Proceedings of the
6th Brazilian Conference on Composite Materials
ISBN 978-65-00-49386-3
Part of ISSN 2316-1337
Organised & Edited by R.J. da Silva & T.H. Panzera
Content available at: doi.org/10.29327/566492

An analytical model for the thermoplastic welding process

DB de Castro[(a), *], MV Donadon[(b)], MA Arbelo[(c)]

(a) 0000-0002-2561-5170 (Aeronautics Institute of Technology – Brazil)

(b) 0000-0001-9016-5340 (Aeronautics Institute of Technology – Brazil)

(c) 0000-0001-5541-6773 (Aeronautics Institute of Technology – Brazil)

* Corresponding author: danieldbc@ita.com

Keywords: composite materials, thermoplastic, welding, analytical model

Abstract: Among carbon fiber polymer composites, thermoplastics have interesting advantages compared to thermoset ones, such as recyclability, wear and impact resistance, and weldability. The high melting point of the thermoplastic resin with the fiber constraints makes it difficult to manufacture complex geometries, which justify the use of joining techniques. Mechanical fastening and adhesive bonding methods have some drawbacks that thermoplastic composite welding can eliminate because it is possible to achieve bond performance similar to the properties of the joined materials separated, allowing reprocessing (recycling). Most studies involving thermoplastic resistance welding are based on experimental tests. However, for further application and certification purposes, consistent models are required. In this paper, an analytical model for the thermoplastic welding process is proposed. The model is based on one-dimensional temperature distribution around the joint interface obtained from the transient heat conduction equation. To evaluate the bond strength, a bonding model that considers the intimate contact and autohesion was used. The material and the thermal properties were obtained from the literature and based on a micromechanical approach.

Fundings: This study was financed in part by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* – Brazil (CAPES) – Finance Code 001 and CNPq Grant (Nos. 301069/2019-0, 311972/2020-9).

1. Introduction

In applications that demand materials of high strength and lightweight, carbon fiber polymer composites are an attractive alternative to aluminum and steel [1]. Carbon-fiber-reinforced thermoplastic composites have interesting advantages compared to thermosetting composites, such as recyclability, wear and impact resistance, and weldability. The high melting point of the resin and the fiber restrictions limit the manufacture of complex geometries and justify the use of the joining technique [2].

Amid the joining techniques, mechanical fastening methods have some drawbacks related to stress concentrations, galvanic corrosion, incompatibility of the coefficient of thermal expansion of the fasteners relative to the composite, weight increase, and delamination during drilling [3]. Adhesive bonding methods require surface preparation, most of adhesives have long curing cycles, and the chemically inert thermoplastic matrix can be hard to bond [3]. Thermoplastic composite welding can eliminate part of these problems because it is possible to achieve bond performance similar to the properties of the joined materials separately, allowing reprocessing [4].

Most of the work involving thermoplastic resistance welding are based on experimental tests [2]. On the other hand, for certification purposes and posterior engineering applications, consistent analytical models are required in order to allow large parametric study aiming at improve the mechanical performance of the welded parts. In this study, an analytical model to evaluate the interfacial bonding quality for the thermoplastic welding process was proposed.

2. Methodology

The model is divided into four parts: heat transfer modelling, prediction of the degree of intimate contact (D_{ic}), degree of autohesion (D_{au}) (also called degree of healing for some authors), and finally the degree of bonding (D_b).

2.1. Heat transfer

The heat transfer model adopted in this work was one-dimensional transient model given by Eq. (1), solved by the explicit form of the finite difference method [5].

$$\frac{\partial}{\partial x}\left(k\left(\frac{\partial T}{\partial x}\right)\right)+\dot{q}=\rho c_p\frac{\partial T}{\partial t} \quad (1)$$

where k is the thermal conductivity of the composite, $\dot{q}$ is the heat generation rate per unit volume, ρ is the density, and c_p is the specific heat.

One-dimensional assumption was adopted because higher temperature variations occur through-the-thickness direction of the joint (x-direction) [4]. This is the first step towards the development of a 3-D model which is underway by the authors at LNCA-ITA in order to handle more complex and realistic geometries. The heating element of thickness $2h_{he}$ was considered as a layer of APC-2/PEEK (polyetheretherketone carbon fiber reinforced composite), similar to the approach done in [4, 6]. The convection heat transfer coefficient to air is h [4] and $\dot{q}$ is the heat generation rate per unit volume. A PEEK resin film h_{rf} was used as an interlayer between the heating element and the composite in order to create a resin-rich region, improving the bonding process. The total half-thickness employed for the model is L and the ambient temperature is T_∞. Figure 1 illustrates the modeling case.

Since the temperature distribution is symmetric about the interface, thermal symmetry boundary condition at the center of the interface ($x=0$) was adopted. The heat generation rate generated within the heating element was considered the mean value of the power input values presented in the works [2, 7] properly converted to heat generation rate per unit volume. Fiber and matrix properties can be found in [1]. The micromechanical approach was used to compute the laminate properties. It was reported in [6] that for power level ranges above $40\ kW/m^2$ there was no significant difference in the time necessary to achieve the melting considering temperature-dependent or independent material properties. In this work, material properties (density, specific heat, and thermal conductivity) were considered temperature-independent.

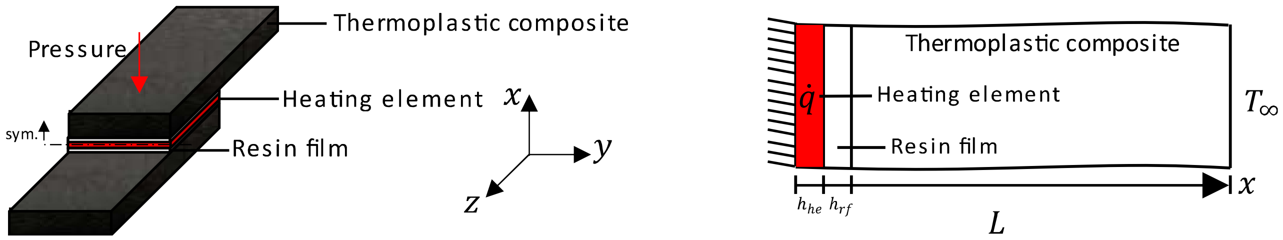

Fig. 1. One-dimensional model - schematic illustration.

2.2. Intimate contact

The degree of intimate contact is a relation that corresponds to the amount of surface that is in contact at the interface. It depends on the surface roughness, temperature and pressure [9]. The roughness of the material prevents the molecules from moving across the interface because of the open spaces. Since the viscosity of thermoplastics is high, in addition to temperature, the application of pressure is needed to achieve the proper resin flow [10]. The expression for the degree of intimate contact is defined by Eq. (2) [2, 7, 9, 11]

$$D_{ic}(t) = a^* \left[\int_0^t \frac{P_{app}}{\mu_{mf}} dt \right]^{\frac{1}{5}} \qquad \mu_{mf} = 132.95 \cdot e^{\left(\frac{2969}{T[K]}\right)} \tag{2}$$

where P_{app} is the applied pressure, a^* is the geometric factor or roughness parameter, obtained by fitting the model to experimental data [4], and μ_{mf} is the temperature-dependent fiber matrix viscosity for the APC-2 matrix-fiber system [11]. The intimate contact calculations start at the glass transition temperature T_g. When the surfaces are in complete contact, $D_{ic} = 1$.

2.3. Autohesion

The autohesion or healing process happens when, once into intimate contact, the polymer molecules are free to diffuse across the interface [2, 4], contributing to the strength evolution at the bond area. The expression for the degree of autohesion is given by Eq. (3) [4, 10]

$$D_{au}(t) = \left[\int_0^t \frac{dt}{2\sqrt{t \cdot t_r(t)}} \right]^{\frac{1}{2}} \qquad t_r = C \cdot e^{\left[\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]} \tag{3}$$

where t_r is the reptation time, T is the temperature in K at the time t, E_a is the activation energy of diffusion of the polymer, C is the constant for the reptation time, R is the universal gas constant, T_{ref} is the reference temperature [4, 10]. Autohesion mechanism is complete when $D_{au} = 1$.

2.4. Degree of bonding

Both intimate contact and autohesion occur simultaneously, the bonding process is coupled and can be defined by the evolution of the degrees of autohesion and intimate contact [8]. Without intimate contact there is no autohesion [9] i.e., intimate contact is a requirement for the development of autohesion. Bonding is complete when the degree of bonding $D_b = 1$ and it can be calculated by the expression in Eq. (4) [2, 8, 9, 11].

$$D_b(t) = D_{ic}(t) \cdot D_{au}(t) \tag{4}$$

3. Analytical Model Predictions

3.1. Model input parameters

The model input parameters used in the simulations are listed in Table 1.

Table 1. Input parameters.

Parameter	L	h_{he}	h_{rf}	T_∞	$\dot{q}$	h	P_{app}	a^*	E_a	C	R	T_{ref}	T_g
Value	4	0.06	0.08	25	7.87e8	10	1.4	0.147	57300	0.11	8.3145	673	143
Unit	mm	mm	mm	°C	W/m³	W/m²°C	MPa	-	J/mol	-	J/mol·K	K	°C

In the heat transfer model, there were two steps, heating and cooling. In the modeling, the heating element was turned on for 45 s and then turned off, cooling down for 45 s, simulating a resistance welding process.

According to [4] and [10], autohesion calculations are discontinued for temperatures below 270 °C due to the lack of molecular mobility, with the bonding process being very slow. In this work, it was assumed that the autohesion starts and ends at 280 °C [9]. Since the process is coupled, the degree of bonding calculations begin with the autohesion at 280 °C (heating) and ceases at 280 °C (cooling).

3.2. Results and Discussions

The physics of the molecular chains on the interface during intimate contact and autohesion process is illustrated in Figure 2(1). The heat transfer model can be seen in Figure 2(2). The curves represent the temperature distribution across the thickness in the time t, where the red ones occur on heating and the blue ones on cooling, both for 45 s each. The maximum temperature achieved in the center of the interface, $L = 0$, was 466.7 °C, 123.6° above the PEEK melting point of 343 °C. According to [8], to achieve effective bonds, semi-crystalline polymers should be processed above their melting temperatures. The heat transfer model was previously validated through comparisons with finite elements analyses predictions performed using ABAQUS FE code.

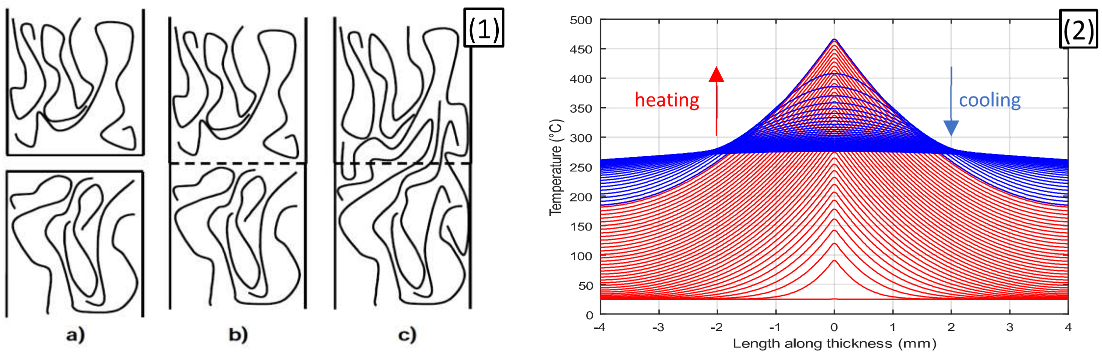

Fig. 2. 1) Healing of a polymeric interface. (a) Two distinct interfaces; (b) intimate contact; (c) autohesion [7]. 2) Temperature distribution.

Adopting a conservative approach as well as [4], the intimate contact and autohesion plot, Fig. 3(1), was calculated on the point at the interface between the PEEK film and the APC-2 laminate because the temperature is slightly lower than the center of the heating element. Figure 3(1) presented a similar shape likewise [8]. Figure 3(2) is a three-dimensional plot that shows the degree of bonding on the temperature along the thickness x.

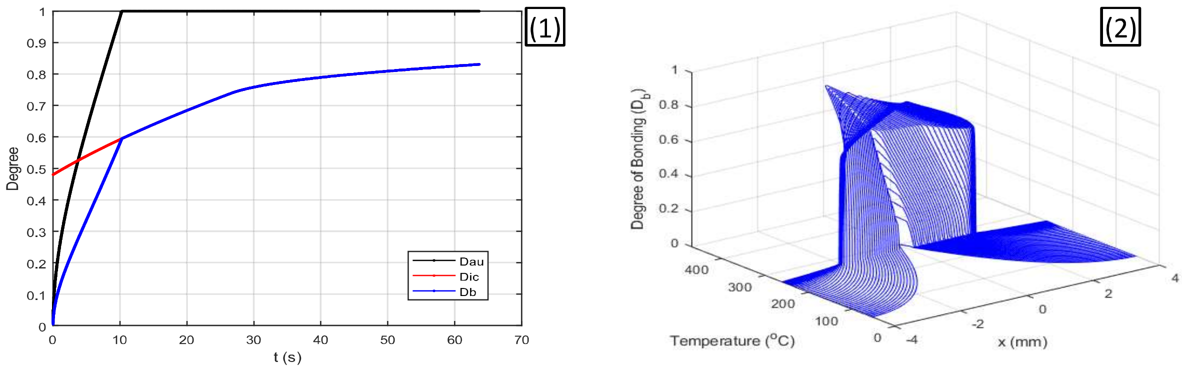

Fig. 3. 1) Degree of intimate contact, autohesion and bonding for APC-2/PEEK laminate under 1.4 MPa pressure. 2) Degree of bonding on the temperature along the thickness x.

According to the thermal model, the time where the temperature at the point at the interface between the resin film and the laminate reaches 280 °C (the beginning of bonding) is 18.3 s. The intimate contact starts at 4.6 s when the temperature at the same spot reaches $T_g = 143\ °C$. The timeline t in Figure 3(1) represents the time where the bonding process begins, i.e., at 18.3 s from the beginning of heating from room temperature. The cooling process can be seen starting in 26.7 s after the beginning of the autohesion process.

4. Conclusions

In this study, a simplified model for evaluating the bonding quality in a thermoplastic welding process was carried out. The heat transfer model provided the temperature distribution along the composite for the degree of intimate contact and degree of autohesion calculations. With that evaluated, it was possible to calculate the degree of bonding.

For the same conditions tested, full bonding ($D_b = 1$) would have occurred if the applied pressure was 3.5 MPa. The proposed model allows large parametric studies at low computational cost by varying variables such as heating rate, heating time, heating element and laminate thickness in order to define the optimum welding parameters for a given composite joint configuration.

Declaration of Competing Interest

The authors declare no conflict of interest.

Credit author statement

DB de Castro: Conceptualisation; Methodology; Formal Analysis; Software; Data curation; Writing – original draft. **MV Donadon** and **MA Arbelo:** Conceptualisation; Resources; Supervision; Writing – review.

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