Brindisi, following a request for technical and scientific support, advanced by CETMA CONSORTIUM for the execution of some research activities within the project "C.E.S.PER.T.: Compositi termoplastici E Strutture PER mezzi di Trasporto".
The material on which the welding tests were carried out is a semicrystalline thermoplastic composite in polyphenylene sulfide (PPS) reinforced with high-resistance carbon fiber fabric (T300 3k 5HS), called *CETEX® PPS* and produced by Brite Technologies Inc.
Firstly, to evaluate the degradation of the *CETEX® PPS* versus time and temperature set in the welding tests, the material was subject to thermogravimetric analysis (TGA), carried out in static air, acquired simultaneously with the measurement of the temperature difference (DTA). DTA curve in the laminate has detected the melting peak only at 275 °C.
In successive welding testing, temperature has been varied in the neighborhood of the melting temperature of PPS (275 °C).
The residence time was set at different values of the order of minutes, in order to have acceptable timing for the purposes of any industrial process. The same applies to the values of pressure, made to vary around 130 kPa.
Furthermore, it is expected to consider three types of

interfaces: the first one, where there is no insert; the second one, where a sheet of pre-preg *CETEX® PPS* is inserted; the third one, where a metal mesh is used.
The purpose of the experimental work was to determine how to set the process temperature, compacting pressure, residence time, and type of weld interface, so to affect the quality of the junction.
Once developed the system and decided to correlate the process parameters and the welding quality, the experimental campaign is planned. To this end, a procedure of "Design of Experiments" has been implemented to reduce the impact of the trial, in terms of time and cost, while retaining good levels of effectiveness and significance.
Each of the three process parameters was varied on three levels in the neighborhood of the set points and the number of test combinations was restricted as to one third as possible, using a reduced orthogonal matrix of the $L_9(3^3)$ type. *Each test condition was repeated twice.* Welded specimens were investigated with ultrasound and mechanical characterization.
The analysis has resulted in the mapping of each sample in order to perform an analytical evaluation of the weld quality and its mechanical coupling composite / composite.
The mechanical characterization was performed by measuring the apparent interlaminar shear strength (ILSS), using the test described in EN ISO 14130. The measure of ILSS values, under different conditions, has allowed the study of the relationship between parameters process and weld quality.
In addition, through statistical analysis of Taguchi, ILSS values were extrapolated for all possible combinations of the three process parameters, even for those not tested. This allowed us to identify, for each type of interface, the conditions that optimize the quality of the weld.
At optimal conditions, the ILSS values obtained are equal to:

- 55 MPa with T=275 °C, P=100 kPa, t=5min, no insert interface;
- 47 MPa with T=285 °C, P=100 kPa, t=8min, *pre-preg CETEX® PPS* insert interface;
- 41 MPa with T=285 °C, P=100 kPa, t=5min, metallic mesh insert interface.

In any case, the ILSS values obtained by welding are well above those of the testing specimens bonded with acrylic structural adhesive – specifically designed for plastics, known as 3M™ Scotch-Weld™ DP 8005 – which recorded a mean value of 18 ILSS MPa, in line with 20MPa reported in literature, for bonded joints.
This comparison lets you easily understand the potential of the "induction welding" technology in terms of mechanical strength and processability. Compared with mechanical joints, this technique has many advantages, typical of continuous joints, to not introducing points of concentration of mechanical stress, to avoid the infiltration of liquid through the cracks, to not having to drill the laminates, etc. In addition, this technology can be easily automated, resulting in a significant reduction of manual labor, due to the absence of contact between the heating device and components to be welded, and because there are no special requirements for surface preparation (typical problem of bonding techniques).

Acknowledgments
Activities have been fully developed following a request for technical and scientific support, advanced by CETMA CONSORTIUM within the project "C.E.S.PER.T.: Compositi termoplastici E Strutture PER mezzi di Trasporto".
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