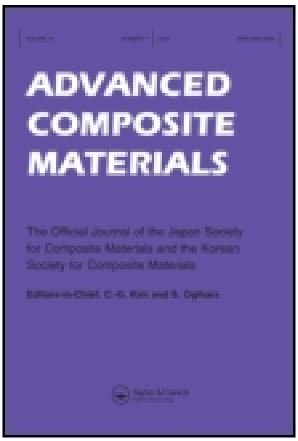

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A study on the induction heating of carbon fiber reinforced thermoplastic composites

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Abstract—Recent work in the literature has identified a new heating mechanism during induction processing of carbon thermoplastic prepreg stacks: contact resistance between fibers of adjacent plies. An experimental methodology has been developed to estimate the contact resistance through heating tests based on the properties of the composite and geometry of the specimen. Measured values indicate comparable resistance values at the contact region, compared to resistance in the fiber direction, for AS-4/PEI prepreg stacks under vacuum pressure. The measured values can serve as inputs for induction heating models and process models of carbon thermoplastic prepreg stacks.

Keywords: Induction heating; contact resistance; dielectric hysteresis; thermoplastic composite; prepreg strip.

NOMENCLATURE

A_{loop}	area of a conductive loop formed by prepreg strips (m^2)
A_s	cross-sectional area conductive prepreg strip (m^2)
$\vec{B}$	magnetic field vector intersecting the composite laminate
B_z	magnitude of the alternating magnetic field normal to the prepreg (Wb)
C_p	heat capacity (J/kg/K)
d_f	fiber diameter (m)
emf	induced ElectroMotive Force at each conductive loop (volts)

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I	electrical current flowing in conductive loop (A)
I_c	electrical current flowing along the induction coil (A)
l	length of conductive prepreg strip (m)
p_f	heat generation rate at fibers due to Joule losses (W)
p_j	heat generation rate at junctions (W)
p_f'''	heat generation rate per unit volume at fibers due to Joule losses (W)
p_j'''	heat generation rate per unit volume at the junction of strips (W)
$\vec{r}$	unit vector from the source of magnetic field to a point in space
R_f	resistance of fiber (Ω)
R_j	junction impedance or contact resistance (Ω)
t	time (s)
t_s	thickness of prepreg strip (m)
T	temperature (K)
T_g	glass transition temperature (K)
v_f	fiber volume fraction of prepreg
V_f	volume of fiber in prepreg strip (m^3)
V_j	volume of junction in prepreg strip (m^3)
w_s	width of conductive prepreg strip (m)
Λ	contact resistance between strips at the prepreg interface (Ω)
μ_0	permeability of free space (Wb/A/m)
ρ	density (kg/m^3)
ρ_f	resistivity of conductive fiber (Ω m)
ω	angular frequency of induction coil (rad/s)

1. INTRODUCTION

Heat generation in carbon fiber reinforced thermoplastic composites, during induction processing, occurs due to induced eddy currents flowing along conductive loops in the composite, as shown in Fig. 1. In each conductive loop, heating occurs wherever there is a voltage drop due to electrical resistance or impedance. The resultant heating is ‘volumetric’ in nature, as it is an internal heat generation mechanism dependent on intrinsic properties of the composite.

The primary advantage of the induction heating of conductive fiber reinforced composites is the possibility of high volumetric heating rates, leading to higher throughput, compared to conventional manufacturing. Traditional manufacturing processes rely on conduction, convection or radiation heat transfer through the thickness of composite, requiring time for the composite to equilibrate at the desired process temperature. However, in the case of induction heating, volumetric heating

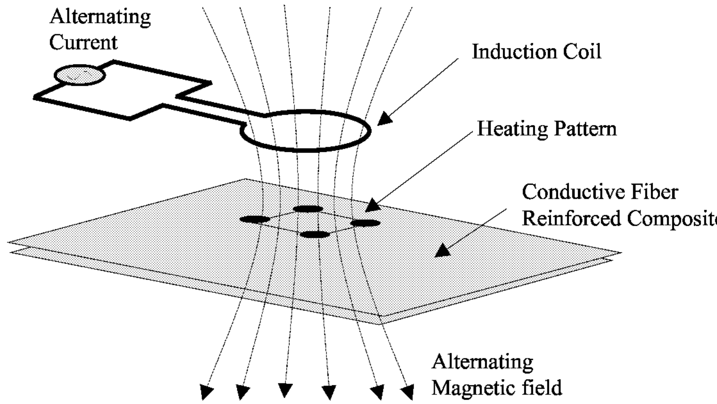

Figure 1. Schematic of the induction heating process.

occurs leading to higher heating rates and process velocities. In addition, induction heating is a multi-ply process, leading to further reductions in cycle times [1].

Research on induction heating of carbon fiber reinforced composites has looked at heating models for consolidated laminates, for the development of process models. Initial efforts on the induction heating of composites were carried out to investigate the possibility of induction-based process for fusion bonding at the interface of thermoplastic composites with nickel coated graphite prepreg or amorphous film between the composites [2–5].

Miller *et al.* [6, 7] proposed theoretical models for induction heating of carbon thermoplastic laminates based on the assumption that Joule heating along the carbon fiber was the primary heating mechanism, and good electrical contact between fibers of adjacent plies (through-thickness) was necessary for effective induction heating. They applied induction heating to production systems such as die-less forming.

Fink *et al.* [8, 9] proposed that the dominant heating mechanism is dielectric polymer heating at the regions (junctions) where fibers of adjacent plies overlap. The contention was that the fibers of adjacent plies are not in complete contact, but separated by a small polymer gap. They formulated models for in-plane heat generation and through-thickness heat generation and correlated them with experiments.

Recent work [10] on the induction heating of carbon/thermoplastic prepreg stacks has raised the possibility of a third heating mechanism: fiber contact resistance at junctions of adjacent plies. Experiments on induction heating of two-ply prepreg stacks have verified this concept. Preliminary results were presented for qualitative comparison with heating tests. The present work examines the third mechanism in more detail.

The focus of this work is on quantifying contact resistance values during induction heating of carbon thermoplastic prepreg stacks. The goal is to establish the relationship between heating and the process parameters, both qualitatively and quantitatively.

2. HEATING MECHANISMS AND ELECTRICAL MODELS

In a carbon fiber reinforced composite, there are two heating regions: fibers, and junctions (where fibers from adjacent plies overlap) as shown in Fig. 2. Fibers can generate heat due to their intrinsic resistance and junctions can generate heat due to dielectric hysteresis if the fibers are separated by a small polymer gap, or contact resistance heating if the fibers are in direct contact.

In a consolidated laminate or a prepreg stack under pressure, all three mechanisms may occur to varying degrees depending on the prepreg quality and processing conditions. One can have regions where fibers of adjacent plies are in complete contact (junction resistance heating) or separated by a small polymer gap (dielectric hysteresis heating) along with Joule heating in the carbon fibers. Pressure and temperature dictate the degree of contact between adjacent plies and determine the through-thickness electrical behavior of the composite.

Of the three possible mechanisms, it is necessary to determine which mechanism is dominant under what conditions. A consolidated laminate can have a different dominant heating mechanism compared to an unconsolidated prepreg stack. Currents in the composite are induced only if there are conductive loops and the formation of loops is dependent on not only the in-plane ply properties (electrical conductivity), but also the through-thickness conductivity of the laminate. Hence, different processing conditions can lead to different heating scenarios. A model is being developed that incorporates all three heating mechanisms and will be used for parametric studies and will be correlated with experiments. This work focuses on quantifying contact resistance values for use in the model.

In a given unidirectional prepreg sheet or strip, electrical contacts between the conductive fibers within the prepreg may occur due to imperfectly aligned fibers and

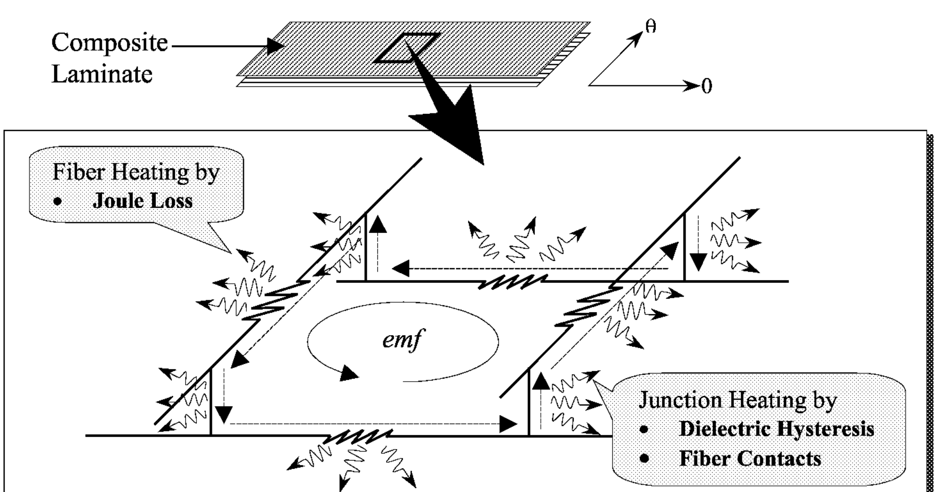

Figure 2. Schematic of the fiber heating and junction heating at each conductive loop of the cross-plied or angle-plied laminate [10].

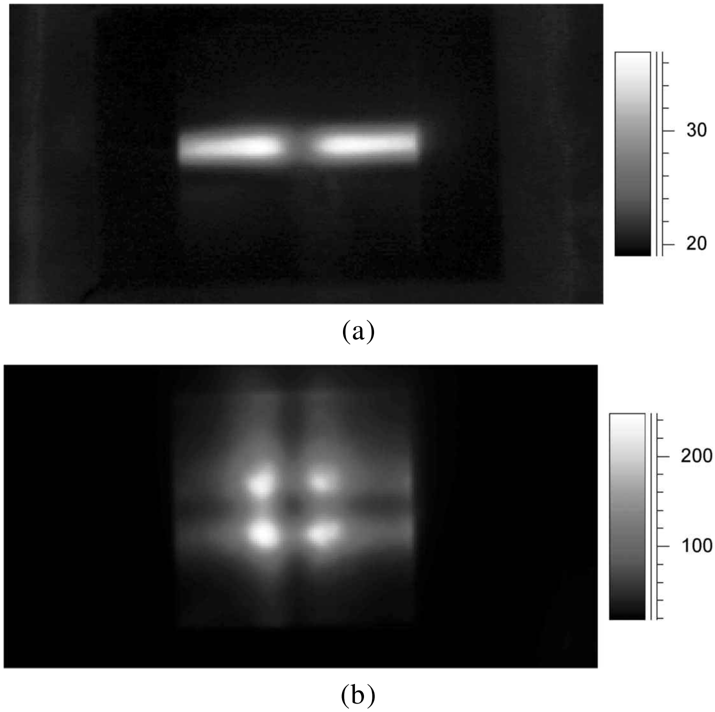

Figure 3. Comparison of heating patterns of prepreg stacks (AS-4/PEI) after 60 seconds of applying same intensity of magnetic fields (3-turn pancake type coil); (a) [0°/0°] of AS-4/PEI prepreg sheets; (b) [0°/90°] of AS-4/PEI prepreg sheets.

high fiber volume fraction. In order to prove that situation, two unidirectional plies of AS-4/PEI prepreg sheets are stacked together and subjected to an alternating magnetic field. As seen in the Fig. 3a, induction-based heating in the sheets takes place and indicates that there are fiber contacts inside the unidirectional prepreg. However, a comparison of heat generation with a cross-ply stack [0°/90°], as shown in the Fig. 3b, shows that the amount of heat generated in the unidirectional stack is much smaller than the cross-ply stack. Therefore, in this study, heat generation in a unidirectional prepreg sheet or strip is assumed to be negligible. This assumption has also been made in the literature [6, 10] when studying induction heating of carbon fiber-based composites.

3. EVALUATION OF CONTACT RESISTANCE

The contact resistance value is a function of prepreg surface characteristics, process pressure and temperature. Figure 4 shows a schematic of a test setup to measure contact resistance as a function of process parameters and prepreg material.

The emf induced along the prepreg loop (Fig. 4) is calculated from the magnetic field as shown in equations (1) and (2). It is assumed that the loop and the coil are

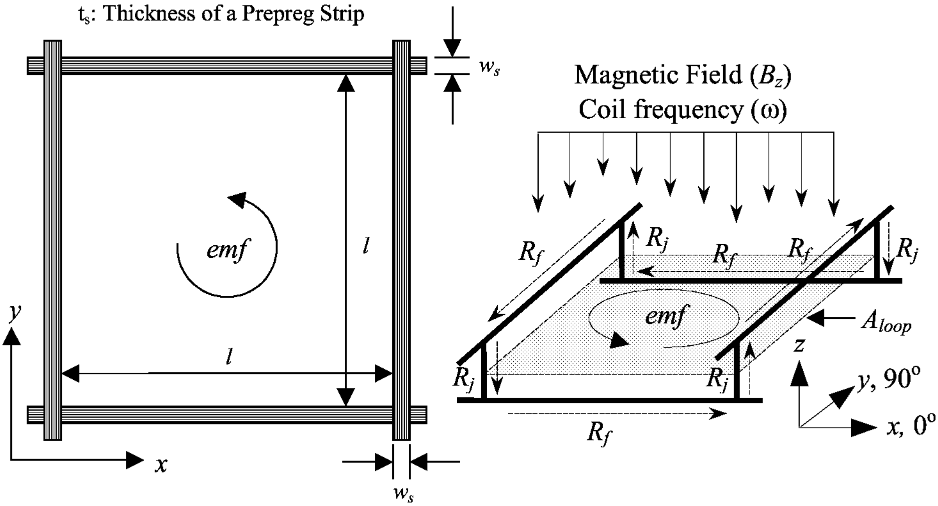

Figure 4. Schematic for the heating test with prepreg strips.

parallel in space and, therefore, only the z-component of the magnetic field induces emf in the loop.

$$\vec{B} = \frac{\mu_0 I_c}{4\pi} \int \frac{\vec{r} \times d\vec{s}}{r^2}, \tag{1}$$

where μ_0 is permeability of free space, I_c is electrical current flowing through the induction coil and $\vec{r}$ is the unit vector from the source of magnetic field to a point in space.

$$emf = \omega A_{loop} B_z, \tag{2}$$

where *emf* is the induced electromotive force along the conductive loop of prepreg strips, A_{loop} is the area formed by the prepreg strips and B_z is the z-component of external magnetic field applied to the surface of A_{loop}.

The current in the loop (I) is calculated based on Kirchhoff's Voltage Law as in equation (3). Note that since there are four strips and four junctions in the conductive loop, 8 resistor elements in total were used to implement the voltage conservation law.

$$emf = 4(R_f + R_j)I \quad \text{or} \quad I = \frac{emf}{4R_f(R_f + R_j)}, \tag{3}$$

where R_f and R_j are resistance of each prepreg strip and junction in Fig. 4, respectively, and I is the global current in the conductive loop formed by conductive prepreg strips.

From equation (3), the ratio of the heat generated in each strip (p_f) and junction (p_j) can be calculated by,

$$\frac{p_j}{p_f} = \frac{I^2 R_j}{I^2 R_f} = \frac{R_j}{R_f}. \tag{4}$$

As seen in Fig. 4, if the length (l), width (w_s) and thickness (t_s) of the composite strip are given, the resistance can be expressed as,

$$R_f = \rho_f \frac{l}{A_s} = \rho_f \frac{l}{v_f w_s t_s}. \tag{5}$$

The contact resistance at the junction (R_j) is denoted as Λ and is to be determined. Combining equations (4) and (5), the heat generation ratio is,

$$\frac{p_j}{p_f} = \frac{R_j}{R_f} = \frac{\Lambda}{\rho_f}\left(\frac{v_f w_s t_s}{l}\right). \tag{6}$$

The volume occupied by each element (junction and prepreg strip) in Fig. 4 is,

$$V_f = v_f(w_s \cdot t_s \cdot l), \quad V_j = w_s \cdot w_s \cdot 2t_s, \quad \text{and} \quad \frac{V_j}{V_f} = \frac{2w_s}{v_f l}. \tag{7}$$

In equation (7), fiber volume fraction was considered in obtaining the volume of the conductive prepreg strip.

Combining equations (6) and (7), the ratio of heating intensity at the junction and composite strip can be expressed as,

$$\frac{p_j'''}{p_f'''} = \frac{p_j/V_j}{p_f/V_f} = \frac{\Lambda v_f^2 t_s}{2\rho_f}, \tag{8}$$

where p_f''' and p_j''' are heating rate per unit volume (or heat genration intensity) in the fibers of each conductive strip and at each the junction of prepreg strips.

For small time scales, the measured rate of temperature change is a good approximation of the heating intensity of each element shown in equation (8). The heat loss due to heat dissipation into air and the laminate is assumed to be negligible in short time scale in the experiment of present study. Also, it is assumed that the volumetric heat capacity (ρC_p) is constant in each element. Therefore, temperature change rate at each strip or each junction can be approximated as in equation (9)

$$\frac{\Delta T}{\Delta t} \approx \frac{p'''}{\rho C_p}. \tag{9}$$

Based on measured rates of temperature change in each element, contact resistance at the junction can be estimated from:

$$\Lambda \approx \left(\frac{2\rho_f}{v_f^2 t_s}\right)\frac{(\Delta T/\Delta t)_j}{(\Delta T/\Delta t)_f}. \tag{10}$$

4. RESULTS AND DISCUSSION

The material for the strip heating test was AS-4/PEI carbon thermoplastic prepreg from Cytec Fiberite, with fiber volume fraction of 60%. Table 1 list the relevant process parameters and material properties used in the study.

A 2.5 kW Lepel induction unit was used to generate the alternating magnetic field. Strips of AS-4/PEI prepreg were vacuum-bagged on a non-conductive base plate and positioned near a pancake coil and heated at constant power levels. The strip configuration is shown in Fig. 4 and formed a [0/90°] loop. During the experiment, temperature at four junctions and four center positions of the composite strip were measured with an AGEMA Thermovision 900 Infrared camera. Figure 5 shows a typical heating pattern of the composite strip and J1-J4 and S1-S4 denote the positions where temperature was measured during the experiments.

Heating experiments were carried out at 3 different induction power levels and fixed loop size (4″ × 4″) of the composite strips. The temperature measured was

Table 1.
Process parameters and material properties for strip heating tests

Input parameter	Value
Coil frequency (f)	2.38 MHz
Inner/outer diameter of coil	6.35 cm (2.5″), 2.54 cm (1.0″)
Coil-part distance	3.81 cm (1.5″)
Number of turns (N)	3
Fiber diameter of AS-4 (d_f)	8 μm
Fiber resistivity ofAS-4 (ρ_f)	0.00153 Ω-cm
Thickness of AS-4/PEI prepreg (t_s)	127 μm (5 mil)
Width of composite strip (w_s)	3.175 mm (0.125″)
Length of composite strip (l)	101.6 mm (4.0″)
Fiber volume fraction of prepreg (v_f)	0.6

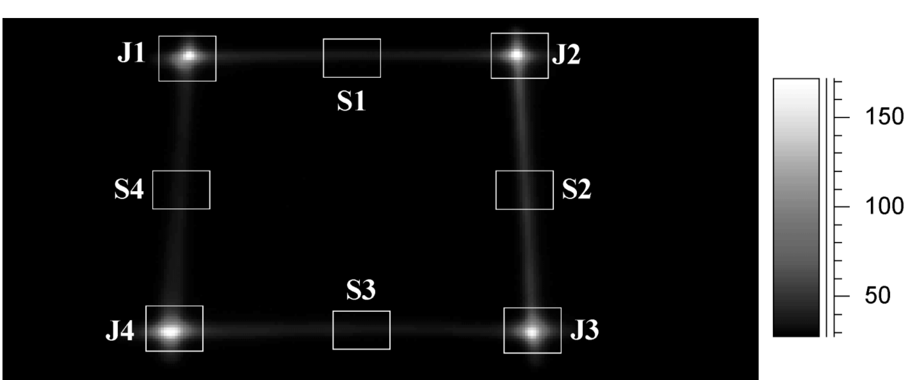

Figure 5. Typical heating pattern of composite strip and the measuring positions for temperature.

averaged and Fig. 5 shows the plot of the temperature change with time. In all the tests, the maximum heating temperature was maintained below T_g of PEI.

Figure 6 reiterates the dominance of junction heating for unconsolidated prepreg stacks. The time scales are short to minimize heat losses due to conduction, convection or radiation for calculation of heat generated in each element. The ratio of heating rates between the junction and the strip is approximately an order of magnitude and the deviation is reasonably small. Table 2 shows the ratios between junction heating and strips heating for different power levels. Based on the ratios in Table 2, the junction contact resistance Λ, can be calculated as

$$R_j = \Lambda \approx \left(\frac{2\rho_f}{v_f^2 t_s}\right)\left[\frac{(\Delta T/\Delta t)_j}{(\Delta T/\Delta t)_f}\right]_{averaged} = \left(\frac{2 \times 1.53 \times 10^{-5}}{0.36 \times 127 \times 10^{-6}}\right) \times 15.5 = 10.37\ (\Omega). \tag{11}$$

The above value is for vacuum pressure and AS-4/PEI, with temperatures maintained below 190°C (T_g of PEI). For temperatures over 190°C, there is development of intimate contact and decrease in contact resistance is expected.

Table 2.
Ratio of temperature change rate between the junction and strip with three different power levels of induction unit

Time (s)	$(P_I)_1$	$(P_I)_2$	$(P_I)_3$
1	$\frac{(\Delta T/\Delta t)_j}{(\Delta T/\Delta t)_f} = 14.0$	$\frac{(\Delta T/\Delta t)_j}{(\Delta T/\Delta t)_f} = 18.2$	$\frac{(\Delta T/\Delta t)_j}{(\Delta T/\Delta t)_f} = 14.2$
2	$\frac{(\Delta T/\Delta t)_j}{(\Delta T/\Delta t)_f} = 11.0$	$\frac{(\Delta T/\Delta t)_j}{(\Delta T/\Delta t)_f} = 14.9$	$\frac{(\Delta T/\Delta t)_j}{(\Delta T/\Delta t)_f} = 12.1$

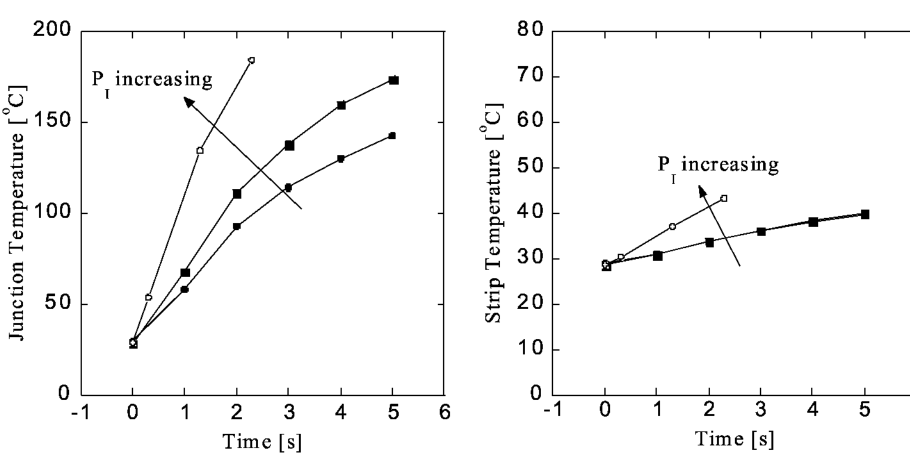

Figure 6. Temperature change at the junction and center of the strip with time.

Work is in progress to estimate Λ for other conditions and prepregs (surface roughness variation). The estimated contact resistance serves as input for the heating model of the system.

5. CONCLUSIONS

An experimental methodology has been outlined for the measurement of contact resistance between adjacent plies in a carbon thermoplastic prepreg stack. Contact resistance heating has been shown to be the dominant heating mechanism in induction heating of unconsolidated prepreg stacks. Measured values serve as input to induction heating models for simulation of heating mechanisms during induction processing of carbon thermoplastics. Work is in progress to study the influence of process parameters such as, temperature (above polymer T_g), pressure and surface quality of prepreg.

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