HEATPIPE / THERMOSYPHON AUGMENTED MANDRELS TO IMPROVE CURE QUALITY AND TO REDUCE CURE TIME IN THE THERMOSET PIPE AND TUBE FILAMENT WINDING PROCESS

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Abstract

Hollow composite tube or pipe sections are typically manufactured using a filament winding process. Rotating mandrels are covered with continuous strand glass or carbon fibers which are impregnated with an uncured resin generally an epoxy. After winding, the mandrel covered with the resin and fiber matrix is then placed in a convection oven to cure. This paper will address a new method for curing these resin/fiber matrices quickly from the inside out while still on the mandrel without need for an oven. By using a heated mandrel which is isothermal and controllable, the resin will cure uniformly with all volatile gases venting to atmosphere rather than being captured within the wall of the matrix potentially causing porosity and delamination. This method of heat curing uses high watt density energy applied directly to the winding/resin matrix. This results in very rapid cure times with a lower requirement for energy and a resultant improvement in part performance characteristics.

Introduction

This paper is broken down into three sections of study and testing of this technology. The first section will discuss the use of heatpipe thermally enhanced (HPTE) mandrels for filament winding applications to eliminate problematic surface porosity on the inner diameter (I.D.) of a glass fiber/epoxy filament wound tube section. The second section will define the functionality of the HPTE mandrel when an intense localized energy source in the form of an RF induction power supply generated, through a water cooled induction coil, is applied to one end of rotating HPTE mandrel. The third section will detail methodology, apparatus and testing to develop an experimental cell for winding and curing a 76.3 mm (I.D.) tube section of different composite materials and wall thicknesses using a HPTE mandrel heated by an induction power supply and induction coil. The laminate tube will be cured while still on the filament winding machine and will be cured only with thermal energy provided by the mandrel, while the mandrel was being rotated by the filament winding machine.

Section 1

Enhanced Cure of Tube Sections Using HPTE Mandrels & Conventional Convection Ovens

An existing production process consists of a glass fiber/epoxy tube section 1219 mm long with a 6.35 wall being wound over a 50 mm X 1879 mm mandrel. This tube section was exhibiting I.D. unacceptable surface porosity. It was thought that by increasing the temperature of the mandrel during the cure sequence as the mandrel and laminate tube assembly was traveling through a convection tunnel oven, the porosity would be reduced to acceptable levels. Because the tube section occupied 80% of the mandrel length, 20% of the mandrel length was exposed directly to the oven heat. It was thought that the HPTE mandrel would absorb energy through that exposed section and transfer the energy into the mandrel, causing the laminate on the I.D. of the tube section to be further heated. This would draw resin to the I.D. of the tube section resulting in decreased porosity.
To set the experiment up, it was decided to utilize one out of a series of 60 mandrels being used in the production cell as a test mandrel to determine the effect of modifying the mandrel using the heatpipe enhancement process. The charts (Figures #1 and #2) track the temperatures at three sites along the length of the mandrels. Thermocouple #1 was located 305 mm from the immersed end of the mandrel and 152 mm above the surface of the fluidized bed. Thermocouple #2 was located at the mid point of the length of the mandrel. Thermocouple #3 was located 50 mm below the top of the mandrel. The mandrels were each, in turn, suspended vertically above the fluidized bed (Figure #3) with 152 mm of their length submerged in the bed. The bed temperature was held at a constant 177°C.

![Transinit Temperature Curves for the Hollow Mandrel](image-url)

- **Date:** Jan. 9, 09
- **Mandrel Outer Diameter:** 47.63 mm
- **Mandrel Length:** 1828.8 mm
- **TC location is the distance from the top of the mandrel**
- **Vertical orientation.**
- **Sand Bath Temp.** 176.7 Deg. C
- **Heat Transfer Rate:** ~12W

**Figure 1: Transient Temperature Curves for the Hollow Mandrel**
For comparison, two mandrels were tested; the first being a hollow mandrel used in the current process, the other, a HPTE mandrel. After undergoing the enhancement process, the HPTE mandrel was tested using a fluidized bed sand bath heat generator (Figure #3).

The hollow mandrel measuring 48 mm O.D. and 1828 mm long with a 5 mm wall was inserted into the fluidized bed to a depth of 152 mm while the bed temperature was controlled at a constant 177°C. The hollow mandrel achieved steady state in 43 minutes. Thermocouple #1, 152 mm above the fluidized bed, achieved a steady state temperature of 49°C. Thermocouples #2 located at the mid point of the 1828 mm mandrel achieved a steady state temperature of 23°C. Thermocouple #3 located 50 mm from the top of the mandrel achieved a steady state temperature of 22.5°C.
Figure #3: The HPTE mandrel was tested using a fluidized bed sand bath heat generator

Figure #1 depicts a chart showing the time/temperature to steady state for temperatures at points described above while the hollow mandrel was in transit to steady state. The blue trace on this chart indicates the time/temperature delta T between the various thermocouples along the length of the mandrel as it was approaching and achieving a steady state condition. Note the significant delta T evidenced early on in the transit. The delta T reached a steady state of 13°C.

Next the HPTE mandrel measuring 50 mm O.D. and 1879 mm long with a 5 mm wall was inserted into the fluidized bed to a depth of 152 mm while the bed temperature was controlled at a constant 177°C. The thermally enhanced mandrel achieved steady state in 91 minutes. Thermocouple #1, 152 mm above the fluidized bed, achieved a steady state temperature of 116°C. Thermocouple #2 located at the mid point of the 1828 mm mandrel achieved a steady state temperature of 116.5°C. Thermocouple #3 located 50 mm from the top of the mandrel achieved a steady state temperature of 116.5°C.

Figure #2 depicts a chart showing the time/temperature to steady state for all three thermocouples mounted on the HPTE mandrel. The blue trace on this chart indicates the time/temperature delta “T” between the various thermocouples along the length of the mandrel while achieving a steady state condition. Note that the delta T of 0°C evidenced early on in the transit which remains essentially constant at 0°C through the entire transit to steady state.
Field Testing

The HPTE mandrel was returned to the manufacturing site where it was placed in the production cell with the other 59 mandrels. The mandrel was marked and used in rotation with the other unimproved mandrels. The filament winding and curing processes were unchanged. The winding used on the mandrels in this application covered approximately 80% of the surface area of the mandrel. The remaining 20% of the surface of the mandrel was directly exposed to the heat of the convection cure oven. The HPTE mandrel was oriented during its transit of the cure oven such that the exposed surface of the mandrel was at the bottom. This further enhanced its thermal performance due to gravitational assist in returning the charge fluid to the evaporation site. This HPTE mandrel was subjected to the same manufacturing and curing process as the unimproved hollow mandrels. Quality Assurance testing confirmed that the HPTE mandrel produced a very consistent and predictable resin rich non-porous I.D. surface every time it was processed while the unimproved mandrels produced an equally predictable 20% scrap rate.

Further Experimentation & Testing

At this writing, the cure time and temperature variables remain unchanged. The next step will be to change first the speed of the conveyor within the oven and then the temperature at which the cure is accomplished in order to determine the further benefits in energy usage, part quality, performance and increased production throughput as line speed is increased.

Section 2

Remote Heating of an HPTE Mandrel with Thermal Energy Provided by RF Induction Heating

Typically, a cure sequence in pipe or tube fabrication using the filament winding process consists of removing the mandrel and the uncured filament/resin matrix winding assembly from the winder and placing that assembly in a convection oven at an elevated temperature or close to a radiant heat bank for a period of time in order cure the epoxy resin. That cure temperature is generally within a range of 110°C to 200°C. Typically, the assembly described above is mounted in a fixture within the oven or radiant heater cure cell to permit slow rotation to assure homogeneous resin consistency within the composite laminate. The time required to achieve a steady state temperature throughout the winding and the mandrel to a temperature sufficient to curing is of long duration, ranging from 30 minutes to 8 or more hours depending on the thickness of the cross section of the winding.

When a HPTE mandrel is used during a convection oven cure sequence, the enhanced heat transfer capability of the HPTE mandrel is beneficial to the process in that any heat presented to the I.D. of the pipe or tube section during the cure process results in; 1) resin migrating towards the heated mandrel surface causing a resin rich non-porous I.D. surface condition and 2) a shorter cure time due to an increase in the uncured composite laminate surface being actively heated and therefore cured. Recognizing the isothermal characteristics of the HPTE mandrel, a methodology was sought to enable an optimum cure time of a typical filament wound pipe tube section which would rely entirely on a uniformly heated HPTE mandrel. This methodology would permit the resin matrix to cure from the mandrel O.D. outward through the resin/fiber matrix to the surface of the pipe or tube section. The manufacturing process would no longer require a convection oven or radiant heater fixture to cure the part. Further, the cure would occur in reverse to the typical cure process; from the mandrel surface to the laminate section I.D. to the O.D.
In order to accomplish this cure process without the use of a convection oven or infrared heating environment, it was necessary to find a power source that would provide sufficient energy to the surface of the HPTE mandrel while not inappropriately heating the resin on the wound section O.D. RF induction heating of the HPTE mandrel offered some significant advantages.

Advantages

1. The heat could be generated by water cooled coil located in proximation to the mandrel but not touching it. This permitted unrestricted rotation of the mandrel during the cure sequence.

2. Large amounts of energy output were available to the mandrel from the induction power supply in very short time periods resulting in very rapid mandrel heat up times. The super thermally conductive characteristics of the HPTE mandrel would assure that the localized intense energy inputs of the induction coil would be transferred throughout the mandrel so as to achieve isothermal conditions on its surface.

3. The energy generated by the induction power supply would not be absorbed directly by the uncured resin. In fact, with the exception of carbon fiber, the RF power would pass through the resin/filament matrix undetected and unaffected. The radio frequency (RF) power would then heat the steel HPTE mandrel. The heated mandrel would then cure the composite laminate tube from the mandrel surface out to the O.D. of the tube section.

4. A byproduct of a cure of this type (I.D to O.D.) would be that the volatile vapours generated by the cure heat would exit the laminate to atmosphere rather than be trapped by a cured O.D. surface. This could potentially reduce porosity and delamination in thicker tube wall sections.

5. To summarize, the heatpipe thermo dynamic of the HPTE mandrel would result in uniformly redistributed RF induced thermal energy to near isothermal conditions throughout the mandrel surface quickly. This would result in the following outcomes: 1) The mandrel surface would be at one predictable temperature as it was heated and cooled; 2) The power input per unit time directly to the mandrel would be much greater than previously possible; 3) the cure would occur from the I.D to the O.D of the tube section.

Apparatus

An apparatus was constructed to examine the real time performance of a HPTE mandrel when being heated by an induction power supply and coil. The apparatus consisted of a prototype HPTE thermally enhanced mandrel 76.2 mm O.D. X 1625 mm L.O.A. with 50 mm hexagon end caps 100 mm long one at each end. The HPTE mandrel was constructed of D.O.M tubing with mild steel being used for the two end caps. The mandrel was then mounted in a small lathe with an adjustable RPM capability. The other end of the HPTE mandrel was supported by a two roller steady rest. An RF induction coil was positioned at the outboard end of the mandrel approximately 152 mm from the end opposite the headstock. The coil was 50 mm wide and had a 25 mm annulus between its I.D. and the mandrel O.D. (Figure #4)
Figure #4: The HTPE testing cell: A HPTE mandrel held in the lathe headstock by its hex end cap. The mandrel is supported approximately 70% out from the drive end by the steady rest. The induction coil also appears in this photo.

An induction power supply rated at 120 VAC with a variable output of from 0 to 1,000 watts was coupled to a water cooled induction coil via an umbilical cable. (Figure #5) A closed loop water cooling unit was used to cool both the power supply and the induction coil. A forward looking infrared camera (FLIR) (Figure #6) was positioned such that the entire length of the HPTE mandrel; the induction coil and lathe were within its view. The output of the FLIR camera was directed to a software based data capture program which had the capability to provide accurate, scaled thermographic video of the thermal transients generated. These transients were monitored and recorded in real time.
The same apparatus was used to also test and monitor a hollow D.O.M steel mandrel of the same size shape and weight. With the same power loads applied; the FLIR camera system was employed to capture the data and video.

Method

The FLIR camera was used to capture a thermographic video of the thermal transient which occurred as power was generated by the induction coil on the rotating HPTE mandrel. That video data captured by software. First, a 30 second film clip was produced at room ambient temperature with no power being applied to the HPTE mandrel. The apparatus consisting of the HPTE mandrel discussed above was then rotated at 100 RPM by the lathe headstock. The induction power supply was then engaged and an output power of 850 watts was applied to the induction coil which radiated RF energy onto the rotating HPTE mandrel. The temperature transient to steady state was then observed and recorded both quantitatively and as a thermographic video clip.

The HPTE mandrel was removed from the lathe and a traditional mandrel of the same physical size and weight was installed. The traditional mandrel was presented with the same 850 watts using the same induction coil. The mandrel was rotated at the same RPM.
Enhanced Curing of Pipe or Tube Sections Using Process Controlled RF Induction Heating

Introduction

In order to determine the direct value of a HPTE mandrel as a cure device within the filament winding process, using the mandrel as the single source for curing, it was necessary to wind tube sections and subject these tube sections to cure by heating the sections while on the rotating HPTE mandrel as it was being heated by an induction power supply and coil.
Apparatus

An experimental filament winding and curing cell was assembled using a conventional filament winding machine in conjunction with a 50 KW variable output induction power supply. The 50 KW variable induction power supply was mated to the same coil used in the initial HPTE mandrel heating tests as described in section # 2. The induction power supply was controlled manually by having an operator continuously adjust the power supply level as well as the on/off cycle as needed to satisfy a cure temperature based on information provided by a second person monitoring the temperature of the HPTE mandrel exposed surfaces at either end of the mandrel. An infra red laser targeted non-contact thermometer was used to monitor temperatures. To reduce the emissivity errors in the readings, flat black paint was applied to the exposed HPTE mandrel surfaces.

Method

A fiberglass epoxy prepreg was wound on the HPTE mandrel to a wall thickness of 5 mm. The tube section was 1219 mm long. The winding sequence and set up reflected typical filament winding patterns. After the filament winding sequence was completed, the HPTE mandrel, now wrapped with the uncured tube section, was removed from the filament winding machine and placed in a convection oven. The assembly was monitored for cure using typical process methodology.

The filament winding technician determined that typically a winding or tube section of this material, size and shape would require 2 hours in the convection oven to fully cure. The tube section was then cooled and removed from the HPTE mandrel. The tube section was examined and determined to be satisfactorily cured. Next, the HPTE mandrel, now at room temperature, was reloaded in the winder and the same winding sequence was followed using the same prepreg material. Upon completion of the winding sequence, the filament winding and mandrel were left on the winder and the rotation slowed from winding speed to 10 RPM.

The induction coil, which had remained positioned around the HPTE mandrel during the winding sequence, was now energized. The temperatures of the exposed surfaces of the HPTE mandrel were monitored. The HPTE mandrel was heated to a temperature of approximately 144°C to 160°C. Manual control of the power supply was achieved by a technician adjusting the output level of the power supply in response to spoken feedback by another technician who was taking temperature readings on the exposed mandrel surfaces with an infrared thermometer.

The filament winding machine technician monitored the cure status of the winding and determined that it had cured to the same satisfactory level of cure as the control tube section which had been cured in the convection oven. The time to cure to this acceptable level was 12 minutes. The HPTE mandrel and cured winding were removed from the winder and allowed to cool to ambient temperature. The tube section was then removed. The filament winding technician determined that both the convection oven cured tube and the HPTE mandrel cured tube exhibited the same performance characteristics.
The HPTE mandrel was then reloaded on the winder and a carbon fiber epoxy prepreg was wound on the 76.2 mm HPTE mandrel using the same winding configuration as was used in the other winding sequences. In this instance the same winding pattern was used however the tube wall stock was increased from 5 mm to 6.35 mm. At the completion of the winding sequence, the induction coil, prepositioned around the HPTE mandrel prior to the winding sequence, was energized. The induction power supply operator manually adjusted the power output to satisfy a 140°C to 160°C temperature on the exposed surfaces of the HPTE mandrel as noted and monitored continuously via the infra red thermometer by a second technician. The filament winding technician determined that after 15 minutes into the cure sequence, the tube section was acceptably cured. The HPTE mandrel and winding were then cooled and the tube section removed. Next, a carbon fiber epoxy prepreg was wound on the HPTE mandrel using the same winding process and pitch as on the other iterations however the wall stock was increased to from 6.35 mm to 12.5 mm. Figure #9 is a photo showing the HPTE mandrel, the RF induction coil and the head stock of the winder during this winding process. After the winding sequence was completed, the induction coil was energized and power applied sufficient to heat the exposed surfaces of the HPTE mandrel to a target temperature of 140°C to 160°C.

Figure #9: The HPTE mandrel, the RF induction coil and the head stock of the winder during this winding process
After about 20 minutes into the cure sequence, it was noted that the exposed surfaces of the HPTE mandrel were increasing in temperature without the need for the induction power supply to provide external energy. After discussion, it was agreed that an exothermic reaction was occurring within the carbon fibre epoxy winding. The temperature on the exposed surfaces of the HPTE mandrel was continuously monitored while the temperature rose to a steady state of 171°C which it maintained for roughly 10 minutes after which the temperature of the HPTE mandrel began a slow reduction. At this time the filament winding technician determined that the tube section was acceptably cured. The duration of this cure cycle was 28 minutes. Figure #10 is a photo showing the 12.5 mm wall carbon fiber epoxy tube section winding during the exothermic portion of the cure sequence. Because of the HPTE mandrel's capability to redistribute energy from local energy inputs, the exotherm energy generated was redistributed uniformly over the entire surface of the HPTE mandrel removing any “hot spots” that would normally occur when an exotherm is established.

![Figure 10: Depicts the 12.5 mm wall carbon fiber epoxy tube section winding during the exothermic portion of the cure sequence.](image)

During all cure cycles, the temperature at both exposed ends of the HPTE mandrel were continuously monitored and read aloud in order to fine tune the energy input to the HPTE mandrel. In all instances, during all cure sequences, the temperatures on the prepreg tube sections appeared to rise in temperature with relative uniformity, appearing to be within 1.5°C to 2°C from random point to point throughout the cure sequence. Examination of the cured tube sections after cooling indicated acceptable levels of structural performance, satisfactory cure and homogeneous resin distribution throughout the thickness of the tube wall and along the entire tube length.
Closed Loop Control of the RF Induction Power Supply

The next step in proving the value and benefit of the induction powered HPTE mandrel cure process was to install a non contact temperature sensor coupled to a process temperature controller to drive the induction power supply and coil thus creating a closed loop control system. This would provide the operator with the ability to select any discrete temperature set point and/or time temperature ramp and hold sequence to optimally control, in a repeatable fashion, the temperature variable during a complex cure sequence. The RF induction power supply and coil system were augmented by a compact infrared thermometer and digital indicating process controller with Proportional-Integral-differential (PID) current output (Figure #11). The infrared (IR) sensor (Figure #12) monitored the exposed surface temperature of the HPTE mandrel’s surface at that point on the surface where the induction coil was radiating energy. The process controller provided a 4 to 20 mA DC output to the induction power supply which in turn varied the output power to the induction coil. The infrared sensor monitored the HPTE mandrel surface temperature at the site of the induction coil location. The component assembly, thus configured, provided a true proportional, integral, and derivative control to the process.

Figure #11: Proportional-Integral-differential (PID) current output

Figure #12: Infrared (IR) Sensor
The control system was assembled and integrated with the HPTE mandrel. The HPTE mandrel was then operated on the winding machine at a speed of 10 RPM and a set point of 177°C was selected on the process controller. PID parameters were fine tuned and a steady state process temperature was achieved on the unloaded HPTE mandrel. Deviation from the process control set point was +/- 0.5°C at steady state.

Process Testing

Due to the combination of the HPTE mandrel and the control loop’s ability to maintain near isothermal conditions on the rotating mandrel at any discrete process temperature, it was decided to wind prepreg materials under two scenarios: 1) Wind the tube section while the HPTE mandrel was a room or ambient temperature and then begin the 177°C cure sequence and 2) Wind the tube section on the HPTE mandrel while the temperature of the mandrel was being controlled at a temperature of 177°C.

Four tube sections were wound using this closed loop process controlled cell using the winding parameters developed for the testing sequences, above. Two of the tube sections were wound with the HPTE mandrel at ambient temperature. The HPTE mandrel was then heated to 177°C for the cure sequence. The time to cure was the same duration as was noted above for the same wall stock thickness and material.

Next the next two tube sections were wound on the HPTE mandrel with the mandrel being controlled at 177°C during the winding sequence. That temperature was maintained on the HPTE mandrel until cure had been satisfactorily achieved. The overall time duration of the winding and cure sequences to satisfactory cure was noted to be reduced by the time typically needed to wind the tube section when compared with the overall wind and cure time of the first two tube sections. As of this writing, fiberglass/epoxy prepreg materials have been wound as tube sections with 4.7 mm wall stock and 355mm long on the HPTE mandrel using both scenarios (1) and (2), above.

Conclusions

During initial testing using a heated fluidized bed sand bath, the HPTE mandrel exhibited a monolithic or isothermal response to a localized thermal energy input through its entire transit to steady state. This isothermal condition on the mandrel face, in response to the localized energy input was implemented in an application where a HPTE mandrel with approximately 20% of its length exposed to the energy in a convection cure oven, resulted in a uniformly heated mandrel surface which transferred heat energy directly to the I.D. of the resin filament matrix during the cure process.

This enhanced heat transfer was beneficial to the cure process in that the heat presented to the I.D. of the tube section by the HPTE mandrel, during the cure process, resulted in resin migrating towards the heated mandrel surface. This resin migration produced a resin rich non porous I.D. surface condition eliminating the porosity typically occurring there. The super thermal conductive characteristics of the HPTE mandrel permitted the use of localized concentrated thermal energy generated by an induction coil. That energy, because of the high speed heat exchange occurring within the HPTE mandrel, was redistributed through the complete HPTE mandrel and resulted in real time near isothermal conditions on the HPTE mandrel face from start up to steady state while the HPTE mandrel was being rotated.
The HPTE mandrel, when mated to an induction power supply of sufficient power, can effectively cure both carbon fiber and glass fiber epoxy prepreg materials in rapid times with homogeneous resin cure without the need for removal of the mandrel and winding from the winding machine or the use of a convection oven. It would appear that the cure time to acceptable cure is significantly reduced when the tube section is heated uniformly and internally via an induction power supply coupled to a heated HPTE mandrel.

The use of closed loop PID control coupled to the induction power supply while monitoring a small surface area of the HPTE mandrel permits continuous sustainable temperature control of the cure sequence at any discrete temperature and time/temperature ramp and hold process chosen. The speed of response of the control loop and the near isothermal energy output from the HPTE mandrel provides for exceptional stability and control of the temperature variable during the cure sequence of the production process.

**Process Implications for the Automotive Sector and CAFE**

There are many possibilities with this new process to further enhance the manufacturing of filament wound structures, composite fiber placement and open/closed molding applications for the transportation sector. Considering the drive manufacture safe, lightweight vehicles and adherence to Corporate Average Fuel Economy (CAFE) intended to improve the average fuel economy of cars and light trucks (trucks, vans and sport utility vehicles) sold in the US and Canada any tubular structure or reinforcement would benefit from the uniform transference of energy during the cure. Some examples could include:

- Drive shafts
- Seating structures
- Front end modules
- Door reinforcements

More work is required for specific components and materials. The uniform delivery of heat during the processing of these parts will have a profound impact in material selections and cure rates. HTPE mandrel technology can be a new tool for light weighting component processing for the automotive sector.