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A Review of Welding Technologies for Thermoplastic Composites in Aerospace Applications

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Abstract: *Reinforced thermoplastic structural detail parts and assemblies are being developed to be included in current aeronautic programs. Thermoplastic composite technology intends to achieve improved properties and low cost processes. Welding of detail parts permits to obtain assemblies with weight reduction and cost saving. Currently, joining composite materials is a matter of intense research because traditional joining technologies are not directly transferable to composite structures. Fusion bonding and the use of thermoplastic as hot melt adhesives offer an alternative to mechanical fastening and thermosetting adhesive bonding. Fusion bonding technology, which originated from the thermoplastic polymer industry, has gained a new interest with the introduction of thermoplastic matrix composites, which are currently regarded as candidate for primary aircraft structures. This paper reviewed the state of the art of the welding technologies devised to aerospace industry, including the fields that Universidade Estadual Paulista Júlio de Mesquita Filho and Universidade de São Paulo are deeply involved.*

Keywords: *Aircraft structural joint, Thermoplastic composite, Welding technology.*

List of Symbols

Q	Heat generation
I	Electrical current
R	Ohmic resistance
t	Time
IR	Infrared
ITA	Instituto Tecnológico de Aeronáutica
LBW	Laser Beam Welding
P	Pressure
PEEK	Poly-etheretherketone
PES	Poly-ethersulphone
PPS	Poly-phenylenesulphide
PEI	Poly-etherimide
T	Temperature
T_g	Glass transition temperature
T_m	Melting temperature
UNESP	Universidade Estadual Paulista Júlio de Mesquita Filho
USP	Universidade de São Paulo

INTRODUCTION

Continuous fiber reinforced thermoplastic matrix composite laminates have shown great promise as materials for current and future aircraft components. When compared to thermoset fiber reinforced composite laminates, thermoplastic laminates are easier to process as they do not require complex chemical reaction nor lengthy curing process, they are easily recycled and do not need refrigeration for storage, displaying practically infinite shelf life. Thermoplastic composites also exhibit very low level of moisture uptake, which means their mechanical properties are less degraded under hot/wet conditions, not to mention their higher damage tolerance characteristics and greater reparability potential as compared to thermosetting matrix laminates (Ning *et al.*, 2007; Sinmazçelik, 2006; Jayamol *et al.*, 1998; Mallick, 1993).

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Unlike thermosetting resins, thermoplastics may be remelted after they are formed. They may also be joined using several different assembling processes. Joining plays an important role in manufacturing of composite structures in marine, automotive and aerospace industry. Mechanical fastening and adhesive bonding are widely used to assemble metals or composite components. However, there are disadvantages associated with these methods such as stress concentration induced by drilling holes in mechanical fastening or extensive surface preparation during adhesive bonding. Nowadays, joining can be achieved using various welding methods such as electric resistance, ultrasonic vibration, hot plate, electromagnetic induction, dielectric/microwave and IR welding (Mouzakis *et al.*, 2008; Botelho and Rezende, 2007; Wang and Hahn, 2007; Jones, 1994; Loos *et al.*, 1981).

Researches involving welding in composites in Brazil were initiated in 2006 by Faculdade de Engenharia de Guaratinguetá of UNESP, ITA and Escola de Engenharia de São Carlos of USP. The work started in these universities with cooperation of Empresa Brasileira de Aeronáutica (EMBRAER, acromyn in Portuguese) focused on the mechanical and thermal characterization of welded laminates of PPS (semi-crystalline PPS thermoplastic polymer) reinforced with continuous high-performance fibers. Nowadays, UNESP is developing resistance welding technology whereas USP is advancing in IR lamp welding methodology.

This paper aimed to examine different welding techniques for thermoplastic composite laminates devised to structural aerospace applications, focusing on recent developments in this area.

HIGH PERFORMANCE THERMOPLASTIC COMPOSITES FOR AEROSPACE APPLICATIONS

The automotive industry has traditionally produced a wide range of thermoplastic parts with the advantage of shorter processing times and fully automated equipments (Ray, 2006; Botelho *et al.*, 2005; Botelho *et al.*, 2002; Botelho *et al.*, 2001; Todo *et al.*, 2000).

In the late 1980s, glass and carbon reinforced thermoplastic PEI laminates were first used in Fokker 100 jetplane, Gulfstream G400 and G500 business jets, and Airbus Beluga transport aircraft as thermoformed flooring panels (Costa *et al.*, 2010; Vieille *et al.*, 2009; Young and Ye, 2005; Botelho *et al.*, 2003).

More recently, thermoplastic composites have found utilization in landing gear doors, winglets, elevators, ailerons, flaps, spoilers, speed brakes, slats, to cite a few applications (De Faria *et al.*, 2011; Rezende *et al.*, 2011; Chevali *et al.*, 2010; Bates *et al.*, 2009; Arici, 2007; Espert *et al.*, 2004; Lee *et al.*, 1993).

A wide range of high performance thermoplastic matrices is available nowadays, with PEEK and PPS the most widely studied and reported. Both of them are semi-crystalline polymers, and crystallinity in high-performance polymers is quite important as it has a strong influence on their chemical and mechanical properties. Crystallinity tends to increase stiffness and tensile strength while amorphous areas are more effective in absorbing impact energy. The degree of crystallinity is determined by many factors including the type of polymer and the processing conditions (Nino *et al.*, 2009; Mazur *et al.* 2008).

Today, joining thermoplastic composite structures is becoming increasingly important since thermoplastic composite usage is rapidly replacing metallic and thermoset composite counterparts to better withstand typical static and fatigue loads applied to aerospace vehicles. Many welding techniques have been developed to joint unreinforced and reinforced thermoplastic polymers, but each technique has its own advantages and pitfalls.

WELDING PROCESSES

In choosing a structural engineered material for aerospace application, an important consideration is how easy is to manufacture, join, inspect, repair and replace it in service. One of the many advantages of thermoplastic over thermoset composites in these cases is that thermoplastic matrices can be melted and reformed. In theory, using adequate temperature and P levels, a composite laminate can be reshaped indefinitely.

Many novel joining techniques have been proposed, developed and evaluated for thermoplastic applications in the last 20 years. In regard to fusion bonding methodologies, they can be summarized as follows in Fig. 1.

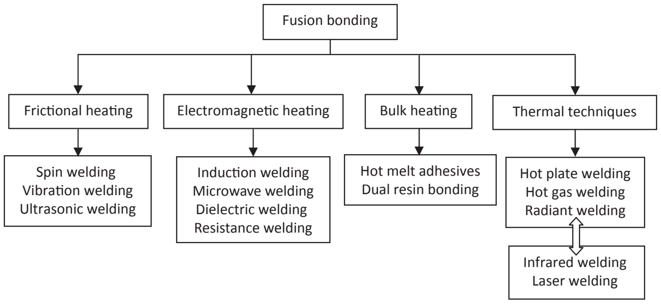

Figure 1. Classification of potential fusion welding techniques for thermoplastic composites (Ageorges *et al.*, 2001).

Seven main welding techniques are described below, according the order they appear in the schematic provided in Fig. 1.

Ultrasonic welding

Ultrasonic welding is a process in which high frequencies are used (typical frequencies range from 15 to 70 kHz) in order to induce molecular motion, thus creating friction, which is converted to heat. The ability to weld two or more components using ultrasonic welding depends on material physical properties, frequency and amplitude of ultrasonic wave and joint design. This joining process can be applied indistinctly to amorphous (welding temperature between the T_g and T_m) and semi-crystalline polymers (welding occurs at the melting point) (Levy *et al.*, 2008; Siddiq and Ghassemieh, 2008; Krüger *et al.* 2004; Ageorges and Ye, 2002).

Figure 2 presents a schematic of an ultrasonic welding machine using a piezoelectric transducer, by which the oscillations are generated by applying electrical power at high frequency. All ultrasonic welding systems are composed of the same basic elements: (i) a press to put the two or more parts to be assembled under *P*; (ii) a nest or anvil in which the parts are placed and allowing the high frequency vibration to be applied; (iii) an ultrasonic stack composed of a transducer; (iv) a converter, to convert the electrical signal into a mechanical vibration; (v) booster to modify the amplitude of the ultrasonic vibration; (vi) a sonotrode, to apply the mechanical vibration to the parts to be welded, (vii) an ultrasonic generator to provide and control the ultrasonic energy (Ageorges *et al.*, 2001; Krüger *et al.*, 2004; Yousefpour *et al.*, 2004; Siddiq and Ghassemieh, 2008; Levy *et al.*, 2008; Ageorges and Ye, 2002).

The application of ultrasonic welding is quite extensive in many industrial branches including electrical, computer, automotive, aerospace, energy, medical and packaging. In particular, aerospace industry employs this methodology to joint lightweight thermoplastic matrix composite materials, and a number of studies have been conducted to find optimum parameters and process windows to produce high quality welds (Siddiq and Ghassemieh, 2008; Krüger *et al.*, 2004).

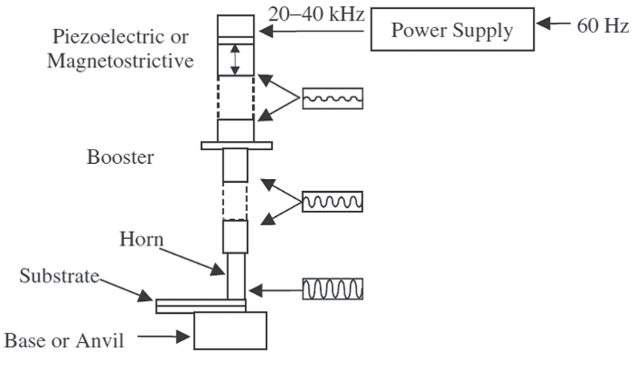

Figure 2. Schematic of an ultrasonic welding machine (Yousefpour *et al.*, 2004; Ageorges *et al.*, 2001; Ageorges *et al.*, 2000).

Lap joint shear strengths of order of 30 MPa have been informed for PPS/carbon fiber laminates bonded ultrasonically (Kagan and Nichols, 2005). This method was also used by Lockheed-Georgia to weld together thermoplastic/graphite tape material for the C-130 Hercules aircraft (Levy *et al.*, 2008).

Induction welding

Induction welding utilizes inductive heating for melting down polymer matrix in the joining zone. The components to be welded are submitted to an alternating electromagnetic field. When there are electrically conductive loops in the component, e.g. due to carbon fiber reinforcement, eddy currents are induced, resulting in efficient, localized heating of the laminate. Glass fiber reinforcements are electrically non-conductive, so that extrinsic electromognetic susceptors, e.g. metal grids, have to be incorporated to the composite array to convert the magnetic energy into thermal energy. In the case of ferromagnetic materials, hysteresis effects contribute further to heating. The heating is based on two mechanisms, namely, the energy dissipation due to Joule heating and energy dissipation due to magnetic hysteresis. The heat generation is described by Eq. 1 (Kagan and Nichols, 2005):

$$Q = I^2 \cdot R \cdot t \tag{1}$$

The above equation establishes that heating depends on time (*t*), ohmic resistance (*R*), and the square of the induced electrical current (*I*). The current is induced by an alternating magnetic field, so it therefore depends on the inductor geometry, the coil current, and the distance to the material (in the case of the material to be welded is not inside the coil), as depicted in Fig. 3 (Moser *et al.* 2008; Kagan and Nichols, 2005; Yousefpour *et al.*, 2004; Stokes, 2003; Velthuis and Mitschang, 2003; Hou *et al.*, 1999).

Kagan and Nichols (2005) refer to three categories of heating sources during induction welding of fiber reinforced thermoplastic composites:

- fiber heating: heating is the result of Joule losses due to the inherent resistance heating of fibers (Moser *et al.*, 2008);

- dielectric hysteresis heating: thin layer of matrix material at the bonding line separates fibers from the consolidated laminates. A capacitor is then created and dielectric heating occurs due to the movement of charge and rotation of the molecules between the fibers (Stokes, 2003);
- contact resistance heating: heating occurs on locations where the fiber-fiber contact is high (crossover points in the case of woven fabrics). This theory explains why several fabric types have a different heating generation (Velthuis and Mitschang, 2003).

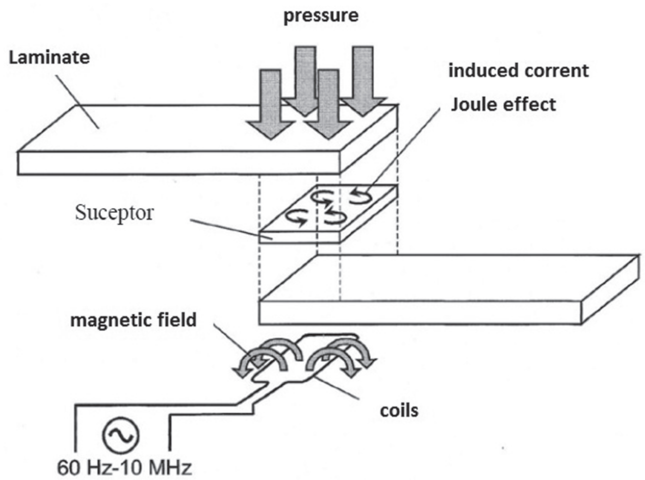

Figure 3. Schematic illustration of a magnetic field and eddy current generated by a electromagnetic coil (Kagan and Nichols, 2005).

A special type of induction welding is the so-called Emaweld-bonding. Here, thermoplastic pastes with metal particles are extruded in various shapes depending on the welding zone geometry, as they form the bonding between the joining parts. The Emaweld-process is fast compared to conventional induction welding. However, due to the metal particles in the welding filler, even small cracks lead to notches in the welding zone thus reducing the mechanical properties of the joint (Hou *et al.* 1999).

As for vibration welding, single lap joint shear strengths of order of 30 MPa have also been reported for induction welded PPS/carbon fiber laminates. Addressed investigations comparing resistance and induction welding showed that, under equivalent heating conditions, induction welded specimens displayed higher shear strengths (Kagan and Nichols, 2005).

Grumman Aircraft Laboratories (Kagan and Nichols, 2005) report induction heating as highly suitable for both the construction and repair of carbon fiber reinforced thermoplastic parts of the F-111A aircraft horizontal stabilizer leading edge demonstration component, using the graphite fibers as the conducting element. Structural elements produced by this method compared favorably to those manufactures by autoclave co-consolidation.

The examples above show that induction heating can be used for welding of thermoplastic fiber reinforced composites and acceptable bonding properties are obtained.

Microwave welding

The possibility of using microwave to weld parts has existed since the development of the magnetron in the 1940s. Its usage in the frequency range from 1 to 100 GHz has been reported in the literature to weld thermoplastic composites (Ku *et al.*, 2003; Wise and Froment, 2001; Chung-Yuan *et al.*, 1999; Vodicka, 1996).

Most thermoplastic do not experience a temperature rise when irradiated by microwaves. However, the insertion of a microwave susceptible implant at the joint line allows local heating to take place. If the joint is subjected simultaneously to microwaves and an applied P melting of the surrounding plastic results and a weld is formed. Suitable implants include metals, carbon or one of a range of conducting polymers, but whichever is selected becomes a consumable in the welding process (Yousefpour *et al.*, 2004; Ku *et al.*, 2003; Wise and Froment, 2001; Chung-Yuan *et al.*, 1999; Vodicka, 1996).

The particular advantage of microwave welding over other forms of welding is its capability to irradiate the entire component and consequently produce complex three-dimensional joints. Welds are typically created in less than 1 minute (Wise and Froment, 2001).

One drawback of microwave energy is that homogeneous material heating is only possible with simple geometries or through the elaborate adaptation of the radiation equipment to task at hand. This technique, however, is perfectly suitable for what are normally straight-line heating tasks in the welding of films and sheeting (Ku *et al.*, 2003; Wise and Froment, 2001; Chung-Yuan *et al.*, 1999; Vodicka, 1996).

Heating in a microwave field essentially takes place by the following physical processes, depending on the target material: polarization heating (polar material), electrical resistance heating (electrically conductive materials), heating through the Maxwell-Wagner effect (multi-phase materials; blends, filled materials), ion polarization (electrolytes, saline solutions and ceramics at high temperatures), electron polarization (Ku *et al.*, 2003; Wise and Froment, 2001; Chung-Yuan *et al.*, 1999; Vodicka, 1996).

Continuous microwave welding can be used for butt-welding of joint elements with low, medium and high dielectric loss factors using focused microwave energy (Wise and Froment, 2001). A typical schematic of the set-up is shown in Fig. 4. Joint elements with low-to-medium dielectric loss factors require no electromagnetic absorbent material in the bondline. The temperature of the bondline increases and reaches the polymer T_m as the bondline passes underneath the focused microwave energy. Meanwhile, localized fusion occurs in the presence of *P*, resulting in a weld. Joint elements with high dielectric loss factor require electromagnetic absorbent materials at the interface. Under microwave radiation, the electromagnetic absorbent materials absorb microwave energy more rapidly than joint elements, and then evaporate, leaving a localized melting zone at the bondline. The fusion bonding occurs in the bondline in the presence of *P*, producing a weld. Materials and solvents with OH, CO, NO, and NH bonds are typical electromagnetic absorbent materials. During the welding process, some of these materials evaporate and some remain in the weld area (Ku *et al.*, 2003; Wise and Froment, 2001; Chung-Yuan *et al.*, 1999; Vodicka, 1996).

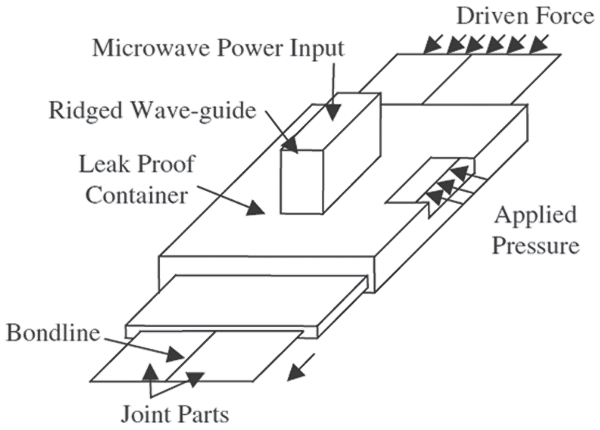

Figure 4. Schematic set-up for microwave heating (Yousefpour *et al.,* 2004).

The technique is still in the development stages and, as such, there are currently no reported industrial applications. However, it is anticipated that microwave welding may prove to be suitable for joining automotive under-body components and aerospace parts.

Resistance welding

Resistance welding has been considered a very promising joining technique for aerospace application. This process is relatively fast (welding times from 1 to 4 minutes), requires little amount of material and can be applied to large structures. Good thermal insulation and a correct amount of input energy can reduce the welding time and enhance weld quality (Ageorges and Ye, 2011; Costa, 2010; Yousefpour *et al.*, 2004; Yang and Pitchumani, 2002a, Yang and Pitchumani, 2002b; Ageorges and Ye, 2002; Xiao *et al.*, 1992). In this process, a conductive element (generally a steel mesh or a carbon strip) is placed at the interface between the laminates to be joined. This conductive element is connected to a power supply, and then a sufficient *I* is applied so that Joule loss generates heat enough to create a bondline (Stavrov & Bersee, 2005; Stavrov *et al.*, 2003; Yang and Pitchumani, 2002A, Yang and Pitchumani, 2002B; Don *et al.*, 1992; Xiao *et al.*, 1992). Figure 5 shows a schematic of the resistance welding process.

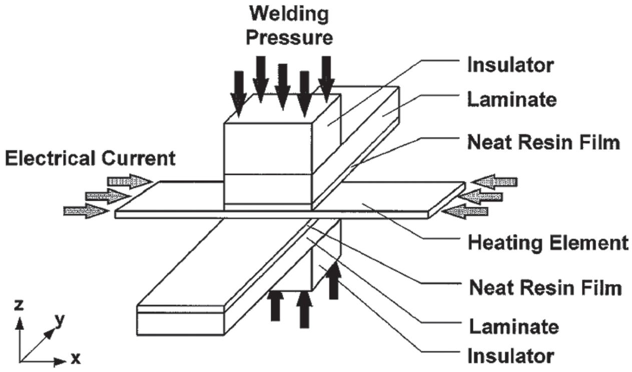

Figure 5. Schematic set-up for resistance welding process (Ageorges and Ye, 2002).

The electrical connection between the heating element and the power circuit is critical to the resistance welding process. In order to introduce adequate current into the heating element, several ways have been used, including: direct clamping on the prepreg; clamping on the bare fibers; prepreg dipped into liquid metal bath; clamping on the bare fibers painted with a silver filled epoxy compound, among others. Instead of using continuous power during the process, the power can be applied in the form of intense pulses. This process is called impulsive resistance welding and requires less energy to melt the matrix due to lower heat losses (Balle *et al.*, 2009).

This welding process can also be carried out under either constant load or displacement control. The method can produce lap shear strength values greater than 33 MPa, and has been used in order to weld PEEK and PEI laminates by the US Air Force (Wang *et al.*, 2006).

Hot plate welding

Thermal welding is a fusion bonding methodology that basically consists in heating polymer matrix composites pieces at their interface causing a decrease of viscosity thus allowing polymer chains to interdifuse as the surfaces are held tightly together, with further slow cooling for joint consolidation (Yousefpour *et al.*, 2004; Ageorges *et al.*, 2001; Ageorges *et al.*, 2000).

Inside of this concept, hot plate or hot-tool welding is one of the most popular methods for joining thermoplastics because it is a simple, reliable, and economical way of producing strong welds. This welding process can be divided into heating, joining and cooling steps. The laminate surfaces to be welded must first be brought into intimate contact or, sometimes, in quasi-contact, with an external heating element (generally is used a polytetrafluoroethylene-coated hot metal plate) in order the interface to be welded to melt. When necessary, adequate *P* must be applied to enforce the hot-tool against the laminates (Fig. 6). In case of excessive *P*, the melt will be pressed into the flash, and insufficient amount of melted material will remain on surfaces. Often mechanical stops are employed to prevent squeezing the entire melt out of the bond-line, which could result in a 'cold weld'. In case of too little pressure, full contact and thus good heat conduction between hot plate and joining parts might not be ensured. The applied pressure should be maintained until the thermoplastic matrix begins to soften and flow. After this, the hot element is removed and melted surfaces are pressed against each other until consolidation occurs. Small parts demand between 5 to 60 seconds to be welded, whereas large parts take at least 30 minutes to guarantee a good connection. Risks of surface contamination are amongst the main drawbacks of this technique (Ageorges *et al.*, 2001; Ageorges *et al.*, 2000).

IR welding

IR welding is another somewhat newcomer to the field of non-contact techniques for joining fiber reinforced thermoplastic polymer matrix composites (Yousefpour *et al.*, 2004; Ageorges *et al.*, 2001).

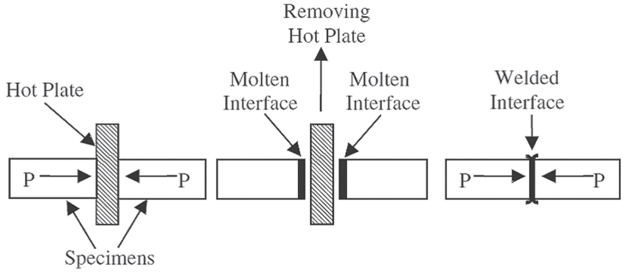

Figure 6. Schematic of the hot-plate welding (Yousefpour *et al.*, 2004).

Main advantages of IR sources are their ability to fast heating (typically 5 seconds), capacity to attenuate contamination risks, thus allowing high productivity rates of reproducible strong joints in automated systems. For instance, retention of 84% of polymer bulk strength has been reported for 20% in volume of short glass fiber in PES matrix (Chen, 2000). Besides high consistent, low scattered mechanical properties of IR welded joints, which is translated in high structural reliability as crucially required in high-demanding component devised to aeronautical industry, huge potential of this manufacturing technique can be forecast in the aeronautical environment by virtue of its great flexibility and capability to join large flat and curved areas (Potente *et al.*, 1993; Chen, 2000; Miller, 2006). In the other hand, a main shortcoming of IR welding is the detrimental effect of colorants and pigments in changing polymer absorption properties thus reducing the quality of the end product. Darker polymers are especially prone to display overheating surface degradation due to low IR energy transfer rates down through melting zone, nevertheless deep heat penetration may be a concern due to possible laminate deconsolidation and warping during heating stage, as well as thermal residual stresses development along cooling stage (Swartz & Swartz, 1989; Potente *et al.,* 1993; Chen, 2000; Ageorges *et al.*, 2001; Kagan & Bray, 2003; Grewell *et al.*, 2003; Grewell & Benatar, 2007).

Basically, the technique comprises three subsequent phases (Silverman and Griese, 1989; Schwartz, 1994; Chen and Benatar, 1995). Figures 7 to 9 feature some important aspects related to IR radiation welding, particularly in regard to the welding system operation, applied thermomechanical cycle and contact interface behavior of thermoplastic joint.

Laser welding

In order to produce integral composite structures and thus make the final composite component more cost effective, the exploration of the LBW, already applied to metallic parts can be useful in the case of joining either thermoplastic polymers or thermoplastic composite components. Thermoplastic polymers have long molecular chains held together by secondary chemical bonds, which allows them to be heated and remelted. Through the activation of this physicochemical mechanism, thermoplastics can be joined using a wide variety of fusion and interlayer bonding processes (Labeas *et al.*, 2010; Prabhakaran *et al.*, 2006; Grewell *et al.*, 2004).

LBW has been envisioned as a suitable technique for joining thin, as well as medium to thick thermoplastic components used in the aeronautic sector. Moreover, size, geometrical requirements, and specifications of aeronautical parts are claimed to be more easily fulfilled by applying LBW technique rather than alternative technologies (Labeas *et al.*, 2010). LBW allows joining thermoplastics, provided that one of the materials (top material) is transparent to laser radiation and the other (bottom material) is absorbent enough for the welding to take place, otherwise only butt joints will be allowed, which is not an attractive possibility for continuous fiber reinforced structures.

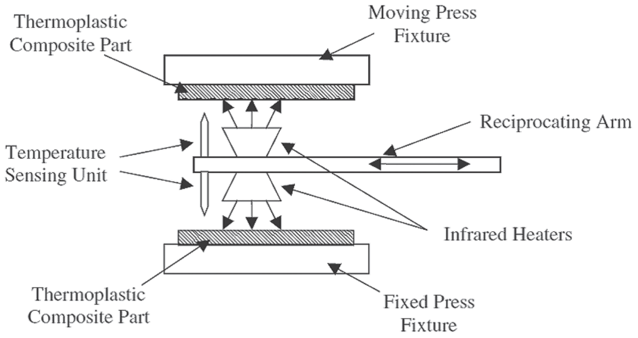

Figure 7. Schematic of infrared lamp welding system conceived to join thermoplastic laminates highlighting the infrared radiation source, polymer parts deployment and pressing plates (Yousefpour *et al.*, 2004; Ageorges *et al.*, 2001; Potente *et al.*, 1993).

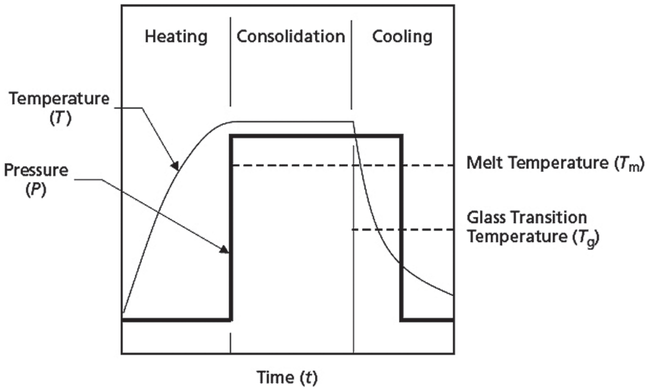

Figure 8. Typical thermomechanical cycle of the infrared welding system depicted in Fig. 7 (Yousefpour *et al.*, 2004; Ageorges *et al.*, 2001; Potente *et al.*, 1993).

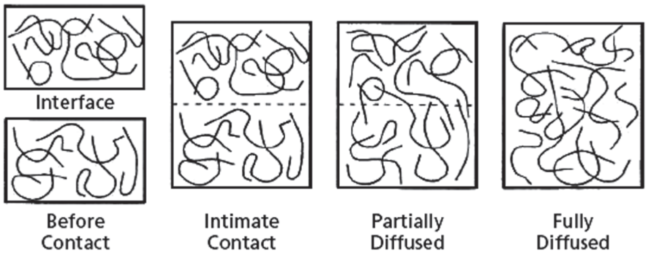

Figure 9. Macromolecular interdiffusion mechanism occurring in between two contacting parts during the infrared welding process portrayed in Figs. 7 and 8 (Yousefpour *et al.*, 2004; Ageorges *et al.*, 2001; Potente *et al.*, 1993).

In the first approach, parts to be joined are brought into direct contact prior to welding. The laser beam is transmitted through the first material and is totally absorbed within the surface of the absorbing material. Direct contact between both parts ensures heating of the transparent part by heat conduction from the absorbing part (Fig. 10). Welding occurs upon melting and fusion of both thermoplastic materials at the interface. The LBW technology offers the possibility of joining separate parts ensuring full continuity of the resin system without the addition of an adhesive system and avoiding also rivet installation, leading to a number of substantial advantages, such as cost savings, weight reduction, and manufacturing cycle time reduction, as well as acceptable bond strength (Labeas *et al.*, 2010).

Only few studies of the application of LBW process for the joining of structural thermoplastic composites such as carbon/PEEK or carbon/PPS are available in the literature, so that reliable application of LBW technology for joining primary aeronautic parts made of thermoplastic composites still requires significant development and investigation (Labeas *et al.*, 2010).

REMARKABLE CONCLUSIONS

From this manuscript it can be concluded that not only one joining technology can be applicable to all situations. All joining methodologies showed in this work present advantages and drawbacks, and they may be more or less suitable to a particular

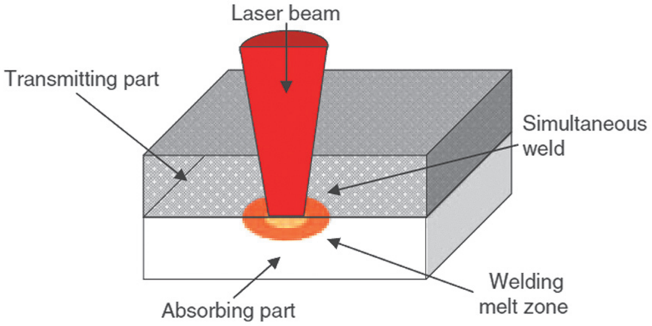

Figure 10. Laser transmission welding technique (Labeas *et al.*, 2010).

application depending on its specific requirements. Fusion bonding methods present a huge potential for volume intensive applications in which short processing cycles are necessary. These bonding processes offer additional advantages including reduced surface preparation requirements, reprocessing, recyclability, and improved integrity/durability. Among the various techniques of this category, the most mature ones are undoubtedly the ultrasonic, induction and the resistance welding.

Process integration is a critical aspect of joining technology. Particular requirements of each joining techniques should be collated in designs codes in order to integrate these requirements at the very early stage of the design process.

Inside of this context, since 2006, UNESP and USP have get involved in development and/or application of welding technologies in aerospace field. Emphasis of the work in UNESP is in the development of the resistance welding technology associated with the environmental influence on the thermal and mechanical properties of thermoplastic laminates, whereas USP is in the forefront of IR lamp welding methodology and advanced destructive and nondestructive characterization of the joints.

Most of the data in this paper were obtained from the literature, since this manuscript is a state-of-the-art review. Therefore, such data do not provide information for deals of repeatability or reproducibility, and they are useful only for an initial mapping of potential techniques over a wide range of weld processing conditions and parameters to be used in aerospace field.

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