E. Development of the Infrared Thermal Forming Process for Production of Aluminum Vehicle Components

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Objectives

- Implement infrared (IR) thermal forming as a preform method for aluminum tubes prior to hydroforming to reduce vehicle weight and achieve greater fuel economy.
- Verify initial IR thermal forming estimates to determine concept feasibility for aluminum tubes.
- Develop IR thermal forming process to form basic preform aluminum tubes for subsequent hydroforming trials.
- Evaluate IR thermally formed tubes after hydroforming.

Approach

- Initiate a 1-year feasibility study, followed by longer-term activities (based on favorable results from this feasibility effort) to address the following four primary process concerns: (1) a process that produces bends in the tubes, (2) a process that can meet production rates required for automotive needs, (3) an estimated cost associated with the process and how it compares to present processes, and (4) the influence of the process on the applications, that is, effects on material properties.

Accomplishments

- Verified, within the feasibility phase of this project, the relative order-of-magnitude for time estimates for thermal forming aluminum tubes using IR process trials.
- Calculated and determined the thermal flux necessary for forming aluminum tubes based on IR thermal experiments, utilizing thermal input results from laser forming experiments as a guide. Experiments determined that existing reflectors are not capable of providing the type of power distribution needed for forming aluminum tubes.
- Developed via collaborations with Vortek and N. A. Technologies, Inc., the initial design (optics) concept for a new reflector that can achieve the heat flux and IR arc profile needed for the pre-bending 4- to 5-in. diameter aluminum tubes. These tubes preforms are intended to be subsequently hydroformed as aluminum vehicle components. This optics design was based on our initial experimental and simulation modeling results. However, the cost of these optics exceeded the allotted project budget. Consequently, an alternate less costly approach was devised (see next item).
- Developed and designed, via collaborations with Vortek and N. A. Technologies, Inc., an alternative, less expensive, reflector design that utilized a current base reflector, but also incorporated a secondary reflector to

control and contour the thermal flux heat profile onto the tube to achieve the calculated/desired heat flux. Although this secondary reflector design was developed and was less costly than the new reflector, the cost associated with this option also exceeded the funding available for this project.

Conclusions

- Within the feasibility phase of this project initial IR trials, based on flat plates, for thermal forming aluminum tubes have verified the relative order-of-magnitude of time estimates using the IR process. Forming of a 45° bend is estimated to be achieved in 5–20 s. Results suggest that a minimum of ~5 s is required using optimized processing with cooling, a range of 10–20 s without cooling.
- Both experimental and simulation modeling results indicated that optics development and validation phases, in addition to cooling control, are necessary to achieve the power distribution required to conform larger tubes to the shape needed for hydroforming preforms.
- Several (new and modified) reflector designs have been proposed and developed that qualitatively provide the thermal flux contouring needed for preforming tubes for subsequent hydroforming.
- The cost estimates for both a new reflector design (optics) and the less expensive side-shield (secondary reflector) concepts exceed the budget allotted for this project, and therefore preclude the further development and implementation of this technology.
- Without additional funding, the reflector (optics) proposed and designed within this project that controls and contours the thermal flux heat profile onto the tube (to achieve the calculated/desired heat flux) can not be fabricated and implemented to demonstrate the success of the IR technology as a more cost efficient and lighter materials approach to pre-forming tubes for subsequent hydroforming.

Future Direction

- Secure additional funding for the reflector (optics) proposed and designed within this project to fabricate, implement, and demonstrate the success of the IR technology as a more cost efficient and lighter materials approach to preforming tubes for subsequent hydroforming.
- Pursue alternate heat sources, for example, induction thermal forming options for comparative costs.

Introduction

During the last 9 years, N. A. Technologies, Inc. (NAT) initiated thermal forming research utilizing the laser as the heat source. Using the laser, NAT has formed a wide variety of tubes in various sizes and materials. The laser thermal forming process has been found to work on both large and small aluminum tubes (see Figure 1). These experiments have demonstrated that the wall thickness of the outside bend of the tube is virtually unaffected, and the inside bend actually thickened in all cases. However, the cycle times required for laser forming are too long to be considered for high-volume applications. Based on some work done on plate-stock, NAT has shown that if the thermal input power level is scaled-up from 4 kW (characteristic of laser technology) to 300 kW (characteristic of IR plasma lamp), IR thermal forming works similarly, but much faster. However, this process still has to be proven for tubes. Consequently, the Vortek lamp that is installed at Oak Ridge National Laboratory (ORNL), with its inherent power levels, offers the potential to move the thermal forming process to speeds that are high enough to reach production rate levels. In fact, the higher power levels available with the Vortek lamp are key to taking this process from the “prototyping” or low-volume production stage, to the actual high-volume production stage. NAT has estimated that utilizing the power capacity of the Vortek lamp, the thermal forming process can be put into actual production (i.e., 60 units/h, as opposed to 2 units/h that can be achieved in the laser lab today). The key to tapping this higher

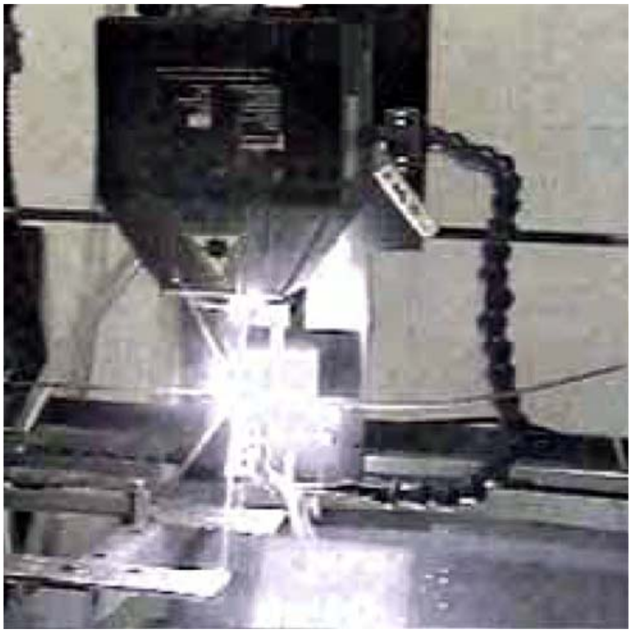

Figure 1. Laser thermal forming process demonstrated on small aluminum tubes.

power source to thermally form the tubes is to develop the correct heat distribution profile.

To date, a great deal of effort has been spent on finite-element modeling at Massachusetts Institute of Technology (MIT), Boeing, Rockwell, Penn-State, Ohio State, British Aerospace, and the best results (from MIT) provide predictions that are off by ±50%. These results emphasize the complexity of the IR thermal forming process. This complexity results directly from the extreme, transient nature of the process with continuously varying surface boundary conditions. Consequently, considerable work remains to be done to develop this process to distribute the heat properly around the tube. NAT has spent nearly a decade developing an understanding of the heat distribution needed to laser form a tube. Developing this process to distribute the heat from the Vortek heat source properly around the tube will be a significant effort. NAT is optimistic that, based on its success at scale-up of plate using the neural-network-based model,[1] developing the right thermal distribution with the Vortek lamp is possible. Success will be defined as demonstrating that the IR thermal forming process works and that it has the possibility of scale-up to real production.

Building on the NAT experience with laser forming and the results from the preliminary experiments involving the IR thermal forming process completed as part of the MPLUS program at ORNL, this project holds the promise of achieving DOE goals of reducing vehicle weight to realize greater fuel economy. The high thermal heat source of the IR lamp technology holds the key to unlock the potential in demonstrating that the IR thermal forming process is more than a laboratory demonstration so that the energy savings potential can be realized.

<u>Status and Summary</u>

Introduction and Background

From the onset of this project, as noted above, it has been known that developing the thermal forming process to properly distribute the heat flux around the tube would be a significant effort. However, based on NAT successful results using laser forming on small-diameter tubes, and its subsequent success at trial scale-up efforts for translating these results to plate, with the neural-network-based model developing the right thermal distribution with the Vortek lamp seems very viable. Consequently, a preliminary *feasibility study* was initiated. Due to the limited project budget available in the first year, the most cost-effective approaches were attempted first to verify the viability of utilizing IR thermal forming to form tubes. Several experimental approaches were attempted to determine the concept feasibility of utilizing IR thermal forming as a fixtureless preforming operation for subsequently hydroformed aluminum vehicle components. These approaches were (1) adapting a long (4-cm) stand-off reflector that was available, (2) modifying the hardware below the reflector to obtain a smaller thermally controlled heat flux zone (thermal footprint), and (3) developing and testing a thermal processing model to run process simulations to determine the appropriate reflector design needed to produce the correct heat flux distribution around the tube. These cost-efficient methods/steps were discussed in the FY 2003 annual report, but are included here for project clarity.

[1]Trained neural networks are attractive predictors for manufacturing processes because they can accurately capture material/process response without requiring actual physical data/models.

Hardware Modifications (FY 2003–FY 2004)

In the initial experimental attempts to form the aluminum tubes, the optics selected and utilized were those that enabled the largest (4-cm) stand-off from the work piece. To accomplish this, the already available 4-cm IR reflector optics were redesigned/reworked to attempt to provide the thermal flux and thermal footprint necessary to thermally bend tubes. Results from these experiments determined that a narrower beam and a higher heat flux are needed. To address this issue, a water-cooled, focusing plate was designed and fabricated to assist in controlling this heat input. The motive behind this inexpensive attempt was to constrain the heat flux at the surface of the tube by merely blocking and absorbing the heat outside of the targeted thermal footprint zone of the IR beam. Experimental trials, however, determined that not enough heat was available to form tubes because the thermal contour was not optimized yet for the tube geometry. However, these experiments did confirm the need to gain a more fundamental understanding of the heat flux required to design an IR thermal forming system to address the more complex case of thermally forming tubes. To accomplish this goal, an IR thermal forming system is needed to address several issues, including reflector shape, focal length, power density, and cooling. Consequently, some basic IR thermal forming trials were initiated to gain a more fundamental understanding of the thermal forming approach needed to bend the significantly more complex tube geometry and to gain a more basic understanding of how the heat flux distribution needs to be tailored to obtain the amount of tube bending necessary. Since these trials were described in detail in the FY 2003 annual report, the results from these experiments will only be summarized here.

<u>Basic Experimental Trials and Modeling Simulations</u>. Utilizing the data obtained from instrumented (thermocoupled) aluminum plates (Figure 2), thermal modeling simulations were run using the experimental parameters as a guide in setting up the modeling boundary conditions. Thermophysical parameters used for the simulations were obtained from the literature. The purpose of the experimental trials was first to obtain experimental temperature data to guide the selection

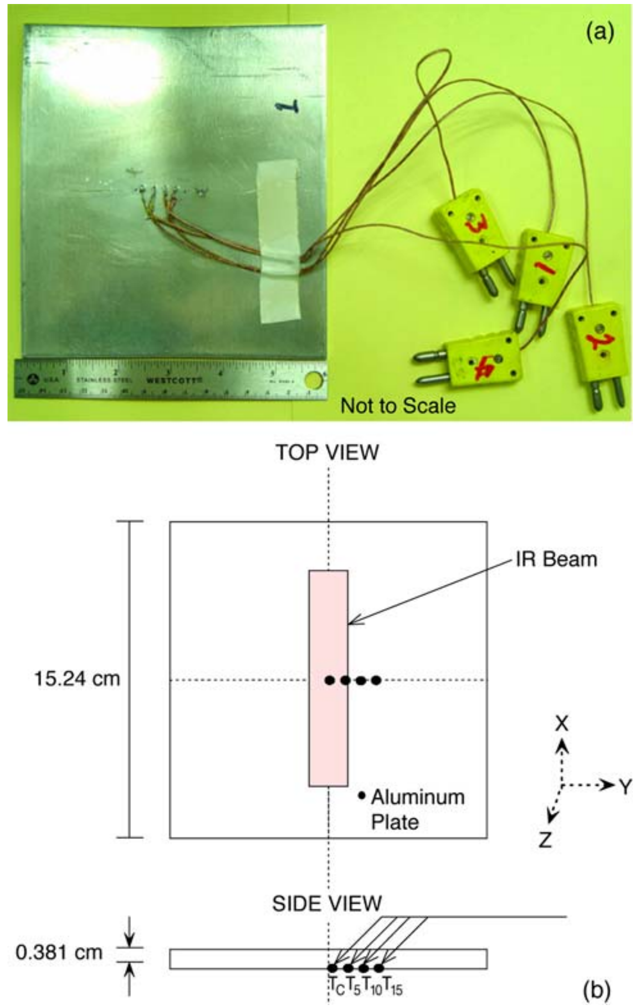

Figure 2. Experimental thermal forming specimens instrumented during trials to gain a more fundamental understanding of the IR thermal forming process.

of the heat flux needed to form aluminum plates and later extend this methodology to the more complex case of forming the tube geometry. The modeling results successfully predicted very similar thermal profiles, (Figure 3) and plate deflections (see Figure 4) with those experimentally measured/obtained from the initial basic experimental study trials. In addition, parametric studies were conducted to predict the effect of plate thickness on the thermal forming response. These results (Table 1) indicated (using these initial non-optimized experimental results) that as the maximum heat flux is increased, the deflection increases; and that as the plate thickness decreases, the plate deflects significantly more. Of course, the thicker plate also

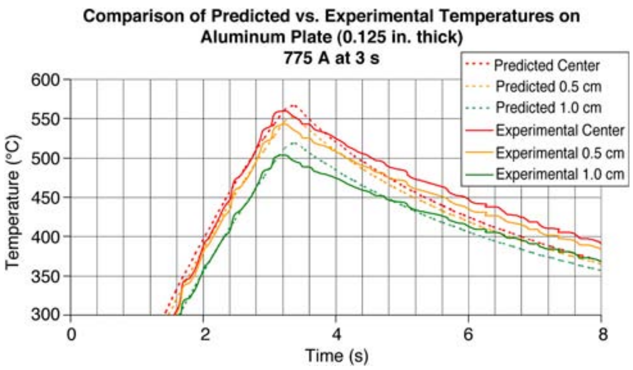

Figure 3. Experimental results and modeling simulation predictions that demonstrate excellent agreement.

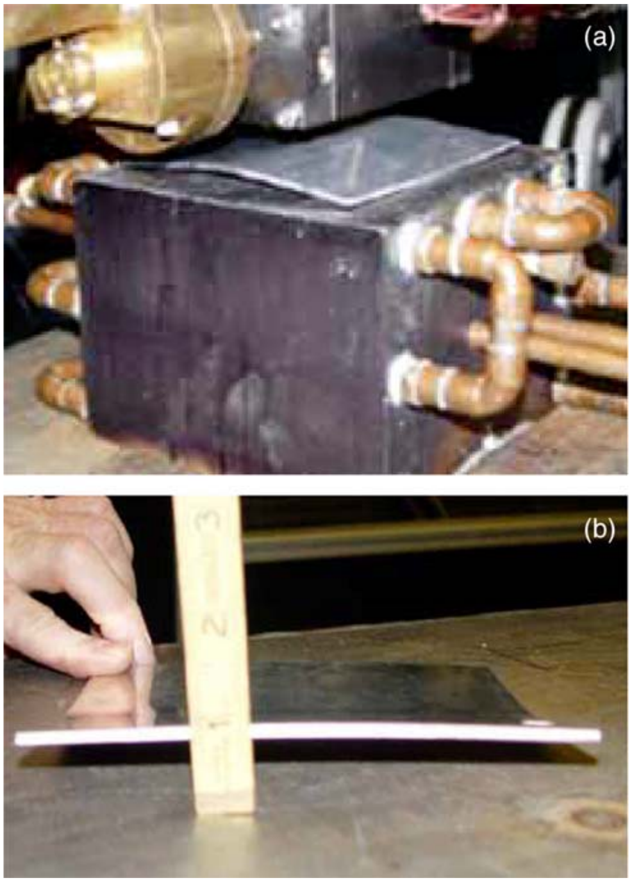

Figure 4. Examples of (*a*) the IR thermal forming setup and (*b*) the aluminum plate deflection observed during initial experimental IR thermal forming trials.

Table 1. Parametric modeling study results

Plate thickness (in.)	Maximum heat flux (W/mm^2)	Maximum temperature (^oC)	Maximum deflection (mm)
0.125	2.25	641	10.92
0.125	2.0	574	9.58
1.0	2.25	203	0.016
1.0	2.0	184	0.014

cools much more slowly, and additional localized cooling, applied immediately after heating likely would provide the necessary constraint to enhance bending. This would also be true for the thinner plate.

Both experimental and simulation modeling results indicated that further optics development and validation phases are necessary to achieve the power distribution required to conform larger tubes to the shape needed for hydroforming preforms.

Neural Net Modeling (NNM) simulations have also been utilized to gain some insight into what the optimized thermal processing parameters need to be to thermally form an aluminum plate. The model allows one to vary each of the three processing parameters independently, and/or as a group to assist in determining the most suitable set of processing parameters (IR power, the number of pulses to obtain a 45^o deflection angle, and the total processing time) defined within the experimental data limits. Consequently, additional experiments are being planned to further optimize cycle times within broader processing limits.

Hardware Modifications

The existing reflectors at ORNL are not capable of this type of power distribution. The depths of field of the available reflectors are much narrower than needed; because of the angle of incidence of the energy on the side surfaces of the tube, a higher power density distribution is needed than what is available in the top 60° quadrant of the tube surface.

Consequently, the initial approach was to first develop a new reflector design (optics) based on the heat distribution experimentally determined in previous IR experiments and laser processing. A couple of reflector design concepts were calculated/ developed based on this information and submitted to Vortek for review and to obtain cost estimates for these new reflector designs.

New Reflector—Proposed Design Concepts. Based on recent extrapolations from laser experiments, the power distribution needed on the tube surface that is expected to achieve the required 45° deflection angle for tube bending was estimated. While the ideal focus distance profile to provide the required power density distribution has been derived from our current knowledge-based experience on laser thermal forming experiments, in reality, it may be difficult to achieve the sharp profile changes that are needed at the far outer side wall limits of the tube. Consequently, another alternate power density, shown in Figure 5 may be easier to fabricate and is expected to get close enough to the ideal power density distribution to provide reasonable results for tube forming feasibility experiments.

For the currently available reflectors, the power density drops off to well below the ≥65% level needed for down the side wall of the tube. However, since laser processing produced good bending results without providing any power at all below the centerline of the tube, it is assumed that a modified (alternate) power density distribution would also provide good results using even an alternate design for the IR reflector (see Figure 5).

The proposed experimental setup to achieve this alternate power distribution is to orient the Vortek lamp/heat source so that the long axis of the heat lamp is perpendicular to the longitudinal axis of the tube to be formed. This is consistent with the LITS-Form approach, which was applied in the laser forming experiments. In this approach, a line source is moved along the longitudinal axis of the tube with the axis of the line heat source perpendicular to the longitudinal axis of the tube. This alternate reflector design concept also has a high probability of success (again, based on laser experiments) only if a variable focus lamp reflector can be designed and fabricated to provide the necessary power density distribution. The optimum focus profile is estimated to be similar to that shown in Figure 6. The quoted cost of this reflector, however, exceeded the allotted project budget.

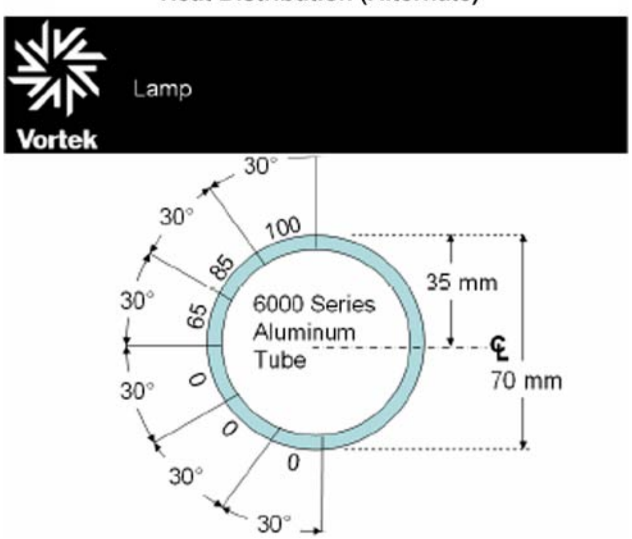

Figure 5. Schematic of modified (alternate) power density distribution needed to form aluminum tubes.

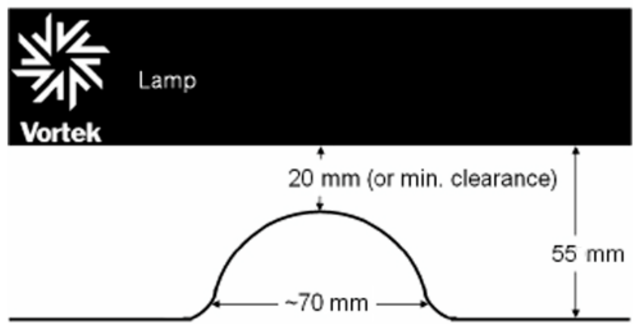

Figure 6. Schematic of the focus distance profile for the modified (alternate) power density distribution needed to form aluminum tubes.

Modified Reflector Optics—Proposed Design Concept. Consequently, an alternative reflector concept was devised. This proposed reflector was developed and designed so that a secondary reflector could be utilized in conjunction with our current *close coupled reflector,* thereby minimizing the reflector, and hence, project cost. A schematic view of this concept is presented in Figure 7. This alternative, less expensive, unoptimized reflector design was developed in collaboration with Vortek and NAT. The goal of this reflector option was to control the thermal heat flux and contour the heat input, but in a more cost-effective way. Several reflector designs were considered, and a final reflector concept was developed. The cost, however, of fabricating and implementing this secondary reflector to achieve the desired heat flux distribution and IR arc profile also exceeded the available funding allocated for this project.

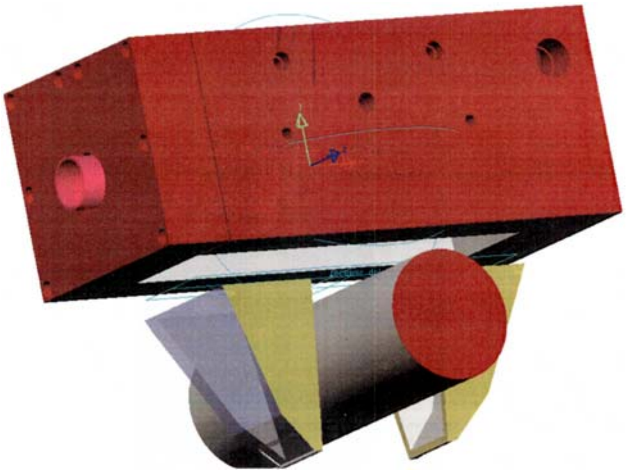

Figure 7. Schematic view of proposed secondary reflector.

Thermal Forming Reflector Design Results

Within the feasibility phase of this project, initial IR trials based on flat plates for thermal forming aluminum tubes have verified the relative order-of-magnitude of time estimates using the IR process. Forming of a 45^{o} bend is estimated to be achieved in 5–20 s. Experimental results in conjunction with laser experience suggest that a minimum of ~5 s is required, using optimized processing with cooling and a range of 10–20 s without cooling.

Two proposed reflector (optics) design concepts for a "new reflector" were developed based on thermal flux calculations from past experimental results and laser processing experience. However, the cost estimates received from Vortek for fabricating the proposed "new reflectors" suggested that additional, less costly approaches needed to be considered. The alternate approach pursued was to develop and fabricate "side shields" that (based on Vortek's experience) would boost the power level to obtain a higher power density needed along the side surfaces of the tube. This approach promised to help experimentally establish/indicate that the higher power densities will achieve the power densities required for the full 45° bend. Because a higher power density can be achieved using the side shield approach, we requested a quote from Vortek. Vortek qualitatively verified that the estimated power distributions expected by incorporating these side shields into our current reflectors were favorable when they compared to the thermal flux requirements that we have calculated based on laser forming experience.

Conclusions

- Within the feasibility phase of this project initial IR trials, based on flat plates, for thermal forming aluminum tubes have verified the relative order-of-magnitude of time estimates using the IR process. Forming of a 45° bend is estimated to be achieved in 5–20 s. Results suggest that a minimum of ~5 s is required using optimized processing with cooling, a range of 10–20 s without cooling.
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- Several (new and modified) reflector designs have been proposed and developed that qualitatively provide the thermal flux contouring needed for preforming tubes for subsequent hydroforming.
- The cost estimates for both a new reflector design (optics) and the less expensive side-shield (secondary reflector) concepts exceed the budget allotted for this project, and therefore preclude the further development and implementation of this technology.
- Without additional funding, the reflector (optics) proposed and designed within this project that can control and contour the thermal flux heat profile onto the tube (to achieve the calculated/desired heat flux) cannot be fabricated and implemented to demonstrate the success of the IR technology as a more cost-efficient and lighter materials approach to preforming tubes for subsequent hydroforming.