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Utilization of Induction Bonding for Automated Fabrication of TIGR

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Executive Summary

Induction welding of titanium foil and honeycomb to graphite fiber prepreg was studied in the laboratory. The process was shown to have the potential for low cost fabrication of aircraft structure at commercial production rates.

The bench-scale experiments demonstrated that:

- With the toroid magnet configuration operated at 1.25 kW, good weld bonds are obtained with heating times of a few seconds.
- At 80 kHz, the process relies on magnetic susceptor heating of titanium, not on high frequency heating of the graphite fiber.
- As many as five plies of prepreg may be effectively heated by a single ply of titanium.
- Both PIXA thermoplastic and PETI-5 thermoset tape could be bonded. The PETI-5 was about 40% cured during welding and may be strong enough to be removed from the tool for post cure
- Even without the use of adhesive film, weld strengths to Ti honeycomb were 30 percent of those to foil.

An induction heater for use on the NASA ATP robot would be quite similar to the bench unit and would be assembled in-house at little cost. Preliminary design calculations are given, and no significant problems are anticipated. The unit would be capable of making both foil-tape and core-tape forms of TiGr in lay-ups currently being considered.

Once the placement process is demonstrated successfully on flat panels, cylinders 5 inches or 24 inches in diameter may be made for testing. This experience would provide valuable information about automated fabrication of TiGr composites.

1.0. Introduction

In conjunction with the research and development program at NASA LaRC on composite materials for aerospace applications, an experimental study was conducted using magnetic induction heating to bond titanium foil and graphite fiber reinforced prepreg tape, a combination known as TiGr. It is made with the polymers PETI-5 and PIXA. The objective of this study was to explore the possibility of developing an induction heater for use in ply bonding during the automated fabrication of structural parts made from this hybrid foil-tape material form.

Using magnetic induction heating as a means of bonding thermoplastic composites has been the subject of a number of investigations (1, 2, 3, 4). The initial research drew upon existing metallurgical methods for induction heating (5), and the composite specimens were either placed in the magnet coil, or heated using a pancake-type flattened coil. A different approach was taken at NASA LaRC, where the specimens were placed across the gap of a modified toroid, or U shaped, magnet (3, 6, 7).

Most investigations of the induction bonding of composites have utilized a metal susceptor (screen) at the bondline to pick up the magnetic energy and do the heating (8). The susceptor remains in the part seam. Studies at the University of Delaware (9) and at Stanford University (10, 11) have explored the possibility of heating the graphite fibers in the composite by magnetic induction without a metal susceptor. Frequencies of 200 to 500 kHz were found to heat composite panels to 300℃ in 15 to 30 minutes. Models of the process are based on resistance heating for current flow along the fibers and dielectric heating for current flow across the fibers and the resin gaps between them, figure 1.1.

Prior induction bonding work at NASA LaRC (3) has dealt with joining carbon fiber composite specimens to titanium in lap shear test coupons. Toroid magnet power input frequencies were between 10

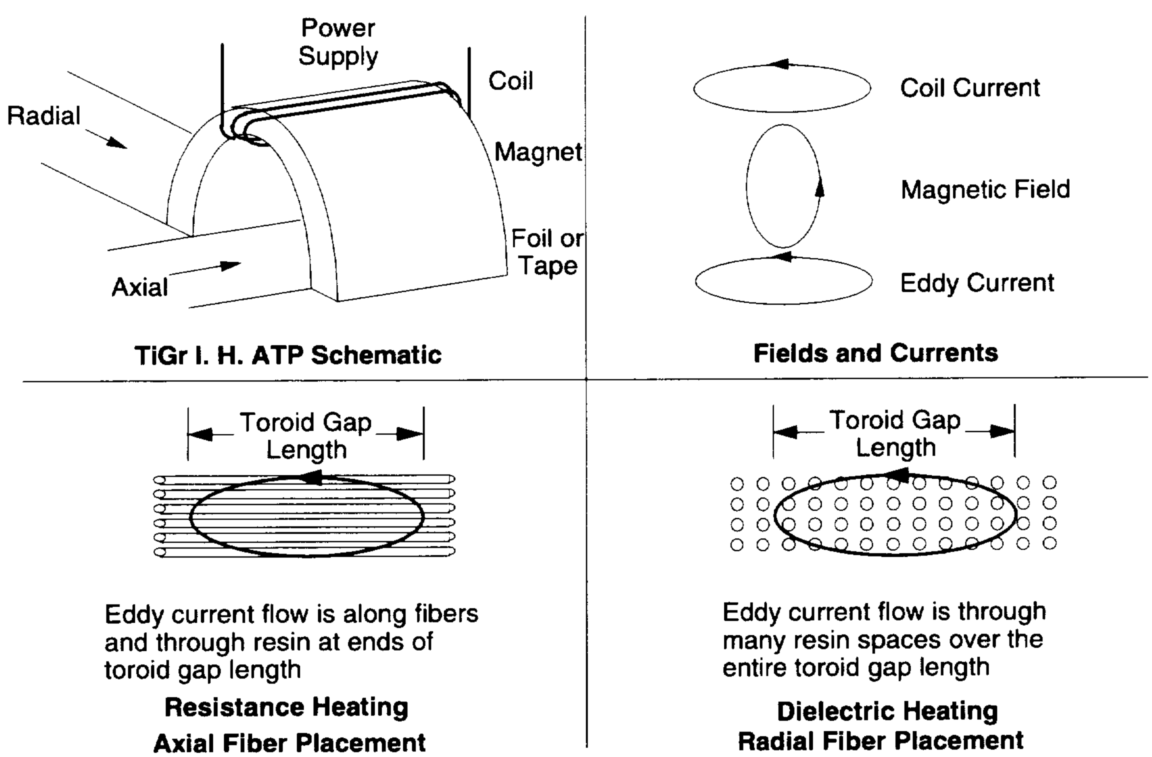

Figure 1.1. Induction Heating Model.

and 20 kHz. For the 0.125-cm (0.050 inches) thick titanium coupons, the heating time needed to achieve good bonding ranged from 0.25 to 5 minutes depending on the composite specimen thickness. NASA also investigated the use of a moving toroid unit to do composite bondline welding for part fabrication. Linear weld rates of 1.25cm per minute, or less, produced acceptable weld-bonded composites. This rate is too slow for commercial applications.

For the planned TiGr lay-ups, there will be several plies of tape between single plies of foil. For the honeycomb sandwich structures the prepreg tape serves as skins. The titanium foil/core susceptor, remains in the TiGr structure and contributes to its mechanical and electrical properties.

Cost studies suggest that for automated manufacturing of TiGr the linear placement rate must be greater than 2.5 cm per second. This is a hundred-fold increase over the rates achieved earlier. Furthermore, because there are several prepreg plies between titanium foils in some of the TiGr lay-ups, heat from the foil must be conducted to the bonding interface rapidly enough to meet the 2.5 cm per second rate requirement without causing thermal damage to tape in contact with the foil. These are the two key issues addressed in this study.

2.0. Bonding Of Pixa Tape And Ti Foil

2.1. Introduction

Prepreg tape made from the thermoplastic PIXA was used in a series of induction bonding experiments. This initial effort provided the groundwork for design of the induction heater and test procedures. It also gave TiGr bond strength data and information needed for fabricating a heater for the NASA robot.

2.2. Experimental

2.2.1. Materials

Titanium foil, Ti-15-3-3-3, 0.0125 cm (0.005 inches) thick was provided by the Boeing Company. The titanium surface was heat aged for 8 hours at 540°C, sol-gel surface treated and baked at 125°C for 30 minutes, after which it was primed with BRX-5 lot 184 polyimide. The 0.0125-cm thick composite tape was made from PIXA thermoplastic polyimide resin (Mitsui Toatsu) powder-coated onto IM-7 fibers (Hercules). The towpreg was consolidated by the method of Belvin et al (12). The Tg of the tape was 252°C. The fully consolidated prepreg tape was dried in a vacuum oven for 14 hours at 200°C to remove water. The material was then cut into 5.08 cm by 5.08-cm (2" by 2") specimens for testing.

2.2.2. Equipment

The induction-heating unit consisted of an RF power supply, a tank circuit and a modified toroid as the magnet pole piece, figure 2.1. The 5.08-cm long, 5.08-cm external diameter toroid magnet had a 2.54-cm wide gap and was made by joining a series of toroid segments pressed from high volume resistivity ferrite powder. A smooth ceramic insert was placed inside the toroid core to allow for even pressure distribution along the specimen.

Two power supplies were used for the study. The initial tests were made with a unit built at NASA. A four-turn coil on the toroid magnet produced an output power of 0.5 kW at 60 kHz. Subsequent tests utilized a unit made by Lepel. With two coil turns it operated at 1.25 kW and 80 kHz and with a one turn coil gave 1.75 kW at 120 kHz.

The toroid was placed in a Carver press for the induction bonding tests, figures 2.2 and 2.3. Modifying the toroid as shown in the figures permits the even distribution of pressure along the specimen to be welded.

The bond strength was determined by wedge peel testing (13) using a Korros-Data tensile test frame. Figure 2.4 illustrates the wedge/peel test concept. A crosshead advance rate of 1.25-cm (0.5") per minute was used during the bond strength tests.

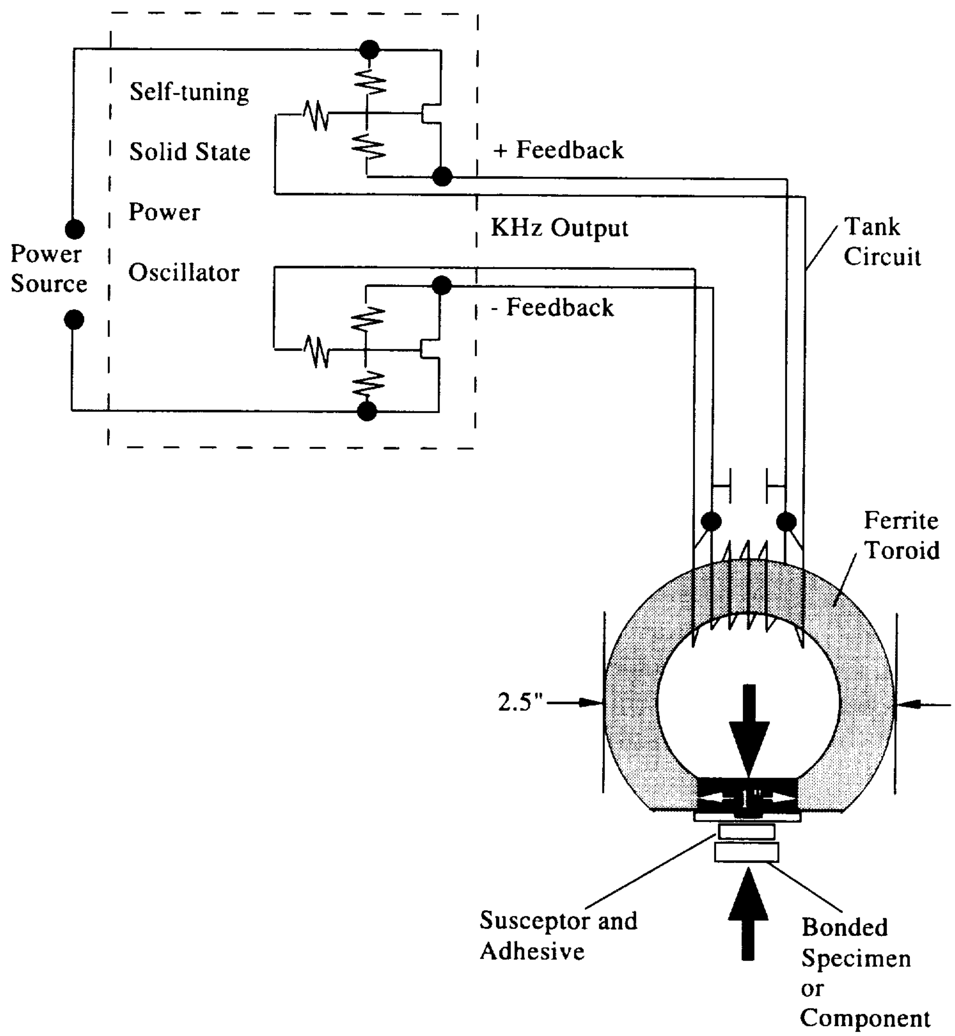

Figure 2.1. Induction Heating Schematic.

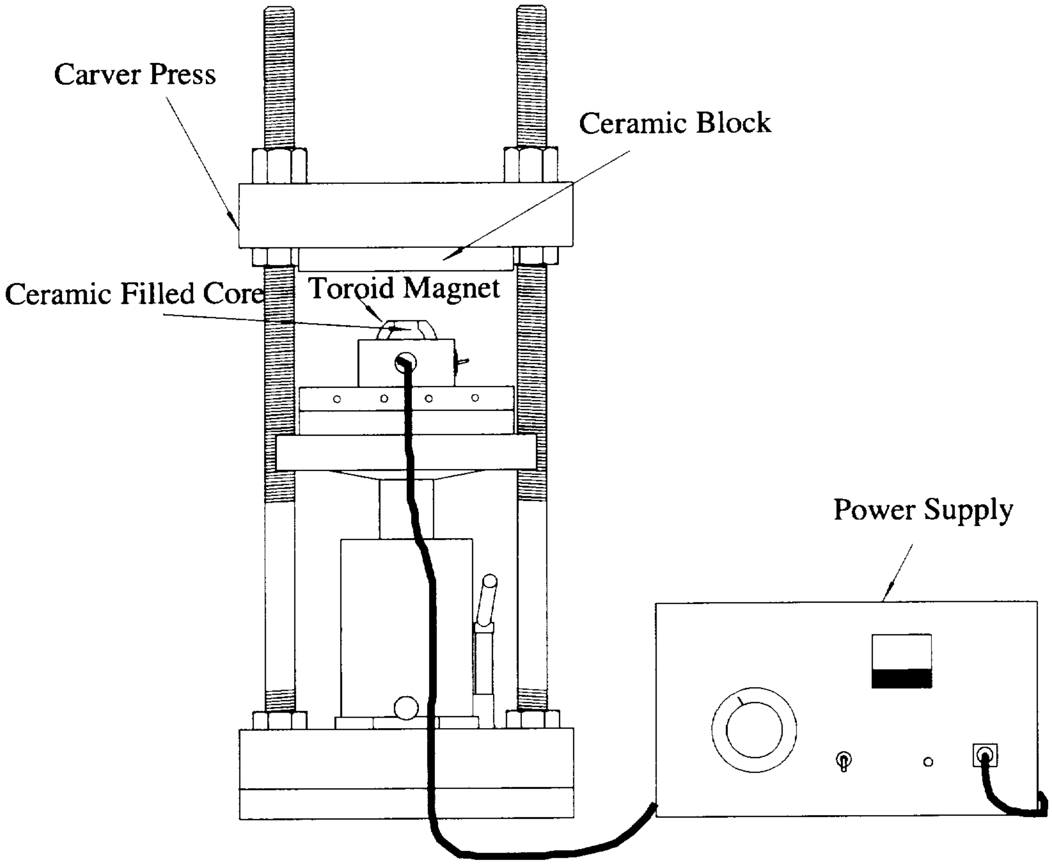

Figure 2.2. Laboratory Experimental Set Up.

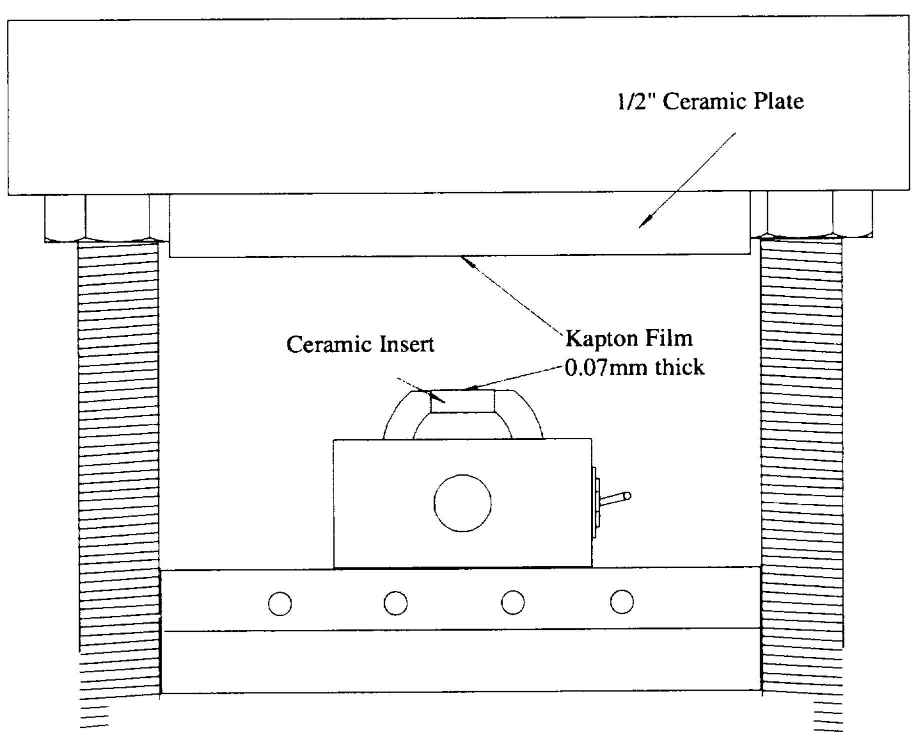

Figure 2.3. Toroid and Press.

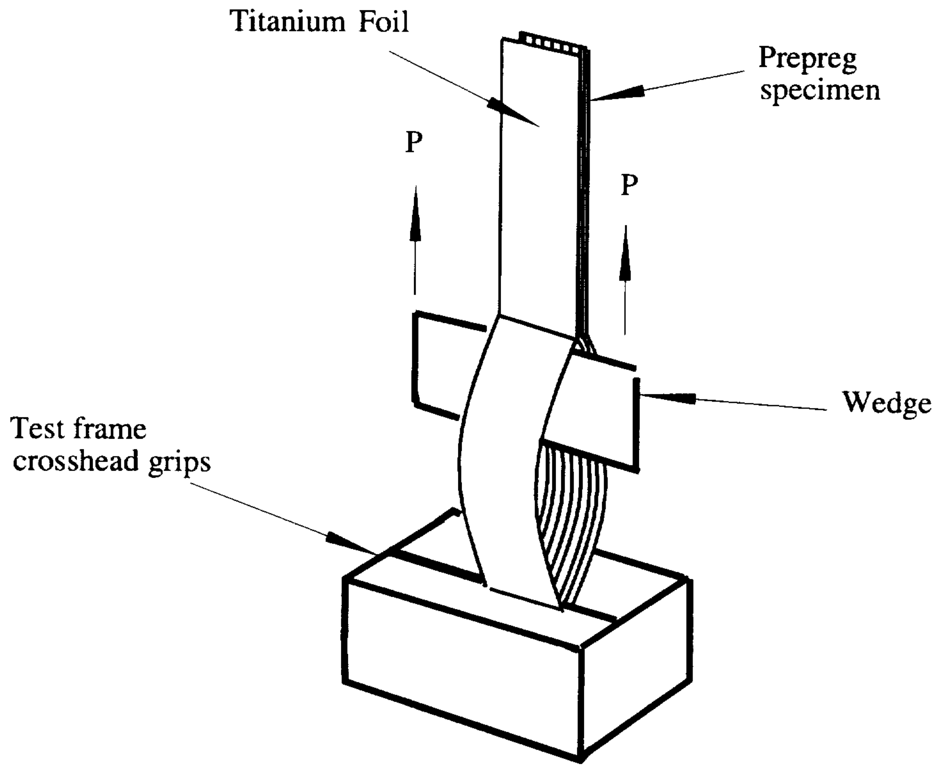

Figure 2.4. Wedge Peel Test.

2.2.3. Induction Heating of Ti Foil

A series of foil heating tests were performed using the 0.5kW NASA power supply. With the 4-turn coil, the tank circuit resonant frequency was ~60kHz as determined by an impedance/gain-phase analyzer.

The initial focus of the preliminary experiments was to determine the parameters that would govern the bonding of carbon fiber reinforced composites to titanium foil.

Length Variation Study - Temperature profiles for three different sample lengths of 2.54, 3.81 and 5.08 cm (1.0, 1.5 and 2.0 inches) were recorded using a K-type thermocouple (TC) fixed to the top-center of the foil specimen. The width of the specimen was fixed at 2.54 cm. Temperature readings, at full power, were taken every minute for ten minutes.

Width Variation Study - The procedure used for this study is similar to the length variation study with the exception that the sample widths were 2.54, 3.81 or 5.08 cm (1.0, 1.5, and 2.0 inches) while the length remained fixed at 5.08 cm. Temperature readings were recorded every minute for ten minutes.

Temperature Variation Study - To determine the temperature variation over the surface of the specimen, a 5.08 cm by 2.54 cm (2" by 1") sample was prepared with three TCs placed as shown in figure 2.5. One was located in the center of the foil (a), one in the center radial edge (b), and one at the mid-point along the axial edge of the foil-magnet contact (c).

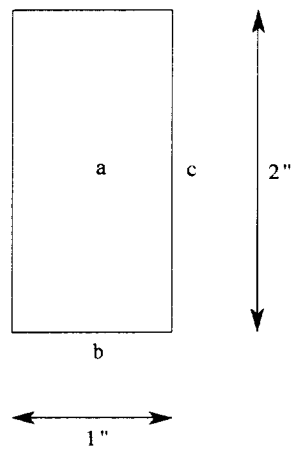

Figure 2.5. Thermocouple Locations on Specimen.

Gap Variation Study - For determining the effect of the toroid gap width, pressed linear-ferrite shunts were placed against the pole ends to narrow the gap from one inch to smaller gap widths. Temperature profiles were recorded at the center of the foil for gap widths of 1.27, 1.91 and 2.54 cm (0.5, 0.75 and 1.0 inches).

2.2.4. Foil-Tape Bonding

NASA Power Unit: Bond experiments were performed for differing weld times and varying lay-ups. A compaction pressure of 0.689 Mpa (100 psi) was applied to all welded specimens. From trial runs, it was determined that 15 seconds was the minimum "power-on" time required to produce a uniform bond. Using this time period as a basis, additional welds were made at 17, 19 and 21 seconds. The experimental lay-ups are shown in figure 2.6.

1. Titanium foil was placed directly against the toroid with prepreg tape on top of the foil. The fibers were directed axially with respect to the toroid.

2. Prepreg tape was placed directly against the toroid with the fibers oriented in the axial direction and the titanium foil was placed on top of the prepreg.

These same lay-ups were welded with prepreg fibers oriented in the radial direction.

Peel strengths for the induction heated TiGr welds were measured via the wedge/peel test. The peeled interfaces of selected specimens were examined via a Hitachi scanning electron microscope (SEM).

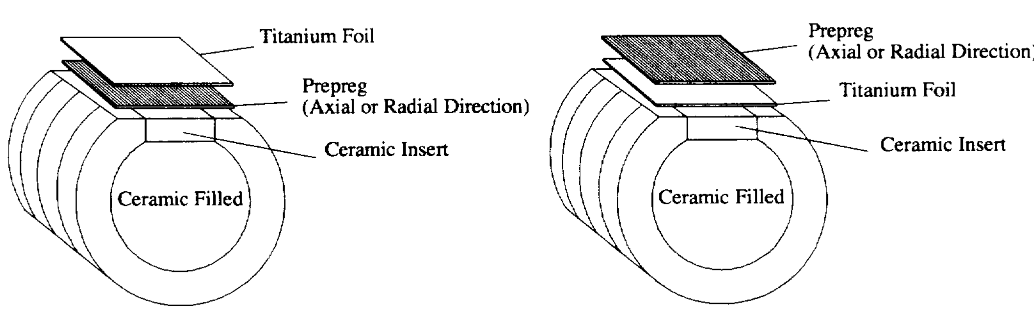

Figure 2.6. Foil-Tape Layups.

Lepel Power Unit: Studies were performed using double and single-turn water-cooled coils that gave frequencies of 80 and 120kHz and powers of 1.25 and 1.75kW respectively.

Weld Time Study - This study examined weld times of 3, 5, 10 and 15 seconds at an applied pressure of 0.345 MPa. Foil was placed against the toroid and prepreg tape placed on top of it with the fibers oriented either parallel to the toroid axis ("axial") or tangent to the toroid ("radial"). Wedge/peel tests were performed to determine the strengths of the welds.

Susceptor Distance - Samples with a thermocouple placed on the center of the foil were exposed to at least 70 second "power-on" times using the single turn coil (1.75 kW and 120 kHz). Layers of prepreg tape with 5.08 cm by 5.08 cm (2.0" by 2.0") dimensions with 0/90 ply orientation were used as shims between the foil and the toroid, figure 2.7. The experiments were repeated with two adjacent titanium plies.

2.3. Results and Discussion

2.3.1. Heating Rate Studies

Foil/Gap Geometry: The temperature variation study indicated that with no applied force the center of the foil reached 205°C in three minutes, while the axial and radial edges of the foil reached an average of 105°C in three minutes. Maximum temperature did not depend on specimen length. Narrower toroid gap widths gave higher foil temperatures for a given power input. Higher temperatures were obtained when the specimen overlapped the ends of the toroid.

Toroid-Foil Separation Study: The effect of distance between the foil and magnet toroid is presented in table 2.1. Heating intervals, figure 2.8, were extended until maximum temperatures of approximately 620°C were reached, where polymer degradation begins. With additional composite shims, the degradation temperature was never reached. In these cases, the maximum temperature was reported. Maximum temperatures decrease as the tape ply thickness between the foil and magnet toroid increases. To achieve bonding, the tape temperature has to reach 300°C or more. For automated placement, this should be achieved in six seconds or less. As indicated by figure 2.9, with a foil temperature of 600°C as many as 5 plies of prepreg can be placed between the magnet and a single ply of titanium foil.

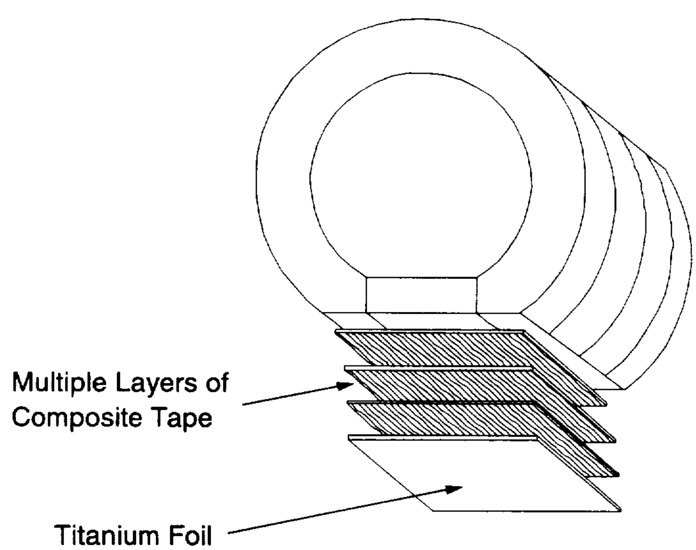

Figure 2.7. Susceptor distance study.

2.3.2. Heat Transfer Analysis

Using information from the induction heating bench tests, an analysis was made of the heat transfer rates and temperature profiles. This allows calculation of the ply-foil temperature differences and the energy utilization efficiency for the experimental setup. These in turn may be used in designing an IH heater for continuous placement of TiGr material.

Table 2.1. Effect of Toroid-Foil Separation

No. of Foil Layers	No. of Tape Plies	Total Thickness [mm]	Tmax [°C]
1	58	17.02	238
1	30	8.89	593
1	15	4.32	606
1	5	1.27	627
1	2	0.76	628
2	30	8.64	585
2	15	4.06	686

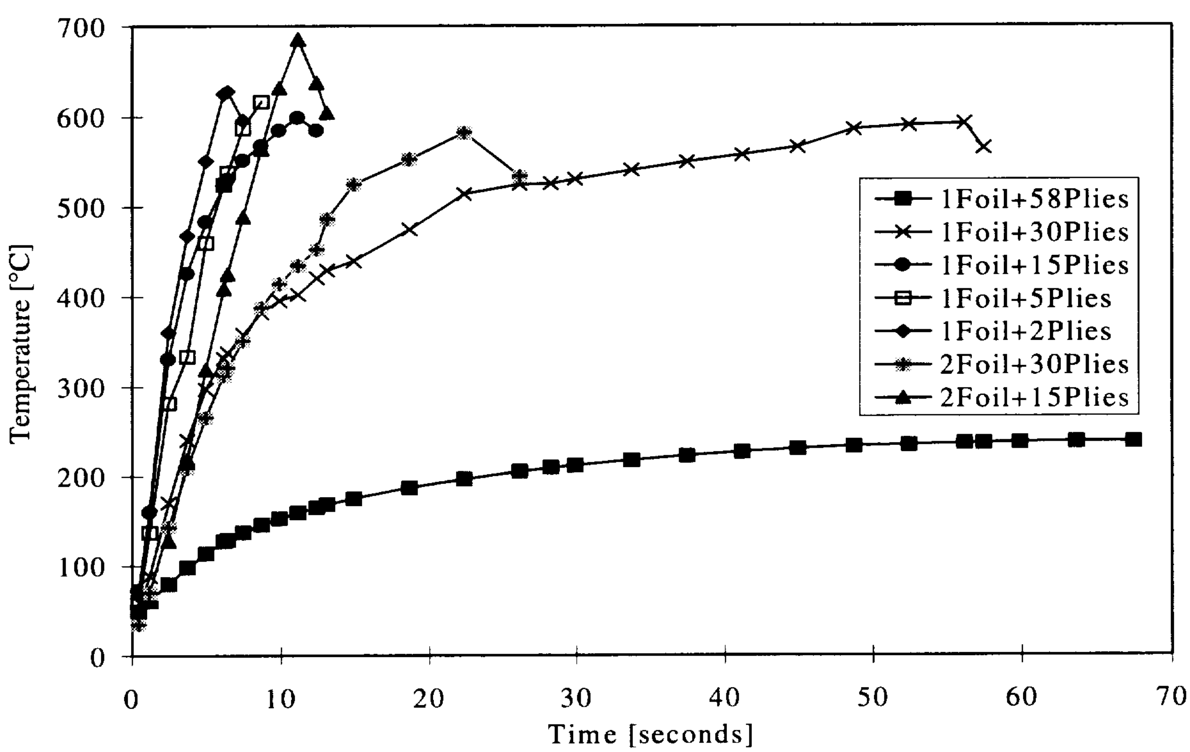

Figure 2.8. Foil temperature ramps for different ply thicknesses.

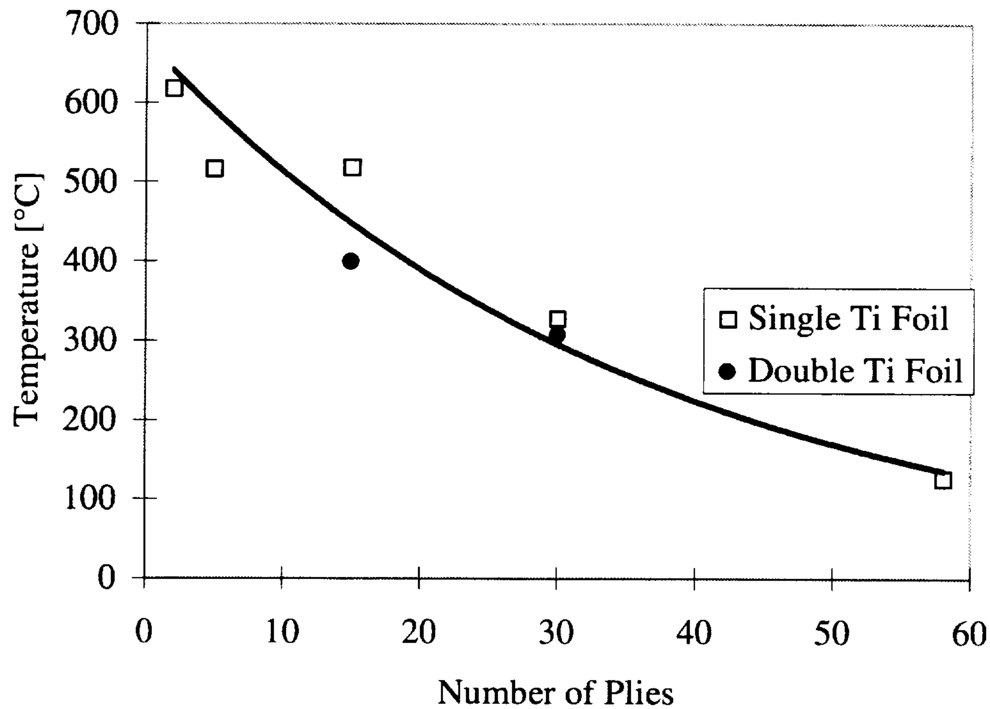

Figure 2.9. Foil temperature after six seconds as a function of number of prepreg plies between foil and magnet.

During the tests the titanium foil served as the susceptor and was heated by the magnetic eddy current. Heat was then transferred from the foil to the prepreg tape. Since the foil and tape width-to-thickness ratio is large, the problem may be formulated as one of unsteady heat conduction from a planar source (foil) into a solid (tape). For the analysis, two solutions to the second order conduction equation with constant surface flux were utilized: temperature profile in a semi-infinite solid (14) and temperature profile in a finite slab with insulated backing (15).

Considering the prepreg to be very thick, (semi-infinite) the temperature profile is:

$$U(x,t) = \frac{F_0}{K}\left[2\sqrt{\frac{kt}{\pi}}\, e^{\frac{-x^2}{4kt}} - x \operatorname{erfc}\left(\frac{x}{2\sqrt{kt}}\right)\right] \tag{1}$$

where: U is the temperature rise of the prepreg, x is the distance into the prepreg from the heat source, t is time, Fo is the heat flux, K and k are the thermal conductivity and thermal diffusivity through the thickness of the prepreg, and erfc is the complementary error function. When the prepreg is of finite thickness and is situated between the heating foil at x = l and the insulating ceramic plate at x = 0, the solution is:

$$\frac{KU(x,t)}{F_0 l} - \frac{kt}{l^2} = \left\{\frac{3x^2 - l^2}{6l^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2} e^{\frac{-kn^2\pi^2 t}{l^2}} \cos\left(\frac{n\pi x}{l}\right)\right\} \tag{2}$$

This solution most closely represents the test arrangement and also would be applicable for the placement of the first few plies on a ceramic tool.

Since the thermal conductivity and diffusivity of PIXA/IM-7 tape were not available, the properties of APC-2 were used to analyze the data. The thermal properties (16) of APC-2 are:

$$K = 0.0072 \text{ Joules/cm}^2 \text{ sec and } k = 0.00324 \text{ cm}^2\text{/sec.}$$

Temperature Across Tape: With a prepreg tape thickness of 0.0127 cm (0.005 inches), the term $kt/l^2 = (0.00324)t/(0.0127)^2 = 20t$. Therefore, at time intervals of a second or more, the summation in equation 2 is essentially zero leaving

$$\frac{KU(x,t)}{F_0 l} - \frac{kt}{l^2} = \frac{3x^2 - l^2}{6l^2} \tag{3}$$

At the titanium-prepreg interface, x = l, and

$$\frac{KU(l,t)}{F_0 l} - \frac{kt}{l^2} = \frac{1}{3}$$

At the prepreg-ceramic plate interface, x = 0, and

$$\frac{KU(0,t)}{F_0 l} - \frac{kt}{l^2} = -\frac{1}{6}$$

The temperature difference across the prepreg tape is

$$U(l,t) - U(0,t) = \frac{1}{2}\left(\frac{F_0 l}{K}\right) \tag{4}$$

This relationship indicates that the thin tape heats up with a constant temperature difference across its depth, figure 2.10. For the Lepel unit at 1.25 kW, if all the input energy goes into heating the foil, then Fo = 50 Joules/cm^{2}sec and the calculated temperature difference across the tape is 43°C. At a power level of 1.75 kW the difference would be 61°C. As shown below only a portion of the magnet input energy is utilized for induction heating, so the actual temperature differences would be lower.

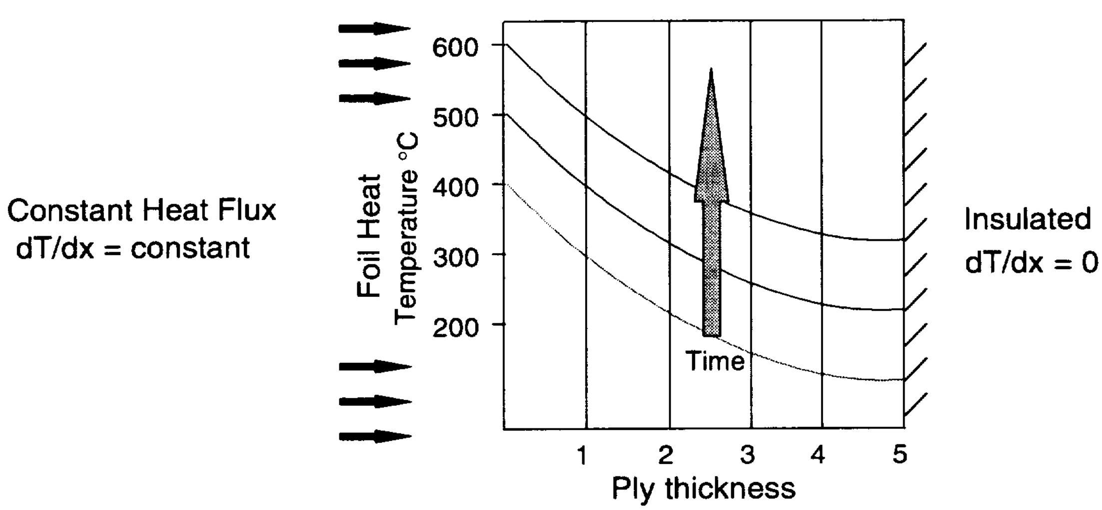

Figure 2.10. Temperature difference through the ply.

Energy Utilization: For thick part or short times, when the heat does not penetrate through the prepreg during the heating interval, or when the tooling has the same thermal properties as the prepreg, equation 1 may be used. This relationship was used to further examine the heat flux and temperature profiles.

At the foil-tape interface, x = 0, and equation 1 becomes

$$KU(0,t) = \frac{2F_0}{K}\sqrt{\frac{kt}{\pi}} \tag{5}$$

Equation 5 was used to calculate the heat flux implied by a temperature rise from 25°C to 380°C in 6 seconds at the foil-tape interface. The corresponding heat flux is 16.2 Joules/cm^{2}sec, which amounts to one-third to one-fourth the power delivered by the Lepel unit.

Equation 1 was then used to calculate ply interface temperatures at power levels that would raise the foil-tape temperature to 380°C in 3 and 6 seconds with an energy utilization efficiency of 33% . (table 2.2)

Table 2.2. Temperature Gradients Assuming 1/3 Power Utilization

Power [kW]	On-time [seconds]	Temperature [°C]		
		Foil-Tape 1	Tape 1-Tape 2	Tape 2-Tape3
1.75	3	380	340	301
1.25	6	380	351	324

These calculations also indicate that there is a 30 to 40°C temperature difference across the tapes.

2.3.4. Foil -Tape Bonding Studies

For all the tests, the weld/bond area corresponded to the toroid gap area, i.e. the wider the gap the larger the bond area. The wedge/peel test was used to determine the peel strength of the titanium/prepreg bond specimens. All specimens were peeled in the fiber direction. The data are presented in table 2.3.

With the NASA unit, the higher strengths were obtained with the foil on the magnet. Axial prepreg placement gave better heating and higher strengths.

Table 2.3. Foil-Tape Bond Strength

NASA Power Unit: 0.5kW, 60kHz; and 0.689MPa						
			Peel Strength [kN/m]			
			Range		Average	
Time [seconds]	Tmax [°C] axial/radial	Ti Placement	Axial	Radial	Axial	Radial
15	-/-	Down	-	-	0.30	0.10
15	-/-	Up	-	-	0.20	0.07
17	-/-	Down	-	-	0.25	0.10
17	-/-	Up	-	-	0.25	0.08
19	-/	Down	-	-	0.33	0.10
19	-/-	Up	-	-	0.20	0.06
21	-/-	Down	-	-	0.25	0.10
21	-/-	Up	-	-	0.18	0.07

- No thermocouples used.

Table 2.3. Continued

Time [seconds]	Tmax [°C] axial/radial	Ti Placement	Peel Strength [kN/m] Range Axial	Range Radial	Average Axial	Average Radial
Lepel Power Unit: 1.25kW, 80kHz; and 0.345MPa						
5	374/351	Down	0.00-0.90	0.00-1.16	0.62	0.37
10	528/523	Down	0.88-1.77	0.77-1.22	1.22	0.93
10	632/616	Down	0.97-1.58	1.18-2.21	1.40	1.58
15	591/576	Down	0.53-1.46	0.60-1.76	1.22	1.00
15	630/577	Down	0.85-1.75	0.53-2.35	1.40	1.25
15	-/-	Down	0.61-2.04	0.50-2.44	1.25	1.23
15	-/784	Down	0.41-0.83	0.17-0.56	0.55	0.33
Lepel Power Unit: 1.75kW, 120kHz; and 0.345MPa						
2	152/242	Down	0.00-0.83	0.11-0.15	0.32	0.12
3	-/378	Down	0.26-0.57	0.39-0.64	0.47	0.50
5	-/-	Down	0.30-0.57	0.28-0.53	0.41	0.44
5	269/357	Down	0.40-0.79	-	0.67	-
10	630/473	Down	0.42-1.33	0.00-0.10	0.71	0.04
10	771/669	Down	0.87-1.43	0.34-0.55	1.04	0.47
15	853/-	Down	0.16-0.71	0.00-0.12	0.46	0.01
Lepel Power Unit: 1.75kW, 120kHz; and 0.689MPa						
5	438/-	Down	0.33-0.85	-	0.49	-
5	397/-	Down	0.19-0.39	-	0.29	-
10	472/-	Down	0.59-0.80	-	0.70	-
10	546/-	Down	0.42-0.92	-	0.59	-
Lepel Power Unit: 1.75kW, 120kHz; and 1.379MPa						
5	280/-	Down	0.15-0.47	-	0.32	-
5	386/-	Down	0.18-0.56	-	0.39	-
10	550/-	Down	0.40-0.61	-	0.54	-
10	525/-	Down	0.18-0.73	-	0.55	-

With the Lepel unit at 80kHz, overall radial bond strengths are only slightly lower than axial. This corresponds to their lower maximum temperatures. Heating times less than 10 seconds gave poor bonds. At 120kHz, the bond strengths were generally lower, with the highest bonding at 5 to 10 seconds. A 15-second weld thermally damaged the resin.

The peel strength data in table 2.3 show significant scatter. However, the general effect of power level and frequency can be obtained by examining the average peel strengths over the time intervals that produced measurable welds (table 2.4). The highest average peel strengths were obtained at 1.25kW and 80kHz with 0.345MPa. These bond strengths were obtained for heating times of 10 seconds (table 2.3).

SEM Peel Surfaces: SEM photomicrographs were taken to examine the effects of pressure and temperature on wetting of the foil by the composite matrix resin. Samples with high and low peel strengths were examined. The TiGr sample with the high bond strength was welded at 10 seconds and a maximum temperature of 616°C while the low strength specimen had a weld time of 15 seconds and an approximate maximum temperature of 850°C. Compaction pressure for both samples was 0.345Mpa (50psi).

Figure 2.11, which had a peak ramp temperature of 616°C, shows approximately 60% of the fracture surface was in contact with the foil. For short heating times the resin did not flow and at long heating times the resin was thermally damaged. Good wetting and maximum peel strengths were achieved at temperatures in the 600°C region. This corresponds to weld times of 5 to 10 seconds. In contrast, figure 2.12 is a photo of the low peel strength specimen and shows little resin on the fibers. The polymer in the specimen degraded as a result of extremely high temperatures, over 800°C.

Additional welds were performed at pressures of 0.689Mpa and 1.378Mpa. SEM photos show that significantly more resin-to-titanium contact occurred as a result of higher pressures, but average peel strengths did not increase. This would suggest that cohesive failure occurs within the prepreg. Figures 2.13 and 2.14 are SEM photos of peel interfaces at 0.689Mpa and 1.378 Mpa, respectively.

Table 2.4. Power and Frequency Effect

Power	Frequency	Pressure	Averaging Time Interval	Peel Strength [kN/m]	
[kW]	[kHz]	[MPa]	[Seconds]	Axial	Radial
0.5	60	0.689	15-21	0.21 Up 0.28 Down	0.07 Up 0.10 Down
1.25	80	0.345	5-15	1.09	0.96
1.75	120	0.345	2-10	0.58	0.26
1.75	120	0.689	5-10	0.52	-
1.75	120	1.378	5-10	0.48	-

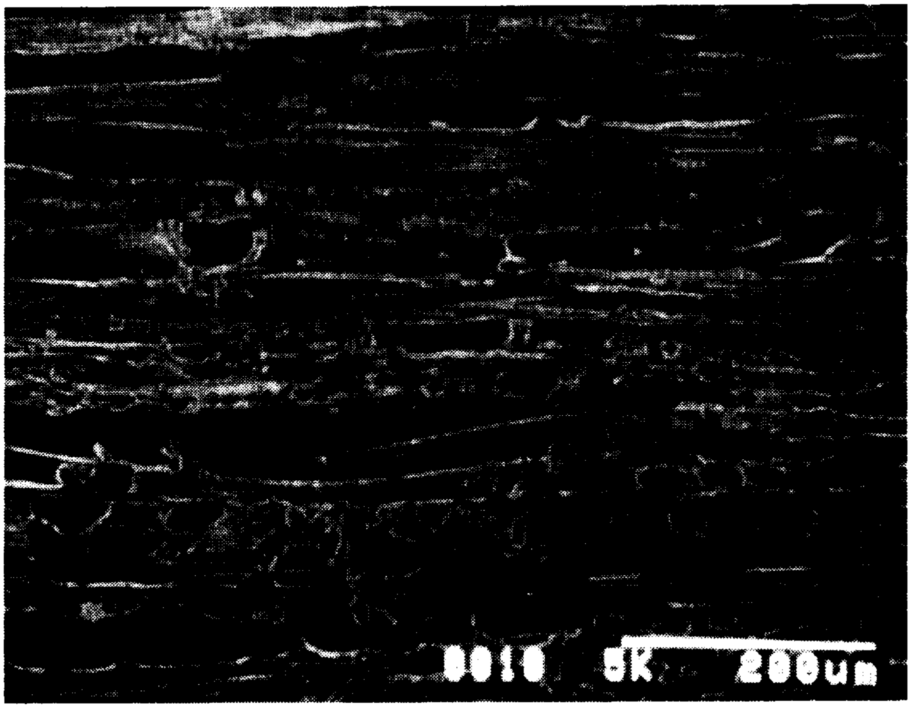

Figure 2.11. Surface Fracture of 10 second Weld at 1.25kW, 80kHz and 0.345Mpa.

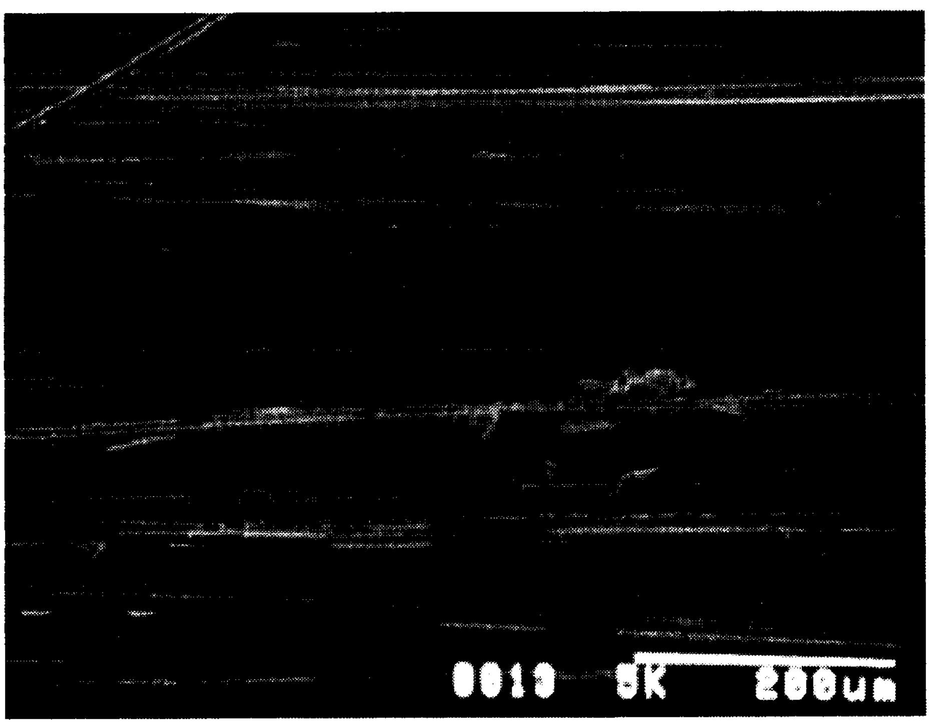

Figure 2.12. Surface Fracture of 15 second Weld at 1.75kW, 120kHz and 0.345MPa.

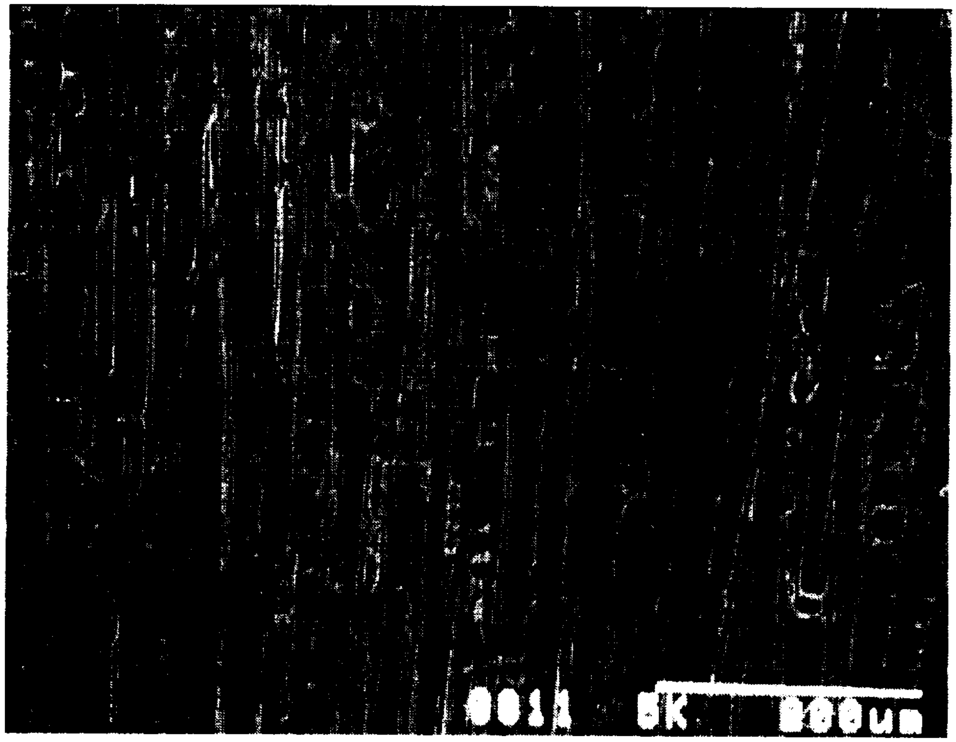

Figure 2.13. Surface Fracture of 10 second Weld at 1.25kW, 120kHz and 0.689Mpa.

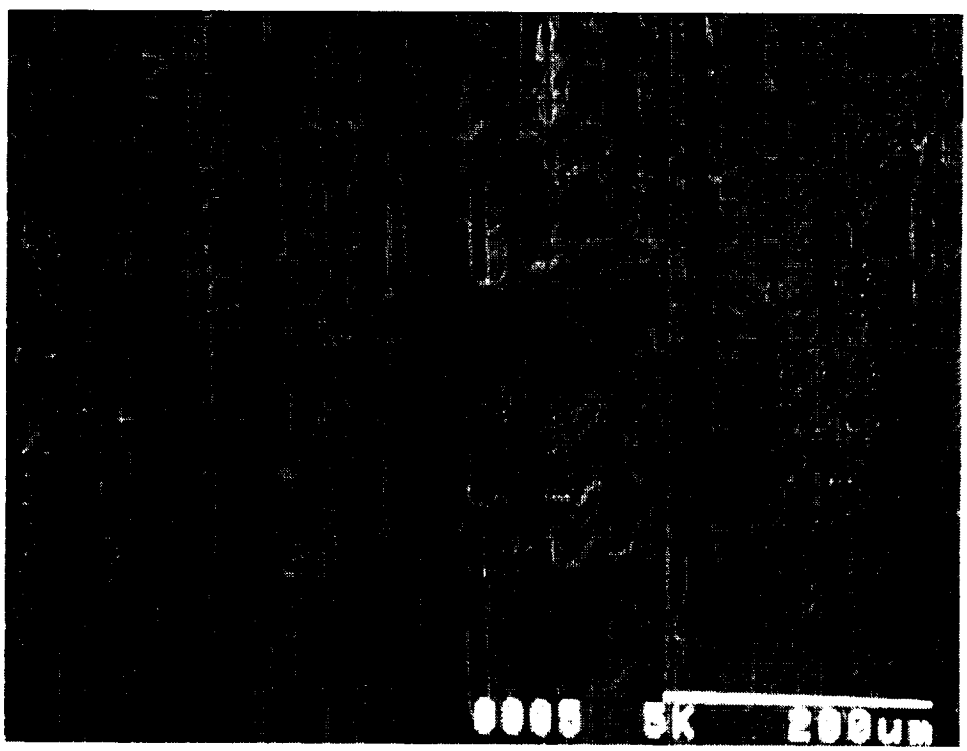

Figure 2.14. Surface Fracture of 10 second Weld at 1.25kW, 120kHz and 1.378Mpa.

2.4. Conclusions

The purpose of the study was to investigate induction heating as a method for ply-by-ply bonding of TiGr during the automated fabrication process. The study with PIXA tape was directed toward finding the conditions for achieving good bonding at heating times of 6 seconds or less as required for automated placement.

Peel strengths of foil-tape bonds depend on the maximum temperature reached during heating and on the applied pressure. Maximum peel strengths were achieved at 1.25kW and 80kHz. Induction heating of the foil appears to be capable of bonding up to 10 plies of tape. Heat transfer calculations indicate that there is a 30-40°C temperature difference through tape during heat-up.

For short heating times, the resin does not flow; at long heating times the resin is thermally damaged. Therefore, welding must be performed at temperatures and times between these limits. Good wetting and maximum peel strengths were obtained at foil temperatures in the 600°C region. This corresponds to weld times of 5 to 10 seconds. Additionally, increased pressures did not increase the average peel strength indicating cohesive failure within the prepreg. However, intimate contact between the resin and foil increased significantly.

Cost studies show that for gas heating to be efficient placement rates must be 1 inch per second or better. Peel tests show that 5-10 second heating times produce the best welds. An IH unit 5-10 inches in length would therefore be required. Such a design appears feasible.

Other findings showed that foil length had little contribution to the heat-up ramp and that foil heating was faster when the foil extended over the toroid ends. However, because of heat losses to the toroid, that portion of foil on the toroid ends heats slowly. The best heating occurs when the foil extends across the gap and the ends of the toroid. Furthermore, the elongated bond region was parallel with the toroid axial direction. To maximize the efficiency of the placement process, the material will be fed in the radial direction.

The results of the experiment revealed that for a given heating period, unidirectional tape with its fibers inline with the toroid axis had a bond strength slightly higher than tape with fibers aligned in the radial direction. These findings are consistent with the expectation that dielectric heating is significant only at frequencies above 100kHz. (9)

3.0. Bonding Of PETI-5 Prepreg Tape And Titanium Foil

3.1. Introduction

Hybrid structural laminates made of titanium foil and carbon fiber reinforced polymer composite offer a potential for improved performance in aircraft structural applications. PETI-5, a thermosetting polymer, has the properties required by the HSR Program, and is being made into prepreg tape. Because the automated process provides heating for only a few seconds, PETI-5 TiGr composites placed this way will require post cure.

3.2. Objectives

The objective of this study was to explore the possibility of using thermoset prepregs in the automated processing of TiGr and to answer the following questions.

- What degree of consolidation is achieved in several seconds using induction heating to bond titanium foil/thermoset tape?
- What is the Tg advancement (degree of cure) of the placed PETI-5?
- How do the TiGr bond strengths compare to those of PIXA?

3.3. Approach and Experimental

The bonding experiments with Ti and PETI-5 were similar to those with Ti and PIXA (section 2.0). Induction heating bond experiments using titanium foil/thermoset prepreg tape were conducted with magnet "power-on" times of 5, 7 and 10 seconds and a pressure of 0.689MPa. The tests were conducted with a single-turn coil that generated an output power of 1.75kW and a frequency of 120kHz. Additional IH bond experiments were performed with a 371°C hold for five minutes. A final test was conducted to determine the bond strength of a 10 second IH sample with a hot press post cure. Laminated specimens were peeled apart using the wedge/peel test followed by SEM observations of the peeled interface. The peel strength data for all PETI-5 TiGr welds were compared to PETI-5 TiGr laminates formed in a hot press. DSC tests were performed to determine Tg of the resin after the heating period.

3.4. Results and Discussions

Foil-Tape Bonding Studies: The wedge/peel test was used to determine the peel strength of the titanium/tape bond specimens. All specimens were peeled in the fiber direction. The data are presented in table 3.1.

The highest average bond strength was achieved with the IH specimens that maintained a 5-minute hold at 371°C. IH samples with weld times of 5, 7 and 10 seconds had substantially lower average peel strengths. Hot press post-cured IH specimens had average peel strengths comparable to those cured by induction for 300 seconds. For a comparison, a fully cured TiGr specimen was prepared by means of a hot press using the standard PETI-5 cure cycle at 0.689MPa. The average bond strength was 1.35 kN/m for the press sample.

Table 3.1: Foil-Tape Bond Strength

Time [seconds]	Tmax [°C]	Peel Strength [kN/m]	
		Range	Average
5	310	0.0757-0.1084	0.0897
5	352	0.0551-0.1153	0.0894
7	420	0.0664-0.1085	0.0910
7	412	0.0506-0.1319	0.1056
10	504	0.1116-0.4763	0.3366
10	519	0.1524-0.7870	0.4329
300	371	0.2783-1.6403	1.3371
300	371	0.1718-1.3979	1.3268
10*	609	0.3015-0.9980	0.9780
10*	576	0.3001-1.6334	1.4920

*One hour post cure at 371°C in a hot press.

SEM Peel Surfaces: SEM photomicrographs were taken to determine the amount of TiGr intimate contact. This provided a means of examining the effect of time/temperature on wetting and peel strength.

SEM photos were used to examine the PETI-5 peeled-tape samples at each time interval. At 5 seconds, figure 3.1, the amount of resin/foil contact was approximately 50-60%, which is comparable to the amount of wetting observed with PIXA. The figure reveals that the resin is brittle as noted by resin shear hackling (no resin drawing). Figure 3.2 is typical of a TiGr specimen welded at 7 seconds. The amount of wetting did not appear to increase, however the evidence of shear hackling was reduced and a more ductile appearance is observed in the matrix resin. At 10 seconds, figure 3.3, more intimate contact with the foil is evident, which explains the higher bond strengths.

Differential Scanning Calorimetry: Tg of the uncured PETI-5 tape prior to welding was 230°C as determined by a differential scanning calorimeter (DSC); fully-cured it is 265°C. DSCs were performed on the tape after each weld time. The degree of Tg advancement during processing is a measure of the degree of cure. In induction heating, the PETI-5 bonded at low weld times was partially cured. With a 10 second heating period, the Tg was 245°C suggesting about 40% cure. Specimens held at 371°C in the hot press or by induction heating achieved full or very near full cure.

Weld Time [seconds]	Tg [°C]	Δ 265-Tg [°C]
5	237	28
5	249	16
7	244	21
10	245	20

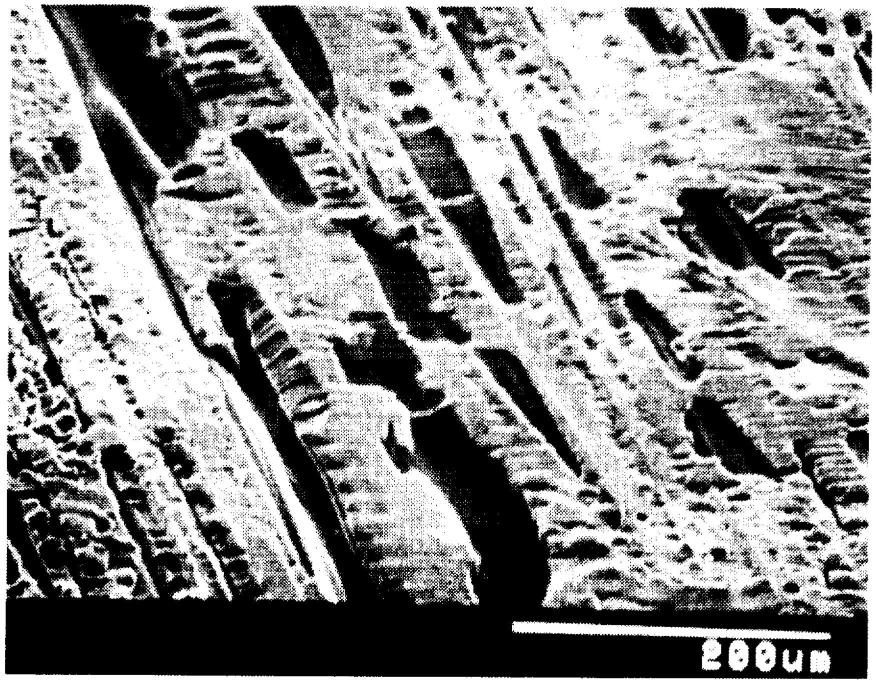

Figure 3.1. Surface Fracture of 5 second Weld at 1.75kW,120kHz and 0.689MPa.

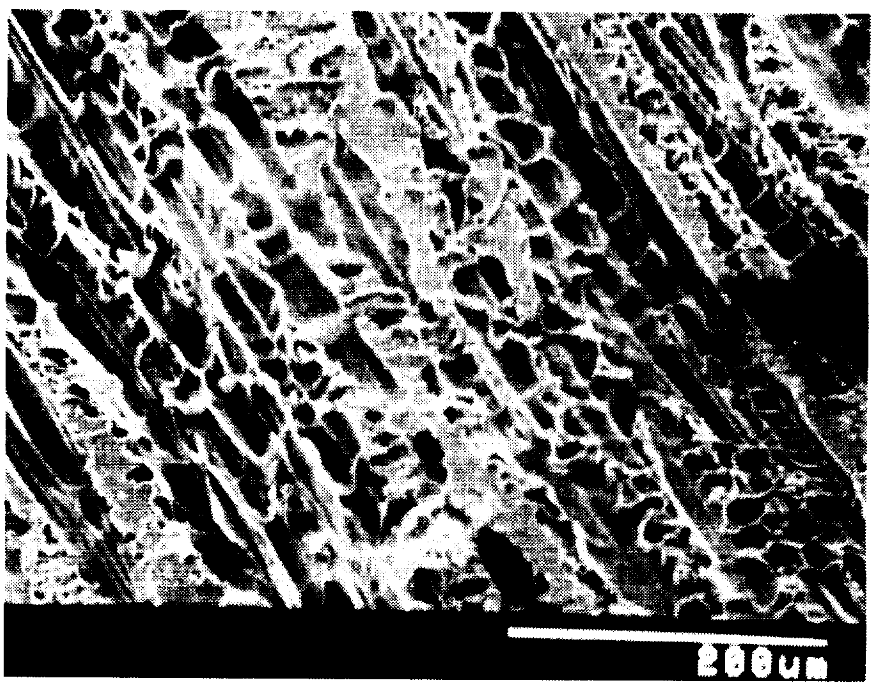

Figure 3.2. Surface Fracture of 7 second Weld at 1.75kW, 120kHz and 0.689Mpa.

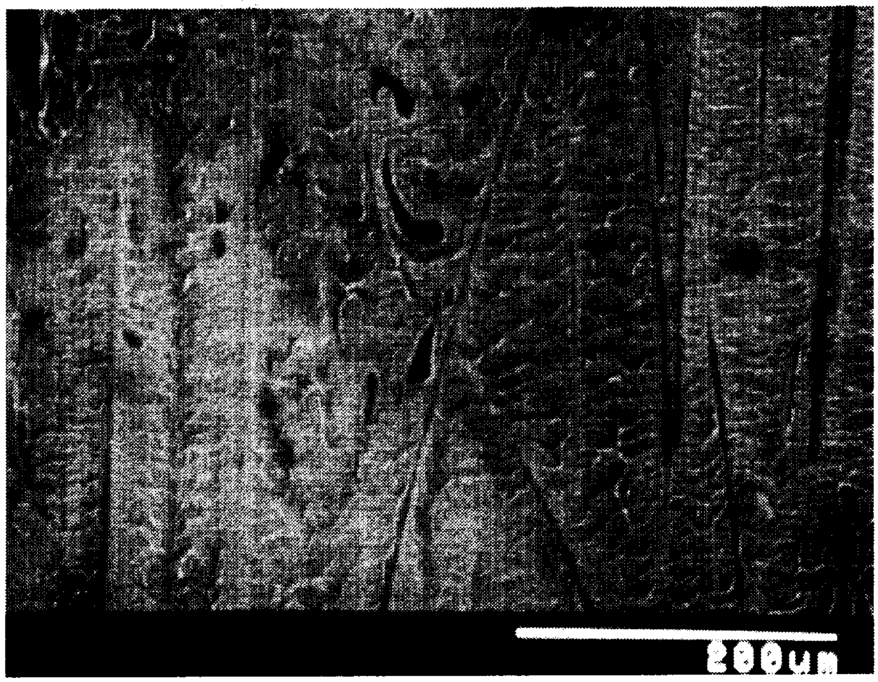

Figure 3.3. Surface Fracture of 10 second Weld at 1.75kW, 120kHz and 0.689Mpa.

3.5. Conclusions

The purpose of the study was to investigate induction heating as a viable method for ply-by-ply bonding of PETI-5 based TiGr during the automated fabrication process. The study was directed toward finding the amount of TiGr bonding achieved during short processing times.

PETI-5 tape to Ti bonds had peel strengths 40 to 75% lower than the PIXA tape gave. Photomicrographs of specimens with weld times between 5 and 10 seconds showed approximately 50-60% resin "wet-out" at 0.689 MPa (100 psi). Resin shear hackling observed in the SEM at low weld times implies low toughness. DSC data suggest that the PETI-5 advanced to about 40% cure during induction heating.

An important aspect of automated placement is to make the part in its final configuration. With thermosetting materials, depending on the part strength at a given degree of cure, the part may be strong enough to be removed from the tool and autoclaved. To avoid damage to a weak part, it may be necessary to place both the part and the tool into the autoclave.

4.0. Welding Ti Honeycomb To Pixa Tape

4.1. Introduction

Honeycomb core sandwich composites are used for aircraft structures and have proved to be durable and lightweight structural components for many aerospace applications. These sandwich composites consist of prepreg plies serving as skins on the honeycomb core.

As part of the High Speed Research Program, NASA and Boeing have made flat honeycomb TiGr composite test specimens at Cincinnati Milacron by automated tow placement. The layup used for placement has 2 plies of FMX-5 film adhesive on the Ti honeycomb. A Ti foil was then placed on the film adhesive and a PEEK film placed on it. A (3-6-2) TiGr laminate (ATP) was placed on this sandwich. This placement was done on both the top and bottom of the honeycomb.

4.2. Objectives

The objective of this study was to use induction heating as an option to gas heating for automated fabrication of honeycomb TiGr panels. An additional objective was to explore placement without the use of film layers between the prepreg tape and honeycomb core. Bonding of a composite consisting of titanium honeycomb between PIXA prepreg tape was investigated, figure 4.1.

4.3. Approach

The equipment and procedures used for the prepreg/foil bonding tests were also used in this investigation (section 2.2). Induction heating bond experiments using a one inch thick titanium honeycomb core and thermoplastic prepreg tape were conducted with weld durations of 10, 12 and 15 seconds. Laminated specimens were peeled apart using the wedge/peel test followed by SEM observations of the peeled interface. Additional studies were performed at varying pressures to explore the "dimple" effect.

The honeycomb core was sol-gel surfaced treated and primed with a 15% PIXA solution. Two methods were used to prime the honeycomb. In the first method, primer was painted or brushed onto the core then dried in an oven at 200°C for 2 hours. The second method incorporated a shallow pan technique in which the honeycomb core sat in a small layer of primer during the dry cycle. Further studies were conducted in which the honeycomb cells were filled with high temperature thermoplastic foam, UTK-EP-IAX.(17)

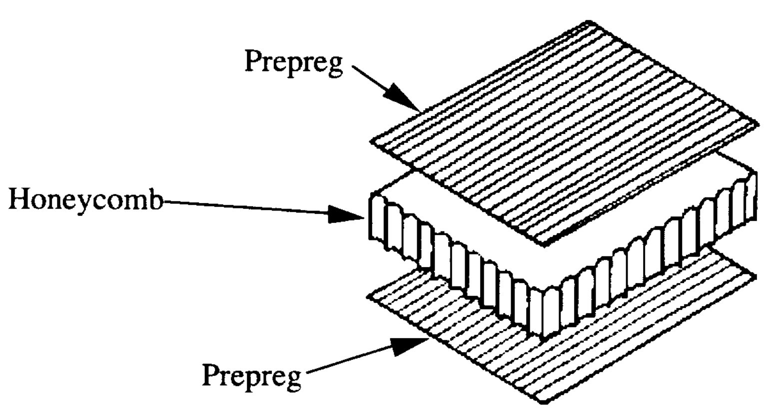

Figure 4.1. Honeycomb structure.

4.4. Experimental

The experimental procedure for bonding and peeling the honeycomb was similar to previous weld experiments. The honeycomb was surface-treated and primed using one of the two methods (brush or pan). The tests were conducted at an output power of 1.75 kW and a frequency of 120 kHz (section 2.2). Weld durations of 10, 12, and 15 seconds at a pressure of 0.689 MPa. Further tests were done at 15 seconds weld times and pressures of 0.172 and 0.345 MPa. Tests were done with a single prepreg ply against the toroid. Wedge peel tests were performed on welded specimens to determine the strength of the bond, figures 4.2a and 4.2b.

For the foam studies, approximately 2 grams of UTK-EP-IAX was distributed evenly throughout the cells of the 2-inch square, 1-inch thick core. The honeycomb core was then sandwiched between single plies of PIXA tape. Individual samples were placed in the IH press with a thermocouple attached to the specimen. The first sample was raised to 140°C and held there for approximately 2 minutes, then raised to 260°C and held for an additional two minutes. The second sample experienced approximately 30 seconds of heating at full power (1.75kW). Cross sectional areas of the specimens were observed and photographed to determine the magnitude of foaming.

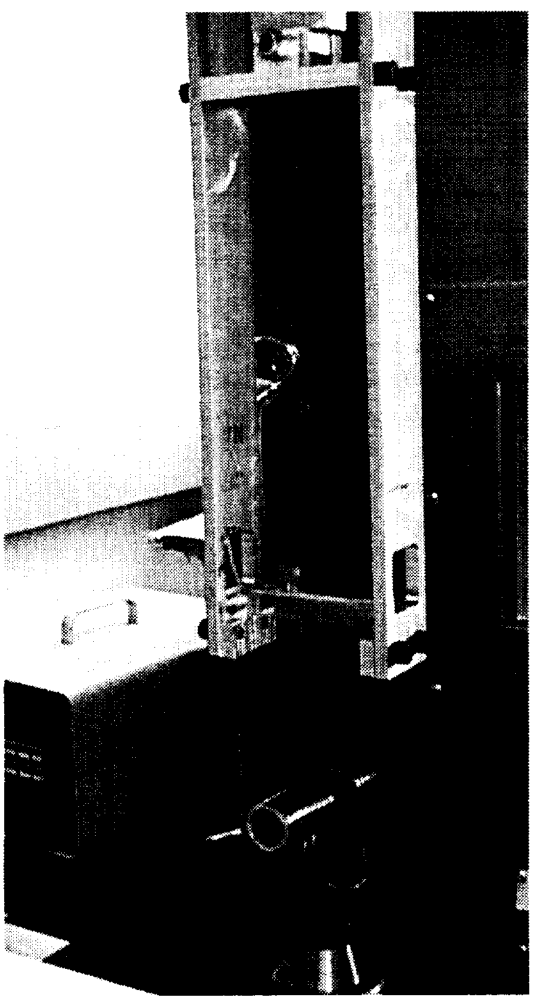

Figure 4.2a. Wedge/peel test hardware.

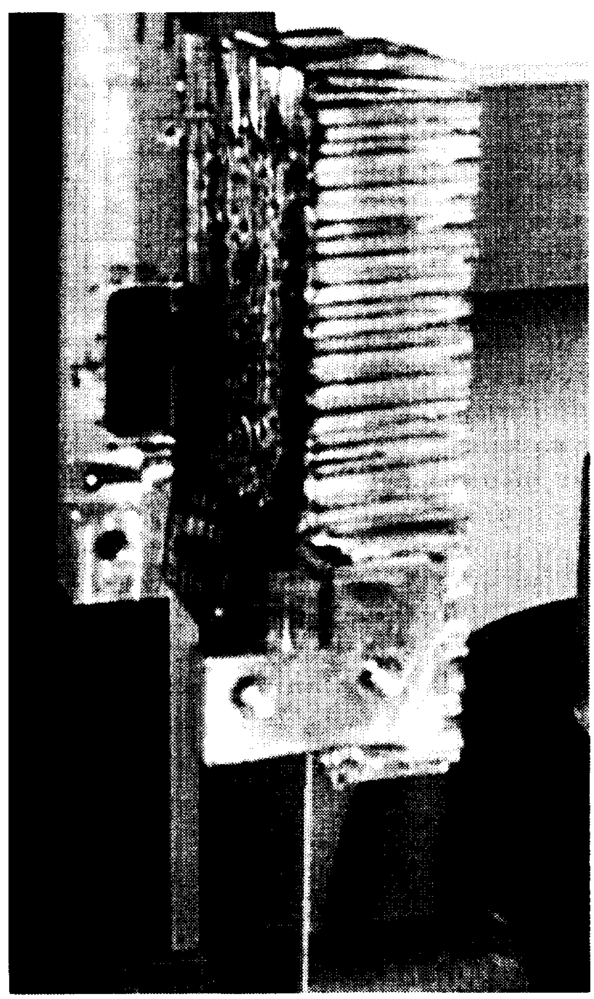

Figure 4.2b. Honeycomb peel.

4.5. Results and Discussion

The wedge/peel test was used to determine the peel strength of the honeycomb/prepreg bond specimens. All specimens were peeled in the fiber direction. The test data are presented in table 4.1.

Table 4.1. Honeycomb-Tape Bond Strength

Priming Method – Brush

Time [seconds]	Tmax [°C]	Pressure [MPa]	Peel Strength [kN/m]	
			Range	Average
10	231	0.689	0.006-0.013	0.008
10	219	0.689	0.016-0.027	0.019
12	231	0.689	0.032-0.039	0.034
12	314	0.689	0.033-0.123	0.078
15	347	0.689	0.084-0.446	0.270
15	357	0.689	0.168-0.600	0.403
Priming Method – Pan				
Time [seconds]	Tmax [°C]	Pressure [MPa]	Peel Strength [kN/m]	
			Range	Average
10	225	0.689	0.036-0.066	0.049
12	257	0.689	0.051-0.106	0.082
15	297	0.689	0.154-0.524	0.283
15	403	0.345	0.071-0.468	0.293
15	309	0.172	0.111-0.230	0.187

The data scatter significantly. This is primarily due to the "boardiness" of the prepreg tape that sometimes caused it to delaminate from the core during test setup. However, some observation may be made. First, the maximum temperatures are much lower than those obtained during foil prepreg bonding. There appears to be little insight between bond strengths regarding specimens primed by brushing and those prepared by dipping. There is a decrease in bond strength at lower pressure. The Ti honeycomb/PIXA tape bond strengths are about 30% of those obtained for Ti foil/PIXA tape, table 2.3.

Figure 4.3 shows the effect of priming on the core. The sample on the left is typical of a specimen primed using the shallow pan method. Primer was brushed onto the honeycomb sample on the right. Less primer is used with the brush method. Figure 4.4 shows prepreg surface dimples for the single ply welded specimens. In the photo, from left to right, the pressure increases from 0.172, 0.345 to 0.689MPa (25, 50 & 100 psi). There appeared to be a direct correlation between surface dimple density and the temperature and pressure used for welding.

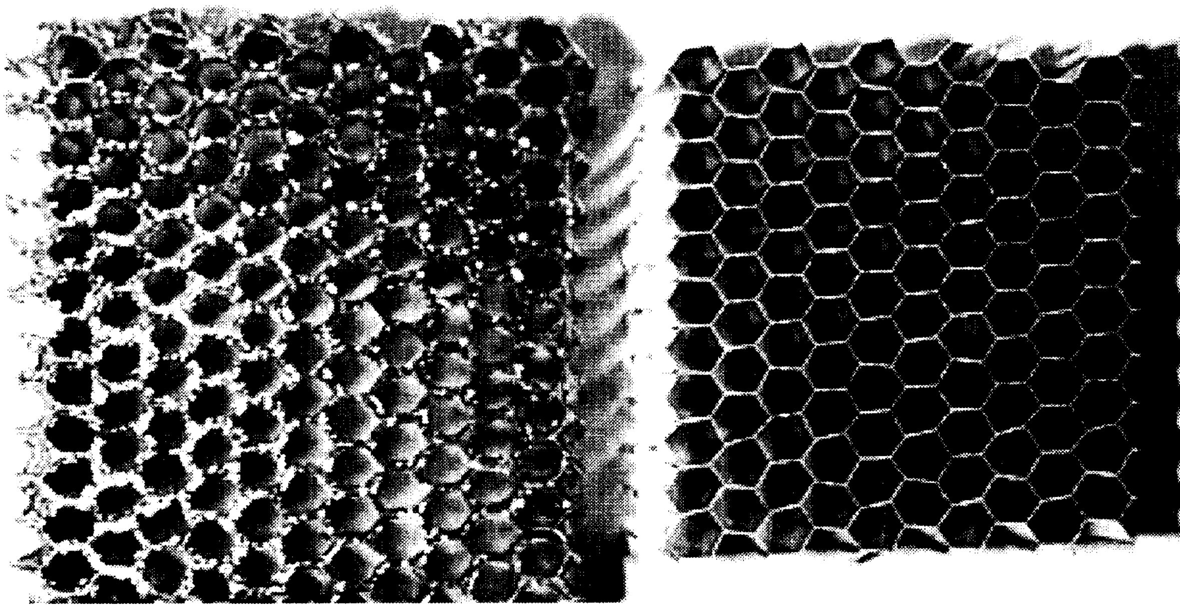

Figure 4.3. Shallow Pan Method versus Brush Method.

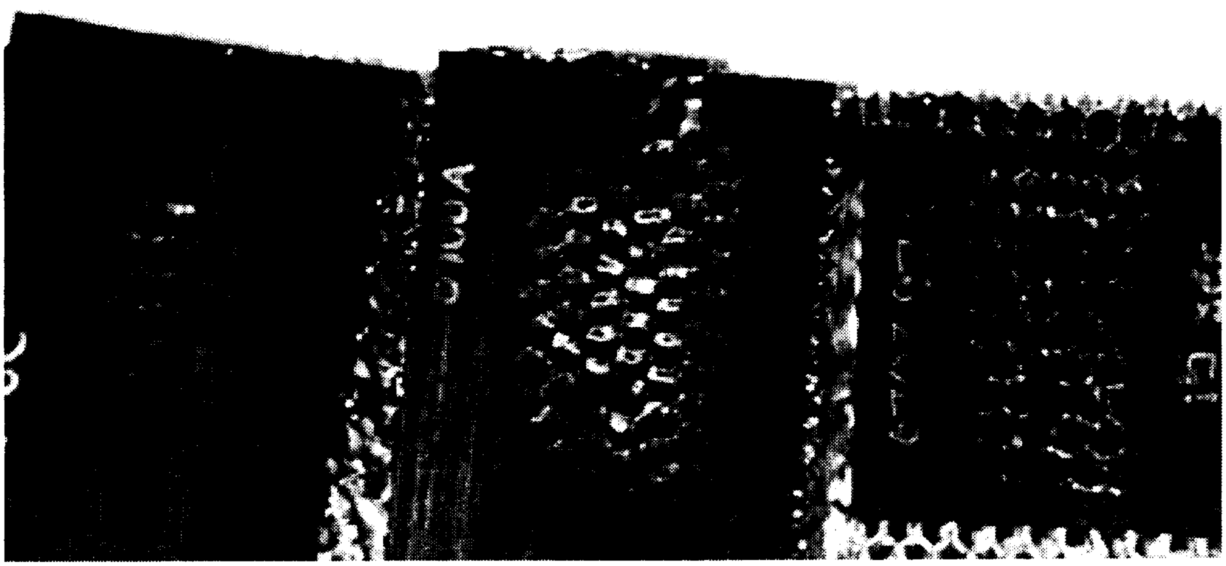

Figure 4.4. Dimple Effect.

Figure 4.5 presents a cross section of the honeycomb foam sample. Minimal pressure was applied and as a result no dimpling occurred. Although bond strengths were not measured, during peeling by hand, they were qualitatively observed to be significantly higher with the foam.

4.6. Conclusions

The purpose of this study was to investigate induction heating as a means of bonding prepreg skins to honeycomb core. The study was directed toward obtaining insight into the role of core surface priming methods and welding load on the skin-core bond strength.

Figure 4.5. Honeycomb Core with Foam.

The key to bonding prepreg tape to honeycomb is the core cell wall-resin-fiber contact achieved during the bonding process. Without the use of adhesive films between the core and the prepreg, induction heating core-prepreg skin bond strengths were found to be 30 percent of those obtained for foil-prepreg. This was the case whether the core was primed by brush or by dipping.

Skin-core bond strength was found to increase with the applied pressure load during welding. However, skin surface dimpling also increases with applied load.

An exploratory study was made of the use of foam to prime the core. While perhaps applied in excess, the foam-primed core was found to bond strongly with the skin when induction welded at low applied loads and no dimpling occurred.

This study demonstrated that TiGr honeycomb composites might be made using induction heating. Some information was obtained about the relationship between core priming and applied load. Concerns about bond strength and core surface dimpling will require that further studies be conducted, however.

5.0. Equipment And Design Issues For ATP

5.1. Introduction

The combination of several years experience operating the NASA ATP robot and the laboratory tests discussed in the previous sections has provided information about the equipment needed to build a prototype induction heater. In light of this background, several issues concerning equipment modifications and design will need to be addressed. This section addresses several of these issues.

5.2. Fabrication Information for Induction Heating

As part of the effort to build a magnetic induction heater to be used on the NASA robot for the manufacturing of TiGr, information was obtained on equipment and material suppliers. In addition, an estimate of the cost for IH head fabrication was made. Currently, it is planned to use either the RF Power Products (RFPP) or the Lepel power supply, as detailed in Section 2.2. Performance information about these units is contained in earlier sections of this report.

IH experiments conducted over the past year have led to preliminary design considerations for rollers, adapter plates, a mounting fixture and possibly a power circuit tuning unit. Depending on the power supply used, the expense of the prototype unit will vary by the cost of a tuning unit (table 5.1).

Table 5.1. Equipment and Cost Estimates

Items	RFPP	Lepel
1.75" Rollers (set)	$ 1,716	$1,716
1.00" Rollers (set)	$ 1,716	$1,716
Adapter Plates (shop fab)	$ 37	$ 437
Mounting Fixture (shop fab)	$ 460	$ 460
Tuning Unit	$ 6,350	NA
Total	$10,679	$4,329

5.3. Non-Conducting Rollers

Because of the concern that the steel rollers might overheat, information was obtained about non-conducting rollers. Two materials were investigated for the rollers: 1) Aremcolox—a medium density ceramic with low thermal conductivity and 2) Finer Grain Alumina. Sources of these materials and contacts are given in table 5.2. Both sources would provide rollers fabricated to design specifications.

Table 5.2. Rollers

Company	Material	Technical Contact	Telephone
Greenleaf Corp. East Flat Rock, NC	Finer Grain Alumina	Chuck Dziedzic	(704)693-0461
Aremco Products Ossining, NY	Aremcolox 502-1550 (Zirconium Phosphate)	James Costello	(914)762-0685

5.4. IH Study with Steel Roller

Concern regarding the possibility that the robot compaction roller would be heated due to its proximity to the toroid. A steel roller heat-shielding study was carried out to determine the amount of heat absorbed by the roller during placement. The first portion of the study involved placing a piece of copper plate between the toroid and a steel roller (1.75" diameter), as shown in figure 5.1, to examine the heating profile of the steel roller. The copper shields the steel roller from the electromagnetic field. For comparison a second test was performed without the copper plate. An additional test determined if eddy currents were induced in the roller when the IH unit lifts off the part away from the titanium foil.

5.4.1. Test Conditions and Material

Using the Lepel Power supply at full power and a single turn coil that operated at a frequency of 120kHz, a 5.5 inch long by 2.5 inch wide titanium foil was placed on the toroid. The copper plate was 0.125" thick and 8.5 inch long by 2.0 inch wide. A "power-on" time of 40 seconds was used for all experiments. Thermocouples were placed in the center of the plate, facing the toroid and on the steel roller next to the foil. In the second test, thermocouples were placed on the foil (at the center in between the toroid pole ends) and on the roller next to the foil. For the third test a thermocouple was located on the side of the roller adjacent to the toroid.

5.4.2. Results

Figures 5.2 and 5.3 are the temperature profiles for the roller test with and without the copper plate, respectively. During a 40-second "power-on" time the titanium foil reached temperatures close to 1400°C while the roller temperature reached approximately 100°C with the interceptor plate. Observing the remains of the titanium foil after the copper plate test revealed that heat was conducted into the copper plate. As indicated in figure 5.3, without the copper shield, the steel roller does not reach 200°C. The third test with the titanium foil removed, which simulates raising the heater for repositioning, produced a temperature increase of only 12 degrees from room temperature.

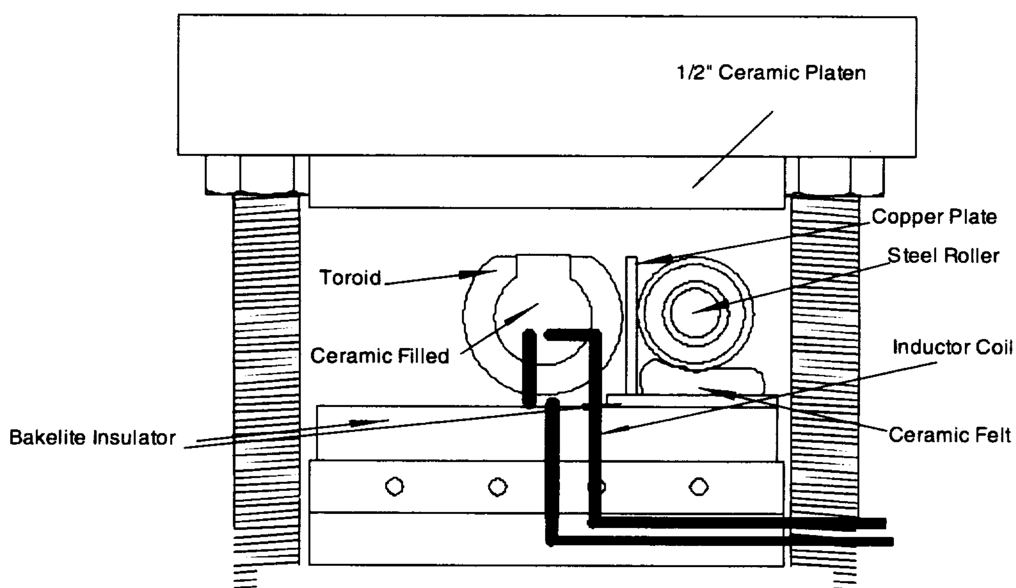

Figure 5.1. Experimental Set Up.

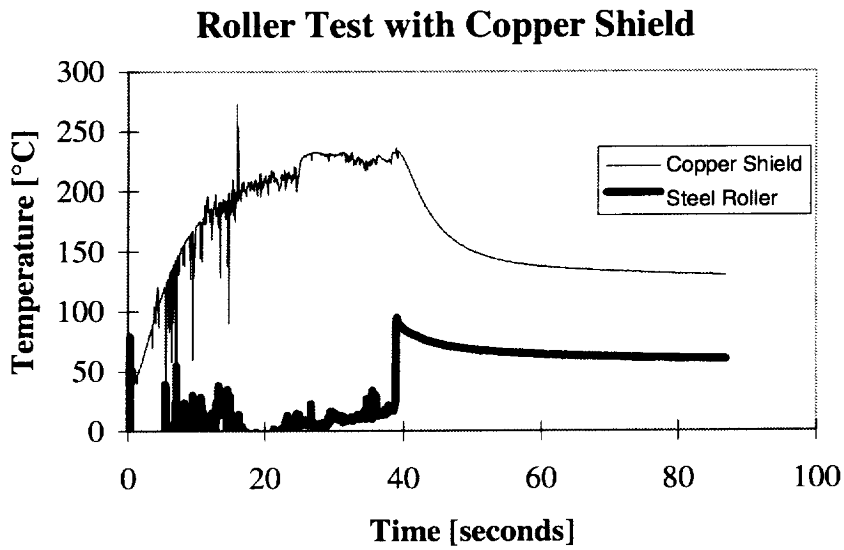

Figure 5.2. Temperature profile for roller test with copper plate.

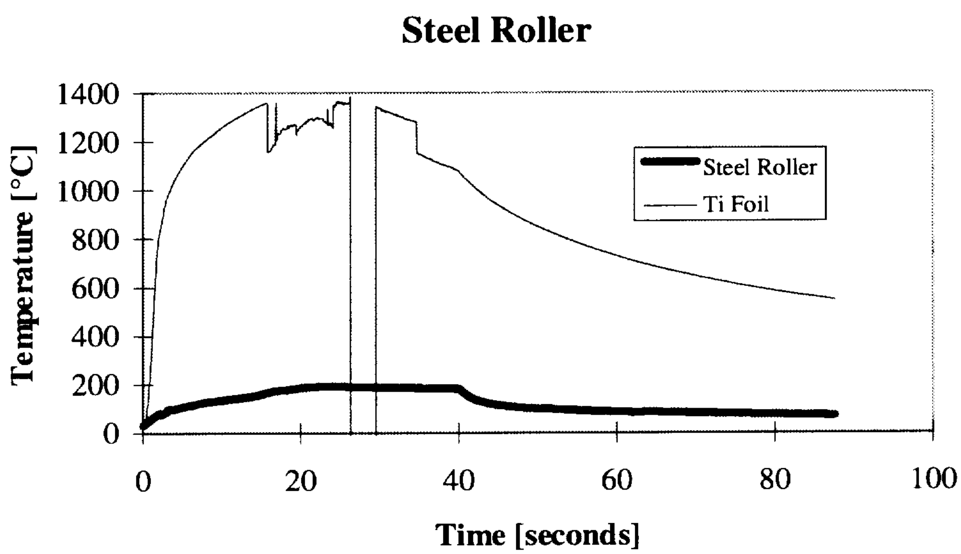

Figure 5.3. Temperature profile without the plate.

5.4.3. Conclusions

Feed and compaction rollers for the induction heating unit can be made of stainless steel without an enormous amount of heat up. Foil temperatures in this study were 1400°C, a temperature well above acceptable processing temperatures for polymer composites. The use of a copper interceptor plate reduced the heating of the roller by half. Even without the plate, the maximum roller temperature was less than the Tg of polymer candidates for automated tow placement. It would be sufficient to air cool the compaction roller for quenching. Additionally, there is expected to be no significant heating of the roller as the IH unit moves away from the foil susceptor. This is important, since a steel roller is much more durable than most alternatives, and can, for example, be cleaned with a wire brush if it becomes fouled with resin.

5.5. Ti Foil Cutting Study

The robot cutter unit was designed for prepreg tape and has been used extensively to cut this material. To determine whether the cutter could also handle 0.005-inch thick Ti foil cutting tests were conducted. The NASA robot cutter was found to be capable of cutting the foil, so long as the foil was securely held during cutting. That is, clean cuts were obtained when a roller, or similar device, rode on the foil at the end of the chute so that it was fairly stable as it entered the cutter.

5.6. Power Supplies and Magnets

It is planned to use the RFPP and the Lepel power units, section 2.2. Information about the units and suppliers is provided in table 5.3.

Table 5.3. Power Supply

Company	Model	Rated Power	Frequency Range	Technical Contact	Telephone
RFPP Voorhees, NJ	LF10	1.0kW	50-460kHz	Mark Spaventa	(609)627-6100
Lepel Edgewood, NY	LSS2.5	2.5kW	50-200kHz	Stewart Burkhart	(516)586-3300 (800)334-0441

The magnets used for this work were made of high-resistivity supplied by Amidon Corporation in Costa Mesa, California at (714)850-4660. Modifications made to the toroids were done at NASA.

5.7. Conclusions

Information has been obtained about several design concerns. It appears that the prototype induction heater can be fabricated for about $5,000. Steel rollers can be used for the unit. A stabilization roller is needed for the cutter to handle the titanium foil. The choice of power supplies to use will be made after more information is obtained from the RFPP supplier.

6.0. TiGr Induction Heater

Preliminary Design Considerations

6.1. Introduction

Experience with operating the robot and laboratory bench studies of the bonding of titanium foil and prepreg tape have provided data useful in the design of a prototype magnetic induction heater (IH) for automated fabrication of TiGr test panels. Several design issues for an IH unit to be used on the NASA placement machine have been identified. These issues serve as a starting point for the design of a prototype IH unit. Information about the induction welding equipment and test procedures are provided in earlier sections of this report.

6.2. Design Concept

The following figures serve to illustrate the IH design concept. Figure 6.1 indicates schematically how the toroid induction-heating unit will be mounted on the robot. The tow guide/feed module, the hot gas torch assembly, and the ribbon cutter assembly will all need to be extended forward several inches to provide space for the unit. A counterweight will be added to provide balance as shown.

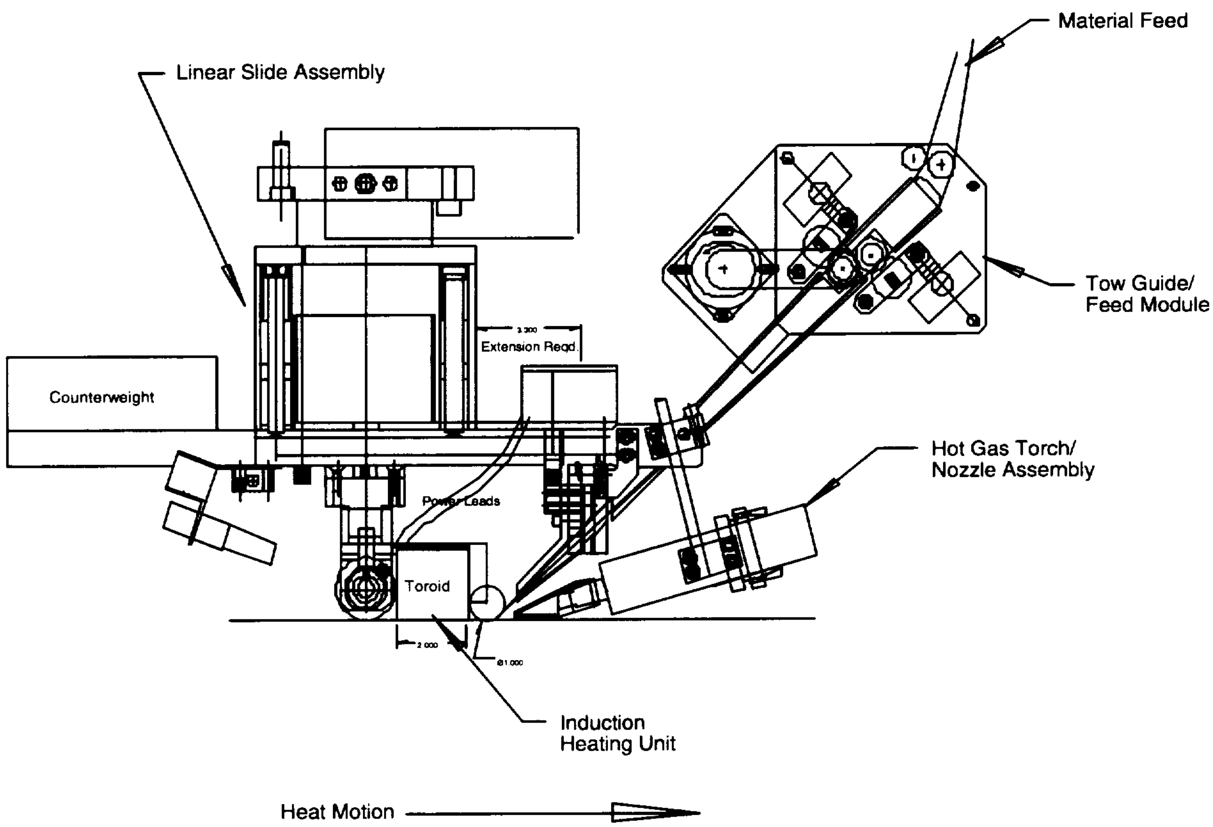

Figure 6.1. IH Head Prototype Mounted to Robot.

Given in figure 6.2 is a drawing of the proposed assembled IH prototype unit mounted on the robot head. This unit would consist of a 5/8-inch diameter lay down roller that serves as a tape-foil guide, and a 2 3/8" diameter × 2.00" wide toroid magnet to heat the foil. Directly to the rear of the IH unit will be mounted the existing 1.75-inch diameter compaction roller. This roller will serve to consolidate and quench the laminate. As can be seen in the figure, the unit will be spring loaded and adjustable so that different toroid loading forces will be possible. For the bench tests, pressures of up to only 200 psi were applied. This results in partial wetting as shown in figures 2.11 and 2.12 of the attached paper. During normal operation of the NASA robot much higher compaction pressures are possible. In addition, due to the rolling contact between the compaction roller and the laminate, a pressure gradient is present which should result in higher void transport.

6.3. Experimental Observations

The induction welding TiGr experiments have provided information about the effect of power level and duration, frequency, and carbon fiber orientation on the peel strength of the resulting Ti foil-Gr tape bonds. The following observations will serve to guide the prototype fabrication and testing.

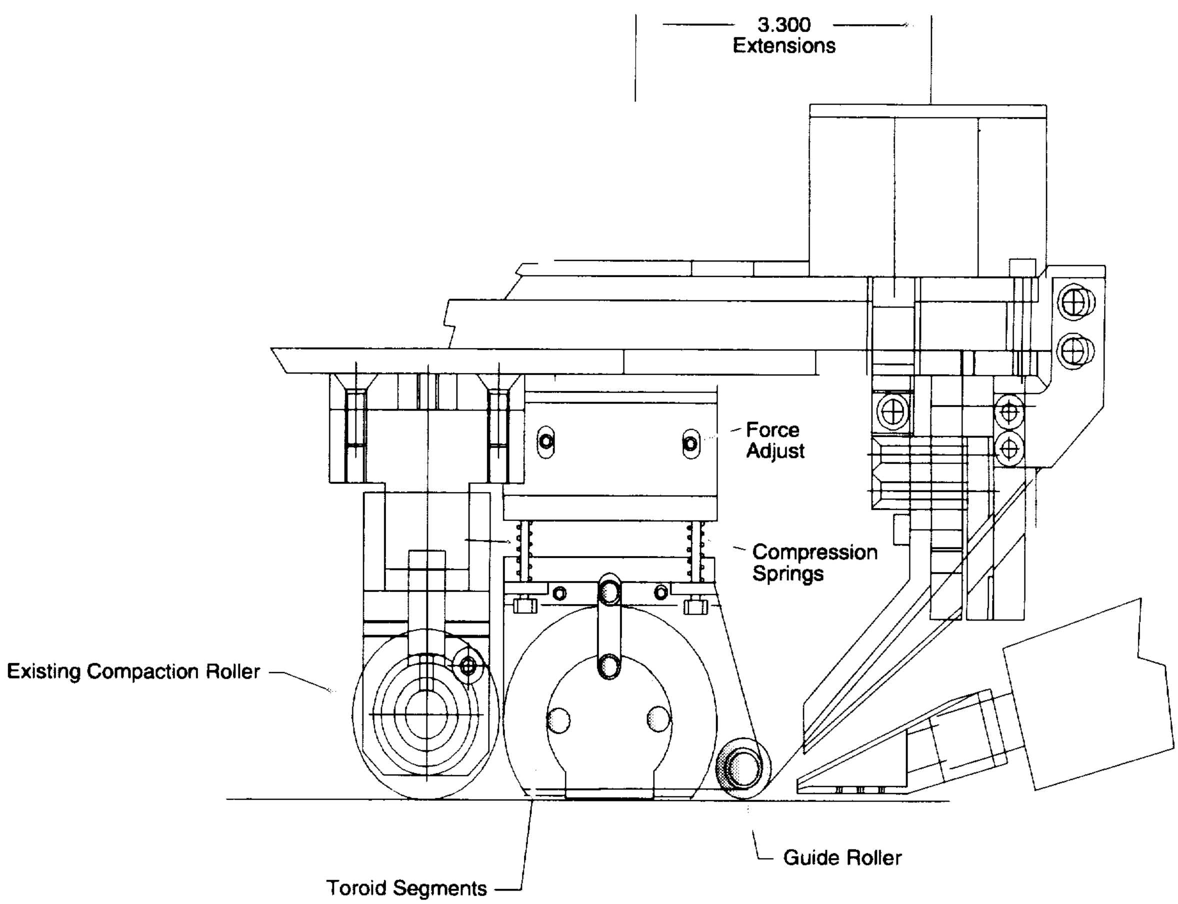

Figure 6.2. Induction heating TIGr placement head.

The laboratory tests (table 2.3) indicate that a 5-cm long toroid induction heater would be adequate for use on the NASA robot. For example, with a 1.75 kW, 120 kHz, magnet power supply, at a placement rate of 1.66 cm/sec, the Ti-Gr interface would reach over 380°C, which corresponds to a heating period of 3 seconds and a peel strength of 0.58 kN/m. In robotic work, as opposed to bench tests, material preheating will increase placement speed and may enhance bond strengths.

6.3.1. Power Frequency and Bond Time

The laboratory studies using PIXA prepreg tape were directed toward providing the data needed to design the prototype induction heater. Studies with PETI-5 tape and with honeycomb served to confirm the PIXA equipment performance findings and primarily showed that these materials could be bonded by induction heating.

Ti foil-PIXA tape bond strengths as high as 1.40 kN/m were obtained at a power level of 1.25 kW and frequency of 80 kHz. Strong bonds were obtained for power-on times between 5 and 10 seconds. At higher power and frequency, bonding was obtained for heating times of 2 seconds. These findings are important in that high placement rates are required to reduce manufacturing costs.

6.3.2. TiGr Lay-Up Study

A study was conducted to determine the greatest distance between the toroid and the nearest ply of titanium foil at which the foil could still provide the temperatures required for bonding plies. At 1.75 kW and 120 kHz, with 0/90 prepreg ply orientation, the thickness and heating results indicate that Gr-Gr bonding can be achieved when the Ti is several plies away. The temperature difference across the thickness of a Gr ply during heating ranges from 30 to 40 °C. Experience indicates that the Gr in contact with the Ti is not thermally damaged (visibly) when exposed to temperatures up to 620°C. Bonding requires temperatures of at least 300°C. Thus, for TiGr lay-ups with about 6 or fewer Gr plies between Ti foils it should be possible to use automated placement with induction welding.

6.3.3. Compliance With Placement Surface

Experiments with the segmented toroid magnet demonstrated that, even when the power is on, adjacent toroid segments easily slide relative to each other. This suggests that the magnet heater might be made to be compliant with the curvature of the placement surface through the upward and downward adjustment of individual segments. In addition, the mounting mechanism can be fairly free to rotate and flex to comply with surface changes, while maintaining the required pressure load.

An important objective of the TiGr placement work using the prototype head will be the fabrication of a 2-foot diameter, 2 foot long, TiGr cylinder. NASA has the cylinder tool and the compaction rollers needed to place prepreg tape on it. As mentioned above, the toroid can be made to comply with the cylinder surface. It will be necessary to design and fabricate guide rollers and the toroid housing units that comply with the cylinder surface for the different placement directions.

6.3.4. Materials

While the primary pressure application is provided by the roller located behind the magnet, the ceramic filled gap must carry a few pounds of applied load to initiate wetting and bonding. These surfaces also must slide over the foil-tape surface that is being placed.

Results from an induction heating steel roller study, as presented in section 5.3, suggest steel rollers will not pick up an appreciable amount of the magnetic field. Heat introduced into the roller would largely be a result of heat transfer from the part. If cooling is required to keep the compaction roller from approaching T_m of the resin, cooling the roller by air internally or externally is a solution.

6.4. Discussion

Bench test data for magnetic induction welding of titanium foil and carbon fiber thermoplastic prepreg tape indicate that the process can be developed for the automated fabrication of aircraft structure. The process relies on susceptor heating of the Ti foil, not on high frequency heating of the graphite fiber. Good weld bond strength may be obtained with heating times of a few seconds, which suggests the potential for achieving acceptable commercial production rates.

These preliminary concepts outline a number of the design and operating issues. The figures illustrate how the equipment may be mounted on the NASA robot. It is envisioned that the first prototype IH unit would be quite similar to the bench unit and make use of the observations described above. It would be attached to the robot and used to make flat TiGr panels for proof of concept and to obtain mechanical properties of the panels.

Once the IH unit has been successfully demonstrated using the flat tool, it would be used to make IH units that conform to these cylinders. For example, the 0/90 hoop/axial TiGr lay up configuration would require only the flat roller unit and a curved roller unit that conforms to the cylinder for axial placement.

7.0. Discussion And Conclusions

The purpose of this study was to determine whether magnetic induction heating is a viable candidate for use in the automated fabrication of the new composite material form, TiGr, which is comprised of titanium foil, or honeycomb, bonded to graphite fiber reinforced polymer prepreg tape. If the laboratory tests were encouraging, the additional goal was to obtain data needed to design a prototype heater for use on the NASA ATP robot.

The PIXA tape test data showed that good TiGr bonds might be obtained with induction heating times between 3 and 10 seconds depending on magnet circuit power and frequency. For magnets of 3 to 10 inches in length, linear placement rates greater than the 1.0 inches per second needed for commercial applications appear achievable.

Since the titanium foil susceptor remains in the part, the process envisioned operates at frequencies (60-120 kHz) suitable for foil heating and bond strength maximization. In the test unit at 1.25 kW and 80 kHz, PIXA tape-Ti foil welds as strong as 1.40 kN/m were obtained. Since the strongest bonds were made at 80 kHz, it may be that this is the optimal susceptor frequency for 0.005-inch thick titanium foil. Tests indicated that temperatures high enough for bonding were reached in six seconds at ply-ply interfaces as many as five plies from the foil. The model prediction of a 30 to 40°C temperature difference across plies agrees with this. For a foil temperature of 600°C, just below the thermal degradation level, the fifth ply will have reached a temperature above the 300°C needed for bonding.

Although induction welding of PETI-5 tape and Ti foil gave bond strengths 40-75% below those obtained for PIXA tape. Structures made of PETI-5-Ti may be sufficiently bonded to permit their removal for post cure without delamination. Tg measurements suggest that the PETI-5 was advanced to 40% of cure during the welding process.

SEM photographs of the fracture surface for both PIXA TiGr and PETI-5 TiGr show about 60% wetout. These welds were made at applied pressures of 0.345 to 1.378 MPa. During robotic placement much higher compaction loads are available so it should be possible to achieve good interfacial contact during placement.

PIXA prepreg was induction bonded to Ti honeycomb. Without the use of adhesive film the skin-core bond strengths were 30 percent of those obtained for PIXA/foil. Exploratory studies of honeycomb priming showed that brush and dipping gave comparable results, while foam priming resulted in a strong bond. Both bond strength and surface dimpling increase with applied pressure. Since foam primed core required little pressure during welding, it may merit further study.

Preliminary design considerations for a prototype induction heater to be used on the NASA robot were outlined. These concepts relied greatly upon the PIXA TiGr study and past experience in robot operation. It appears that a prototype unit can be designed and built at little cost. The unit would be capable of making flat TiGr test panels as well as cylinders to demonstrate aspects of fuselage and wing manufacture.

As currently envisioned, the prototype unit would have a two-inch toroid magnet placed such that the tape and foil passes under it for induction heating. Placement would occur with magnet motion in the radial direction. Existing power supplies would be utilized. The present tape cutter can cut foil. Testing proved that the existing steel rollers will be sufficient in the new design.

In summary, there appear to be no significant problems in fabricating the heater to demonstrate TiGr automated placement. The unit should be capable of making both foil-tape and core-tape forms of TiGr in any of the lay-ups currently being considered.

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A laboratory study of magnetic induction heat bonding of titanium foil and graphite fiber reinforced polymer prepreg tape, TiGr, demonstrated that the process is a viable candidate for low cost fabrication of aircraft structure made of this new material form. Data were obtained on weld bonding of PIXA and PETI-5 prepreg to titanium. Both the foil and honeycomb forms of titanium were investigated. The process relies on magnetic susceptor heating of titanium, not on high frequency heating of graphite fiber. The experiments showed that with a toroid magnet configuration, good weld bonds might be obtained with heating times of a few seconds. These results suggest the potential is good for the induction heating process to achieve acceptable commercial production rates.

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