Consolidation of Braided Carbon Fiber/ Thermoplastic Tubes by Induction Heating

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ABSTRACT

Thermoplastic composites (TPCs) have experienced renewed enthusiasm within the U.S. aerospace industry, due in part to opportunities for rapidly manufacturing large structures. Unlike the lengthy cure cycles required by thermosets, the thermoplastic matrix prepreg requires only heat and pressure to consolidate consecutive layers of material; with sufficient inter-ply contact time to develop a strong interface. The manufacturing requirements for thermoplastics provide manufacturing flexibility and of particular interest are in-situ consolidation processes, i.e., consolidation during layup on a tool.

In-situ consolidation removes the time-consuming and costly secondary processing step of autoclave or press consolidation. Process variables which contribute to laminate quality include temperature, heat transfer, inter-ply contact time, and consolidation pressure; all of which must be considered when evaluating an in-situ manufacturing method. Most of the work in this area to date has focused on consolidation during automated fiber placement (AFP), where prepreg tows are consolidated when placed on the tool. Considering this process for a braided structure adds complexity relative to AFP due to the rapid lay-down rate of the braider and simultaneous placement of multiple prepreg tows. As such, processes considered for AFP consolidation could not be applied to a braided part.

Alternatively, a fully braided preform could be consolidated on the tool using well established thermoplastic welding / heating techniques. The goal of this effort was to evaluate the effectiveness of induction welding (heating) to consolidate braided carbon fiber/thermoplastic composite tubes up to eight plies in thickness. The manufacturing process, thermal characterization, and initial mechanical property data of the consolidated tubes are reported.

1. INTRODUCTION AND BACKGROUND

Carbon fiber reinforced thermoplastics are attractive for manufacturing and joining large structures due in-part to opportunities for rapid manufacturing. Unlike the lengthy cure cycles required by thermosets, thermoplastic matrix prepreg only requires heat and pressure to melt and consolidate consecutive layers of materials; with sufficient inter-ply contact time to develop a strong interface (cohesive bond). These processing requirements provide manufacturing flexibility with two specific areas of interest (1) the ease of joining through fusion bonding methods and (2) in-situ consolidation of fiber-placed thermoplastic prepreg tows.

In-situ fabrication eliminates the time-consuming and costly secondary processing step of autoclave or press consolidation. Data on the physical mechanisms controlling laminate quality during in-situ consolidation by automated fiber placement (AFP) are available in literature, [1-4]. A study at the University of Delaware investigated the effect of process variables such as heat transfer, inter-ply contact time, and void reduction were modeled, tested, and quantified. The causes of inadequate consolidation and/or reduced mechanical properties were correlated with process, material, and machine parameters. Studies conclude that heat transfer, lay-down speed, and consolidation pressure (intimate contact) were the principle controllable process variables affecting laminate quality.

Welding of thermoplastics is a manufacturing process which enables both the joining of two separate parts or the joining of consecutive thermoplastic layers by fusion bonding and consolidation of the interface [5]. Fusion bonding occurs by heating the polymer at the interface of parts or plies above the melting temperature (for semi-crystalline polymers) which induces intermolecular reptation, diffusion and entanglement of polymer chains across the interface, and lastly solidification during cool-down. When full entanglement and ideal uniform re-crystallization occurs (for semi-crystalline polymers), the bonded region is indistinguishable from the parent material. Welding techniques are often classified by the method of heat generation method, where three common methods include resistance welding, induction welding and ultrasonic welding.

Taking the ply-by-ply in-situ consolidation used in AFP a step further, traditional welding methods may be utilized to consolidate multiple plies of a thermoplastic preform. As described with welding, consolidation involves establishment of intimate contact between opposite surfaces of two different parts or plies, heating to induce intermolecular reptation and diffusion of polymer chains across the interlaminar interface (healing) and void removal, or minimization, over a period of time.

The approach of preform consolidation is particularly attractive for braided composite preforms, as the braiding process presents added complexity relative to AFP due to the high rate and simultaneous placement of a multiple prepreg tows and orientations simultaneously (see Figure 1). An alternative to following each tow with heat and pressure, the braiding process allows for manufacturing of a preform that can then be consolidated by a welding method (in-situ), post braiding. This effort focuses on evaluating induction welding / heating as a method of in-situ consolidating braided preforms.

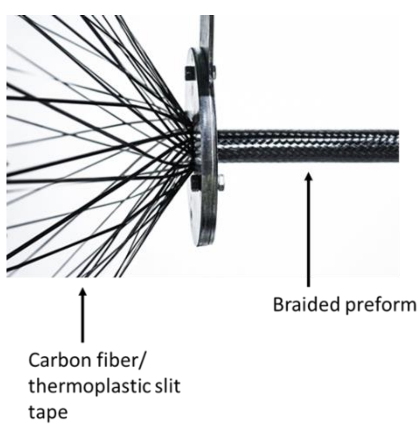

Figure 1. Example multi-tow braiding of tube

Induction welding / heating is defined as a high frequency alternating current flowing through a coil to generate an alternating electromagnetic (EM) field. When the coil is placed near an electrically conductive material (e.g., carbon fiber reinforced TPCs), it induces volumetric heat generation from eddy current flow within the material [6], [7].To weld parts using induction welding, tooling is required to hold the parts together and apply pressure along the weld line (e.g., clamps, pressurized bladder, actuated rollers and tooling). An induction coil is then moved along the weld line to induce heating and welding. No contact is needed between the coil and parts. If joining of non-electrically conductive materials is desired (e.g., glass fiber reinforced thermoplastics), susceptors with ideal electrical conduction properties can be placed within the weld line [5], [8]. The EM field will induce heat generation in the susceptor and provide controlled/focused heating, see **Error! Reference source not found.** for schematic.

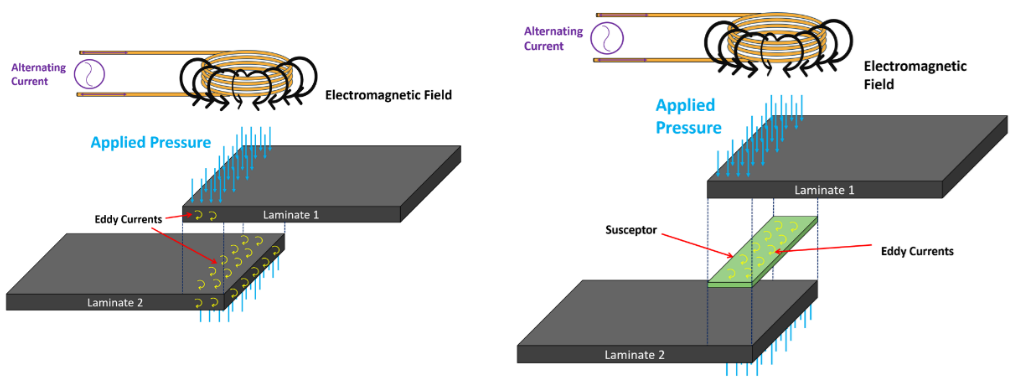

Figure 2. Induction welding schematic with (left) and without (right) susceptor

This paper details first principles evaluation of induction welding/heating as a method of melting and consolidating up to eight plies of biaxially braided tubes. The preform fabrication and induction based consolidation parameters are discussed along with preliminary characterization of tubes include microscopy, differential scanning calorimetry (DSC) for crystallization, and crush strength.

2. EXPERIMENTS

The experimental evaluation for induction heating as a method of consolidation focused on a single material type (Toray TC1225) and braiding pattern (biaxial ±45°). Three different preform thicknesses were evaluated, 4-ply, 6-ply, and 8-ply combined with two different mandrel tooling materials used during induction heating experiments, aluminum, and stainless steel. Details for the TC1225 material, braiding of tube preforms, induction heating setup, and manufacturing testing activities are provided in proceeding sub-sections.

2.1. Material

Toray TC1225 low melt polyaryletherketone, trade name LM PAEK, with T700GC standard modulus carbon fiber is used for fabrication of braided preform tubes. TC1225 was provided in 305 mm (12 in.) width, unidirectional (UD) tape format and slit into 6.35 mm (1/4 in.) wide tows prior to braiding. Physical properties of the parent TC1225 UD tape include fiber areal weight of

145 g/m^2, 34% resin content by weight, and consolidated ply thickness of 0.137 mm (0.0054 in.). Thermal processing information for TC1225 includes melting temperature (T_m) of 305℃ (581°F) and processing temperature (T_p) range of 320-380℃ (600-710°F). For further details on Toray TC1225 see reference [9] for product datasheet.

2.2. Braiding of tube preforms

Biaxial ±45° braided preforms of 4-, 6-, and 8-ply thicknesses were fabricated on mandrels of 65 mm inner mold line (IML) diameter and 560 mm length. Mandrels were release coated and covered in Kapton film prior to braiding, to ensure release. After the mandrels' preparation, a 40-carrier braiding machine was used to deposit each ply of the preform over the mandrel, referred to as overbraiding. The ply count on the preforms varied between 4 and 8 total plies. A ±45° fiber orientation was maintained for every ply. Table 1 provides example details of each ply in the overbraid process, per preform tube.

Table 1. Example summary of preform overbraiding data

Ply #	1	2	3	4	5	6	7	8	Stdv.[a]
Fiber orientation	±45°	±45°	±45°	±45°	±45°	±45°	±45°	±45°	±1°
Inside Diameter (mm)	63.5	64.0	64.5	65.0	65.4	65.9	66.4	66.9	-
Outside Diameter (mm)	64.0	64.5	65.0	65.4	65.9	66.4	66.9	67.3	-
Ply thickness (mm)	0.25	0.24	0.24	0.24	0.24	0.24	0.23	0.23	0.01
Ply Areal Weight (g/m^2)	395	392	389	386	383	381	378	375	6.9
Ply weight (g)	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	0.00

[a]standard deviation

Two material types were used for the mandrels: (1) aluminum 6061 T6 (Al6061-T6); and (2) stainless steel 304 (SS-304). Two material choices were selected to evaluate the effects on induction heating and tube removal after processing. All mandrels had a wall thickness of 6.35 mm (1/4 in.) with a hollow center to allow for coaxial tooling to hold the mandrel during braiding and induction heating testing. A summary of braided tube preforms with mandrel ID numbers is provided in

Table *2*, with an example of ±45° ply braided on mandrel shown in Figure 3, respectively.

Table 2: Material product codes and mandrel ID's

Mandrel ID#	Braid type	Qty	Number of plies	Mandrel type
1	±45° Braid	1	4	Al60601-T6
2	±45° Braid	1	6	Al60601-T6
3	±45° Braid	1	8	Al60601-T6
4	±45° Braid	1	4	SS-304
5	±45° Braid	1	6	SS-304
6	±45° Braid	1	8	SS-304

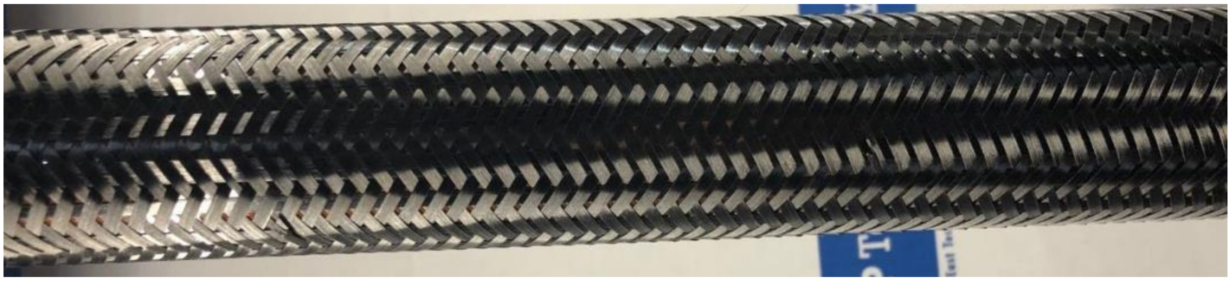

Figure 3. Example of first $\pm 45°$ braided ply on mandrel

2.3. Induction heating test setup

To evaluate induction heating of braided preform tubes, a holding fixture was constructed to hold the mandrels and allow external cylindrical access for induction heating the braided preform. See Figure 4 for schematic of holding fixture constructed for testing.

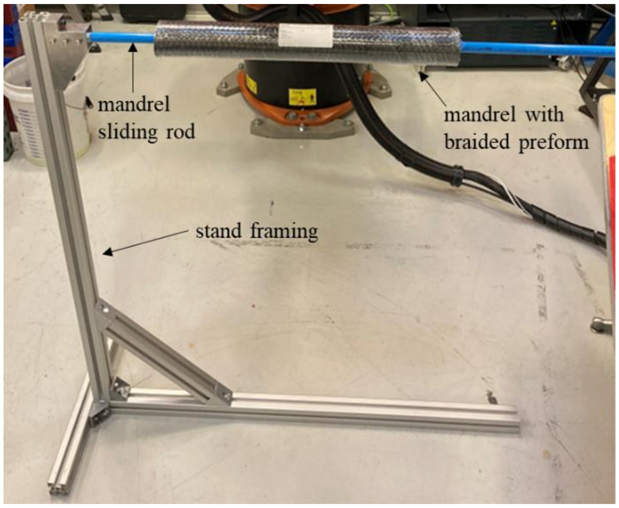

Figure 4. Mandrel holding fixture for cylindrical mandrel mounting

Induction heating trials were performed using University of South Carolina's (UofSC) induction weld cell which consists of a 10kW Ambrell EasyHeat induction heating generator and workhead; water cooling chiller for internal cooling of induction heating system and induction coil; compressed air cold gun for surface based active cooling during induction heating; FLIR infrared (IR) camera for surface temperature monitoring; and a KUKA KR60 HA Robot for induction coil end-effector manipulator. High temperature Kapton film vacuum bagging was used for pressure application and was applied to the braided preform mandrel on the holding fixture. See Figure 5 for induction heating equipment and example vacuum bagging setups, and Figure 6 for schematic of full induction heating setup used for testing.

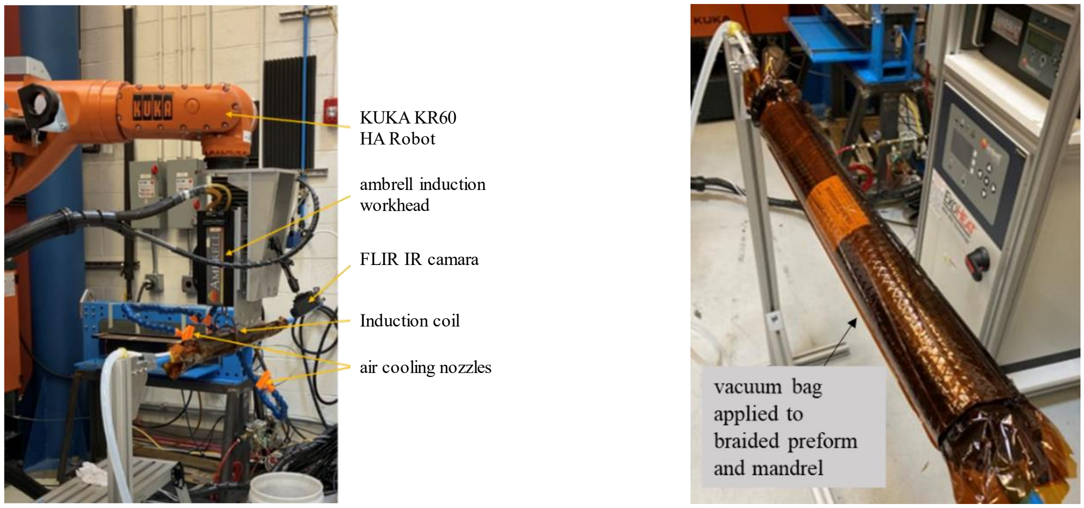

Figure 5. UofSC induction welding cell configured for braided tube induction heating (left); and vacuum bagging example setup for braided preform and mandrel on holding fixture (right)

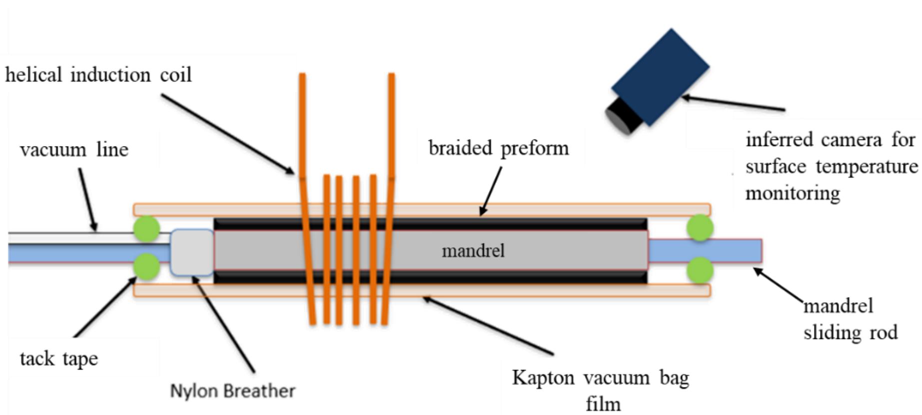

Figure 6. Schematic of induction heating test setup

To account for the cylindrical geometry of the braided tubes, a helical induction coil was fabricated using UofSC proprietary method for use in induction heating trials. The helical coil is defined as a 'half-helix coil' consisting of 3 co-axial turns and fabricated from copper tubing, primary geometrical information is specified in Figure 7.The frequency of the half-helix induction coil is 250 kHz when connected to the Ambrell induction heating system.

It is important to note that the coil offset height for each preform configuration 4-, 6-, and 8-ply vary since the same coil is used for all three preform types for the effort, Figure 8. This is a variable that was fixed to allow for simplicity in evaluating first principles feasibility induction heating of the various thickness tube preforms, due to the cylindrical geometry challenges. For future work a fixed offset height from the preform surface and coil will be used for maintaining consistent offset heights.

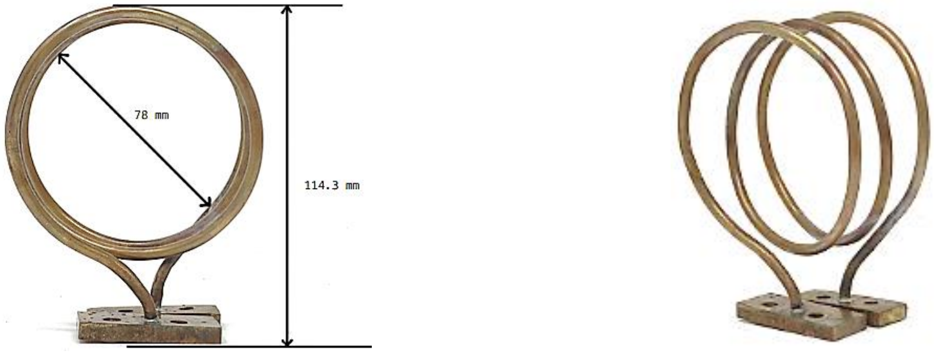

Figure 7. Half-helix coil front view (left) and isometric view (right)

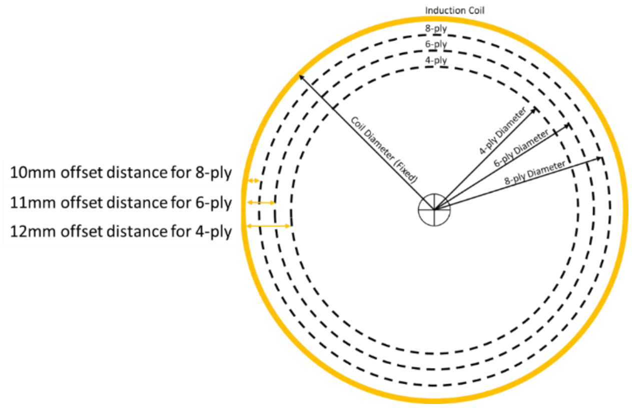

Figure 8. Fixed coil offset distance from surface of tubes

2.4. Static induction heating testing

For the first set of testing to evaluate feasibility of induction welding / heating braided tube preforms, static induction heating trials were performed for 4-, 6-, and 8-ply tubes on Al6061-T6 and SS-306 mandrels. An IR camera was used for monitoring temperature profiles on the outside surfaces of each tube only, no access was available for placement of thermocouples on the IML of the tubes, therefore was omitted.

For static trials, the half-helix coil was placed in the center of each preform, as shown in Figure 6, with current settings of 625 and 375 set for the induction generator for Al606-T6 and SS-306 configurations, respectively. For duration of heating, the time to reach 300℃ was monitored for each preform configuration to evaluate heating rates per configuration and minimize risk of overheating preforms. Data collected from static trials are shown in Table 3 and Table 4 for Al6061-T6 and SS-306 mandrels, respectively.

Table 3. Static heating trial data for braided tubes on Al6061-T6 mandrel (625A)

Coil type	*Number of plies*	*Duration (sec)*	*IR temperature (˚C)*	*Surface heating rate (˚C/sec)*
Half-Helix	4	50	299	6.0
Half-Helix	6	15	306	20.4
Half-Helix	8	21	298	14.2

Table 4: Static heating trial data for braided tube on SS-306 mandrel (375A)

Coil type	Number of plies	Duration (sec)	IR temperature (˚C)	Heating rate (˚C/sec)
Half-Helix	4	30	375	12.5
Half-Helix	6	30	290	9.7
Half-Helix	8	36	300	8.3

Table 3 shows that the highest static heating rate (20.4 °C/sec) was recorded for the 6-ply panel with an aluminum mandrel. While for the stainless steel mandrel the 4-ply preform observed the highest heating rate, approximately 12.5 °C/sec, in Table 4. From static induction heating trial data, the aluminum mandrels overall showed higher heating rates compared to stainless steel. Additionally, all configurations, except the 4-ply preform on the aluminum mandrel, showed potential to reach Tm for TC1225 at the surface under 40secs.

Based on the results from the static heating trials, heating rate and amperage of the per ply configuration, were used to determine the coil speeds for the induction heating setup to maintain T_p of TC1225 (320-380°C) for the tubes when moved across the mandrel.

2.5. Moving coil induction heating testing

For the second set of induction heating trials, the induction coil was moved across the braided preforms for evaluation of consolidating the tubes. Moving coil induction heating testing focus is placed on the middle section of the overall braided tube preforms; starting at 100 mm from the left side and finishing 100 mm from the right side, leaving 250 mm length of tubing for testing, see Figure 9. This is done to minimize risk associated with induction heating edge-effects for the effort [3]. As with the static heating trials, an IR camera was used to monitor surface temperature with the addition of variable coil speeds and holds to ensure processing temperatures were reached. The moving heating trials were conducted based on three varied parameters (illustrated in Figure 9**Error! Reference source not found.**): (i) the hold time required to reach T_m prior to moving coil; (ii) coil speed for the first half of the tube; and (iii) coil speed for the second half of the tube.

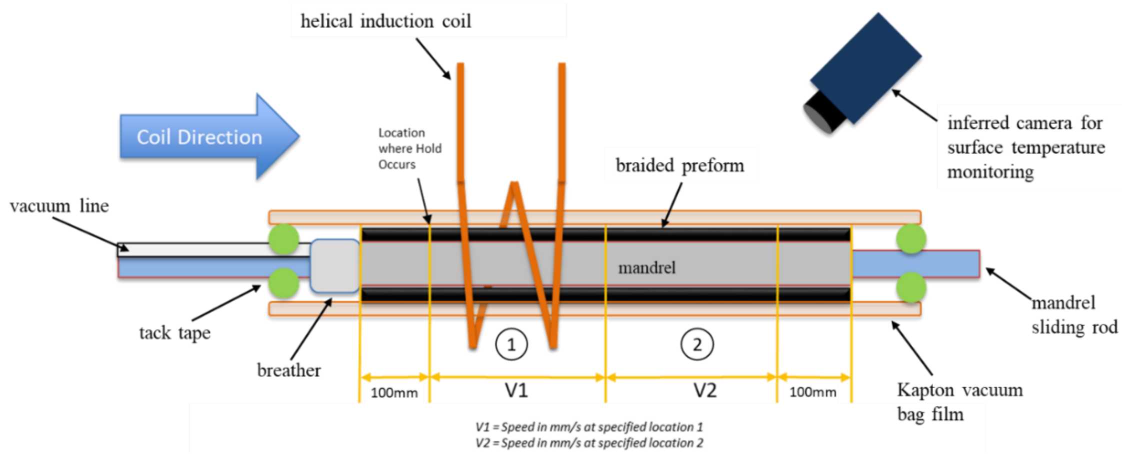

Figure 9. Coil speed parameterization locations for moving coil induction heating trials

The braided tubes were only melted in the center section leaving 100mm of non-melted tubing on both edges. It was observed during preliminary trials, due to the Al6061-T6 and SS-306 thermal properties (heat capacity and thermal conductivity), the mandrel temperature remained consistent when moving at select coil speeds. These coil speeds were dependent on the ply thickness and amperage produced by the induction heating system. The hold was included in the parameterization to melt a larger area of the tube and maintain T_m and T_p ranges by varying the coil speed along the length of the tube target area (250 mm). Data collected for ideal welding recipe per mandrel and preform configuration is provided in Table 5.

Table 5. Process parameters for induction heating braided tubes

Mandrel type	**Number of plies**	**Coil type**	**Amperage (A)**	**Max IR surface temperature (℃)**	**Welding speeds**		
					Hold (sec)	**V1 (mm/s)**	**V2 (mm/s)**
Al6061-T6	4	Half-Helix	625	399	60	1	2
Al6061-T6	6	Half-Helix	625	400	20	1.5	1.5
Al6061-T6	8	Half-Helix	625	425	15	2	2
SS-306	4	Half-Helix	375	405	20	1.2	1.2
SS-306	6	Half-Helix	375	420	15	1.5	1.5
SS-306	8	Half-Helix	375	440	15	1	1.3

Visual inspection of all tubes, after induction heating, showed wrinkling from the vacuum bag along with void pockets in select wrinkled locations. Further investigation is required for use of alternative pressure application methods such as fixed/hard tooling or rollers to mitigate out-of-plane wrinkles if induction heating is used for melting and consolidating braided tubes. Photos of the tube sections extracted using wet tile saw are shown in Figure 10**Error! Reference source not found.**.

Figure 10. 250 mm cutout sections of consolidated braided tubes

The tubes were numbered according to the product specification shown in

Table *2*

Table *2*. Visual inspection of all tubes showed polymer flow along the IML, outer mold line (OML), and where the 250 mm cuts were made. The through-the-thickness heating, (melting of the inner most ply) proved sufficient on all tubes except the 8-ply Al6063-T6 mandrel (tube 3). The latter was attributed to insufficient heating generated by the coil to reach the innermost layers of the tube in combination with the Al6063-T6 mandrel acting as a heat-sink, dispersing the heat generated and preventing melting. SS-306 mandrel was observed to not have the same issue.

A glossy smooth finish was visually observed on both OML and IML of the tubes indicating melting temperatures were reached and polymer flow occurred. Out-of-plane wrinkling was seen on all tubes with tube 2 and tube 6 showing significant wrinkling, compared to others. Wrinkling was concluded to be a result of the vacuum bagging quality for tube 2 and tube 6 and pressure limitations of the vacuum bag. Further investigation is required for improved pressure application methods, beyond vacuum bagging used in this effort, to minimize wrinkling. An example of the smooth finish and out-of-plane wrinkling can be seen in Figure 11.

Figure 11: Pictures showing OML and IML surfaces and defects

Based on experimental testing results, Al6061-T6 mandrel provided ideal better working conditions and cool down rates for mandrel sections when compared to SS-306 tooling. Additionally, the braided tubes were easily removed from the Al6061-T6 mandrel compared to the SS-306 mandrels. This is contributed to the higher coefficient of thermal expansion (CTE) in Al6061-T6 providing beneficial ‘shrinking’ of the mandrel from the tubes after cooling, and prior to removal.

3. ANALYSIS AND DISCUSSION

Various methods are used for characterization of braided tubes consolidated by induction welding / heating. The following section details analysis results and discussions for consolidated ply thickness (CPT), microscopy, DSC for cold crystallization checks, and crush testing for mechanical performance evaluation.

3.1. Consolidated ply thickness (CPT) analysis

The CPT of induction heated tubes were physically measured using calipers at various locations for each tube. Results from caliper measurements are shown in Table 6, with a plot in Figure 12 showing total consolidated thickness versus the ply count, with standard deviation from target consolidation thickness. Minimum and maximum gauge limits were defined using 1.5 and 2 times parent UD tape TC1225 CPT as limits defined for $\pm 45°$ braided TC1225 CPT. Results show improvements can be made for reduction of CPT and improved consistency with greater pressure application in induction heating of braided tubes.

Table 6. Initial consolidation checks for braided tubes

Mandrel type	**Number of plies**	**Avg. thickness (mm)[a]**	**Statistical thickness range (mm)[b]**	**consolidated ply thickness, CPT (mm)**
Al6061-T6	4	1.195	0.84 – 1.12	0.299
Al6061-T6	6	1.724	1.26 – 1.68	0.287
Al6061-T6	8	2.245	1.68 – 2.2	0.281
SS-306	4	1.253	0.84 – 1.1	0.313
SS-306	6	1.719	1.26 – 1.6	0.286
SS-306	8	2.224	1.68 – 2.2	0.278

[a]thickness measured using calipers on edges of 250 mm sections extracted from mandrel, after trimming using wet tile saw

[b]10 measurement points selected per tube, 5 along each edge

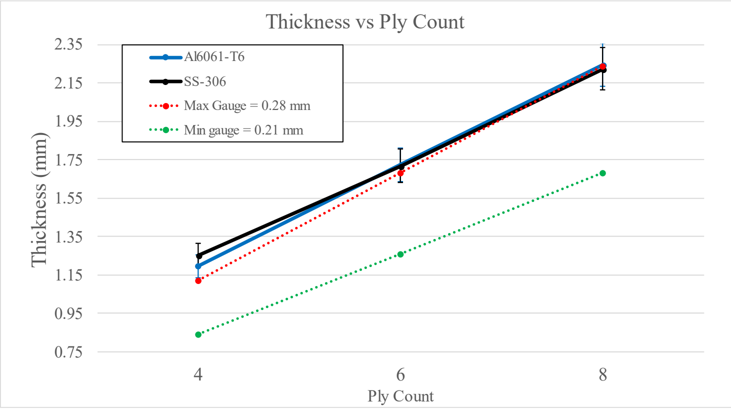

Figure 12: initial standard deviation consolidation checks for braided tubes

3.2. Microscopy

Consolidation quality of the tubes was a critical metric for success and initial trials provided mixed results. The cross section of consolidated 4-, 6- and 8-ply tubes are provided in Figure *13*-Figure *15* . Photomicrographs of 4-ply tube consolidated by induction welding show no evidence of voids content in the sectioned parts, whereas interlaminar voids were observed throughout the 6- and 8-ply thick tubes. The observed variation in void content can be attributed to the process, which has not been optimized. The results are based on initial consolidation trials and the success of the 4-ply part is indicative of the feasibility of the approach.

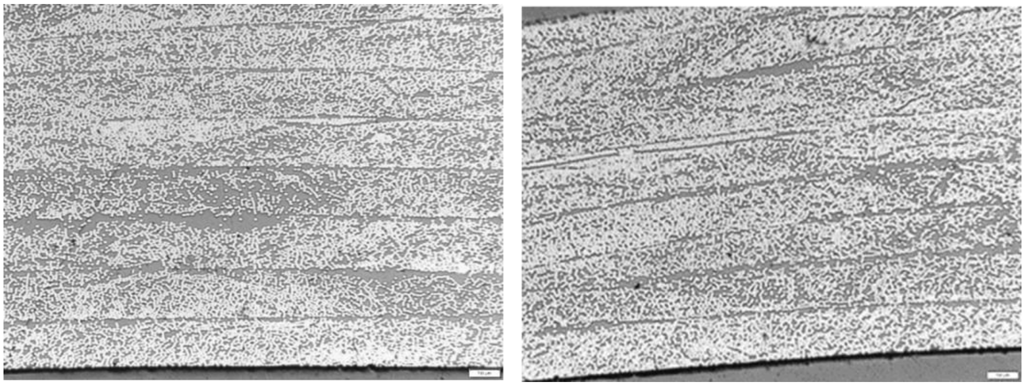

Figure 13. Optical microscopy of 4-ply tube cross-section

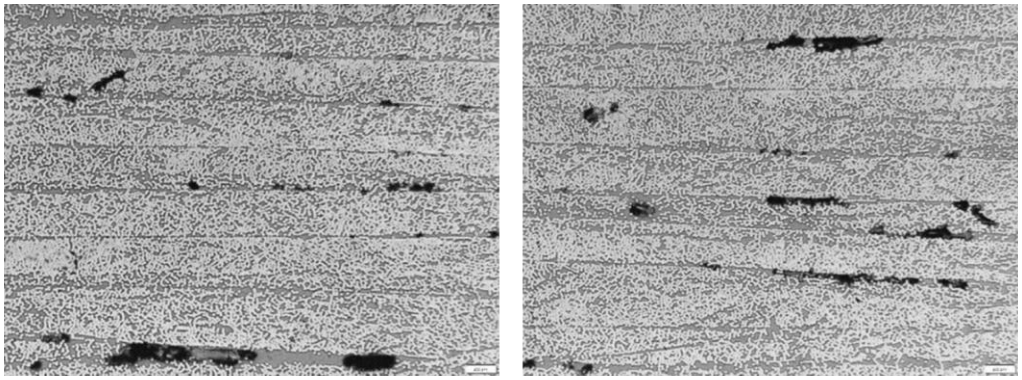

Figure 14. Optical microscopy of 6-ply tube cross-section

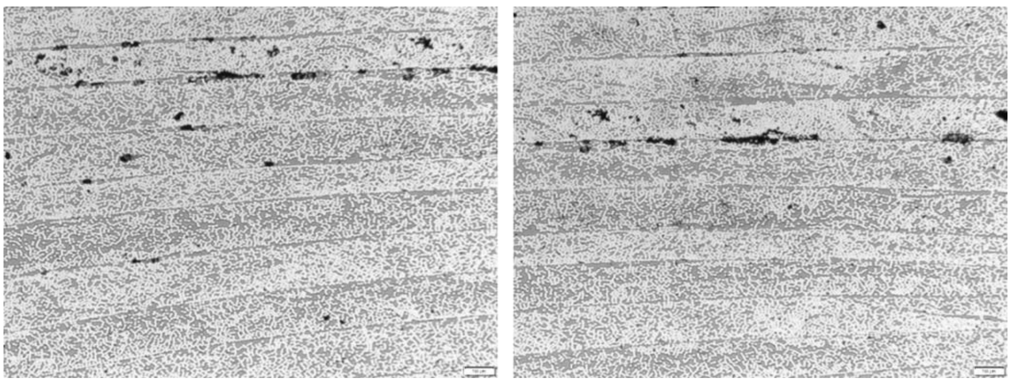

Figure 15. Optical microscopy of 8-ply tube cross-section

Acid digestion of coupons extracted from the tubes indicates an increase in void content with an increase in the number of plies consolidated. Average void content is provided in Table 7 along with the standard deviation. This effort was focused on process development and therefore the variability in void content within the consolidated tube was greater than what is typical of a well-established process for part production.

Table 7. Average void content summary

Ply-count	Void content (% by volume)	Standard Deviation
4-ply tube	4.2	2.2
6-ply tube	7.0	3.9
8-ply tube	9.5	2.3

3.3. Differential scanning calorimetry

DSC thermograms, see Figure , of consolidated tubes lack a cold crystallization exotherm above the 147^{o}C glass transition temperature of LM-PAEK indicating complete crystallization. This was unexpected considering the uncontrolled cool-down rate of the process.

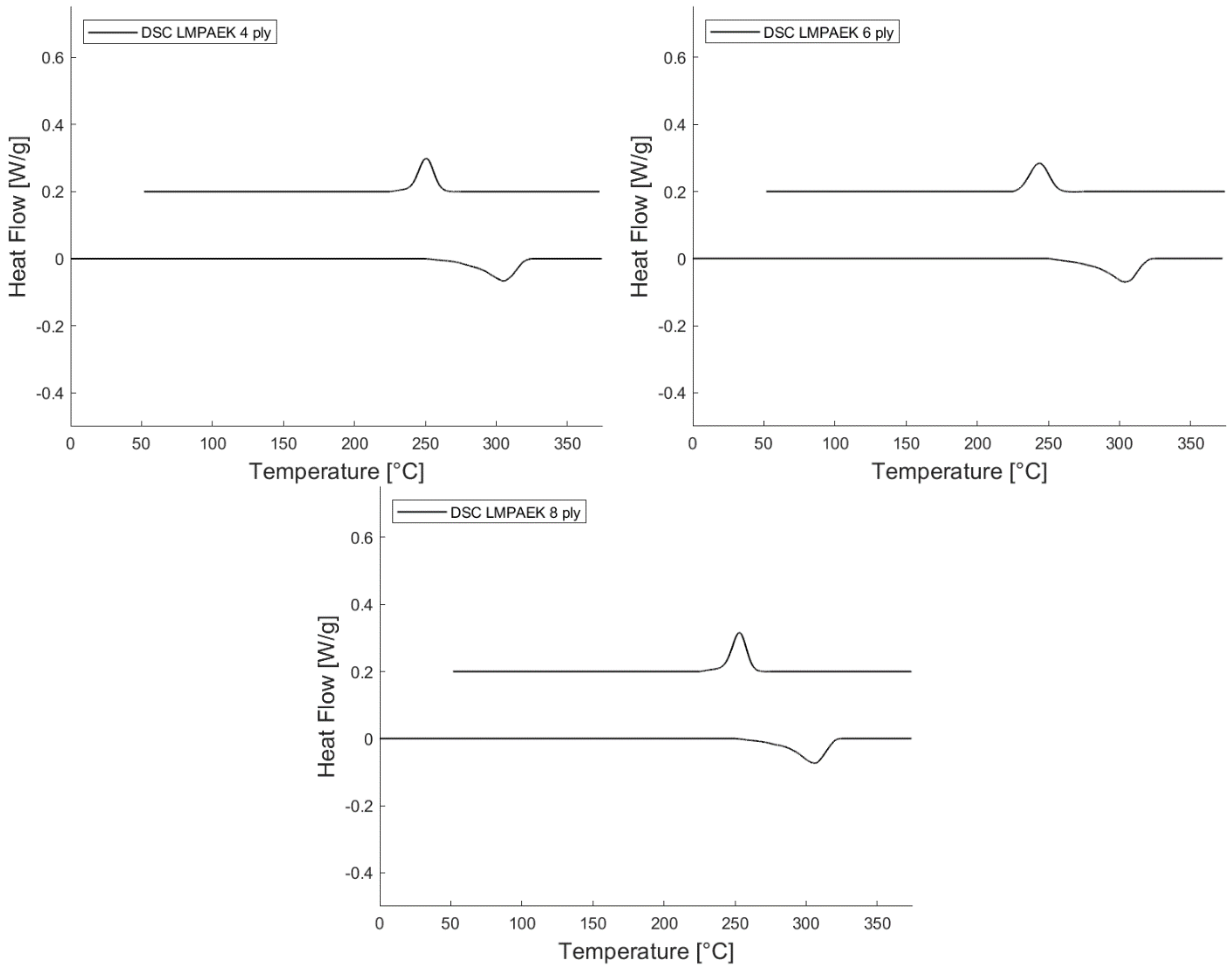

Figure 16: DSC thermograms following consolidation of 4- and 8-ply tubes

An exotherm related to cold crystallization results from incomplete crystal development during cooling from the melt. When reheated to a temperature higher than the glass transition temperature (T_g), increased polymer chain mobility enables crystallization. The degree of crystallinity was calculated as 24% for the 4-ply tube and 26% for the 8-ply tube using Equation 1.

$$X_{mc} = \frac{H_m - H_{cc}}{H_f\,(1 - x_{mr})} \tag{1}$$

where X_{mc} = mass fraction of crystallinity, H_m = heat of fusion at T_{m}, measured as the area of the melt endotherm, H_{cc} = heat of fusion for cold crystallization, measured as the area of the crystallization exotherm. Cold crystallization is identified as occurring higher than T_g on heating, H_f = theoretical heat of fusion for a pure crystalline phase; 130 J/g was used, per the prepreg supplier and x_{mr} = mass fraction of carbon fiber reinforcement.

3.4. Crush testing

The dynamic crush characteristics of the induction welding consolidated tubes were measured using a pneumatic sled facility. Details of the test method are described by Haluza, et al. [10]. In this test a mass is accelerated horizontally, with the use of a pneumatically propelled ram, axially into the test specimen, which is supported on a second larger mass, that is free to move. The base of the specimen is supported with epoxy in a 13mm deep cutout in the base plate the same shape as the specimen cross-section. A crush initiator is machined on the inner circumference of the impacted end of the specimen at a 45° angle.

The impact energy was controlled by varying the mass and velocity of the accelerated mass. Independent measurements of the impact force on the specimen were made using force sensors as well as accelerometers attached to the impacting and support masses. Crush measurements were made using a high-speed camera and photogrammetry software. Measurements were made of the force-displacement response of the tubes and the specific energy absorbed (SEA), which is the energy absorbed by the specimen normalized by the mass of the crushed material.

Tests were conducted on two specimens each of 4-, 6-, and 8-ply tubes. All tubes crushed in a stable manner except for one of the 4-ply tubes, which buckled and yielded invalid results. The measured specific energy absorption (SEA) values for all thicknesses were similar, with an average of 58.3 J/g ($\pm$ 3.3 J/g and 95% confidence level.)

SEA measurements were compared with results from T700S/PR520 thermoset composite tubes manufactured using a resin infusion process and T700GC/LMPAEK tubes consolidated in an oven with pressure applied through thermally activated shrink tape [11]. Figure 16 shows the performance of the induction welding consolidated tubes was statistically equivalent to that of the thermoset and thermoplastic composite tubes manufactured by a traditional process.

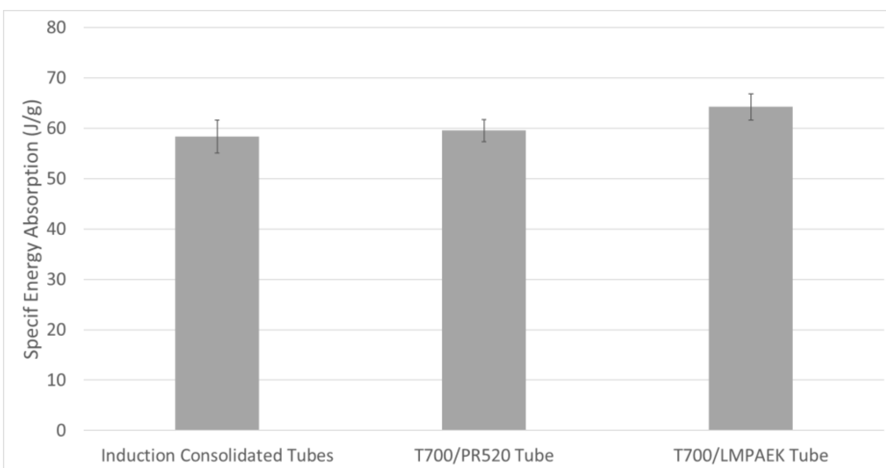

Figure 16. Specific energy absorption measurements comparison between induction heated LM-PAEK vs resin infused PR520 and oven consolidated LMPAEK

The dynamic crush testing demonstrated no significant differences in the specific energy absorption response for the three different ply thickness tubes. However, the 4-ply tube has a risk of buckling due to thin wall thickness. The results were statistically equivalent to conventionally manufactured thermoset and thermoplastic composite tubes of similar material properties, indicating that this manufacturing process would be acceptable for structures in dynamic crush applications.

4. CONCLUSIONS

Braided carbon fiber/thermoplastic preforms were consolidated by induction welding with vacuum bag pressure. The tubes manufactured for this study represent initial consolidation trials by induction welding. Little-to-no void content was observed in the 4-ply thick tubes whereas increasing preform thickness to 8-plies prior to consolidation resulted in void content in the outer ply regions. Crush tests of the tubes demonstrate a crush strength comparable to autoclave consolidated parts. Future work would focus on optimization of the consolidation parameters to reduce void content in thicker parts, a demonstration of reproducibility, and an expanded mechanical test matrix.

5. References

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