Final Technical Report

Induction Consolidation/Molding of Thermoplastic Composites Using Smart Susceptors

DOE Award No.: DE-FG36-08GO18135 Project Period: 9/30/2008 – 3/31/2012

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REPORT 6/14/2012:

This report is based upon work supported by the U.S. Department of Energy under Award No. DE-FG36-08GO18135.

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EXECUTIVE SUMMARY

This project has focused on the area of energy efficient consolidation and molding of fiber reinforced thermoplastic composite components as an energy efficient alternative to the conventional processing methods such as autoclave processing. The expanding application of composite materials in wind energy, automotive, and aerospace provides an attractive energy efficiency target for process development. The intent is to have this efficient processing along with the recyclable thermoplastic materials ready for large scale application before these high production volume levels are reached. Therefore, the process can be implemented in a timely manner to realize the maximum economic, energy, and environmental efficiencies.

Under this project an increased understanding of the use of induction heating with smart susceptors applied to consolidation of thermoplastic has been achieved. This was done by the establishment of processing equipment and tooling and the subsequent demonstration of this fabrication technology by consolidating/molding of entry level components for each of the participating industrial segments, wind energy, aerospace, and automotive. This understanding adds to the nation's capability to affordably manufacture high quality lightweight high performance components from advanced recyclable composite materials in a lean and energy efficient manner.

The use of induction heating with smart susceptors is a precisely controlled low energy method for the consolidation and molding of thermoplastic composites. The smart susceptor provides intrinsic thermal control based on the interaction with the magnetic field from the induction coil thereby producing highly repeatable processing. The low energy usage is enabled by the fact that only the smart susceptor surface of the tool is heated, not the entire tool. Therefore much less mass is heated resulting in significantly less required energy to consolidate/mold the desired composite components. This energy efficiency results in potential energy savings of ~75% as compared to autoclave processing in aerospace, ~63% as compared to compression molding in automotive, and ~42% energy savings as compared to convectively heated tools in wind energy. The ability to make parts in a rapid and controlled manner provides significant economic advantages for each of the industrial segments. These attributes were demonstrated during the processing of the demonstration components on this project.

This initial set of components fabricated under this GO-18135 contract shows the basic feasibility of the process for each of the industrial segments. Furthermore, initial analysis and tests to verify the basic feasibility for large scale induction consolidation and joining of thermoplastic composites using smart susceptors were conducted. Also, process improvements have been outlined to enable the rapid cycle needed for automotive rate production. These initial development efforts have verified the key fundamental technical soundness of making large parts and joining integrated thermoplastic composite structures along with reaching the needed cycle time for automotive applications. However, implementation risks still exist in scale-up and joining for wind energy and aerospace and cycle time for automotive. These risks will need to be reduced and process maturity validated via process/component demonstration before implementation on the order necessary to bring the 3T BTU's energy savings to fruition.

The implementation strategy for this technology consists of starting with the most easily implemented components and then progressing to more critical/challenging structure. The following proposed implementation plans would rely on the completion of the additional risk reduction activities mentioned above. In regard to implementation in the automotive business sector, the initial implementation articles would start with shields, cross members and seat frames then proceed to instrument panels and spare wheel wells, then finally on to closures and body panels. Implementation would begin in approximately 2018 and then proceed through 2023. Automotive implementation would be driven by efficient

manufacturing attributes aimed at meeting higher fuel economy and recycling targets. In regard to implementation in the aerospace business sector, initial interior part fabrication using this process could begin as soon as 2015 with additional scale-up applications such as floor beams and frames following in 2019 with the large fuselage, empennage, and wing structure following in 2024. Aerospace implementation is driven by efficient fabrication of lightweight structures aimed at meeting longer range and higher fuel economy targets. The quicker thermal cycle, improved durability of the thermoplastic polymer, and integrated structure fabrication enabled by the induction processing of thermoplastic composite system would drive this implementation effort. From a business perspective, this process represents a potential for large productivity gains when dealing with high production rates and/or high instance components for composite airplane designs. In regard to implementation in the wind energy business sector, initial implementation of nacelle panels is planned for 2015. Small blade/spar fabrication and assembly would follow in 2018 and large blade/spar fabrication and assembly be implemented in 2022. Wind energy implementation is driven by efficient fabrication and assembly of very large integrated structures aimed at meeting greater energy generation efficiencies along with improved durability and recycling targets. The quicker thermal cycle, improved durability of the thermoplastic polymer, and integrated structure fabrication enabled by the induction processing of thermoplastic composite system along with the improved recyclability of the thermoplastic material would drive this implementation effort.

This technology has the potential to provide significant productivity gains in all three represented business sectors. In the wind energy and aerospace sectors, the productivity gains are produced by more rapid consolidation thermal cycles enabled by induction heating and improved performance due to improved durability and strength enabled by thermoplastic composites. In the automotive sector, this processing would provide a less capital intensive infrastructure enabling increased usage of lightweight thermoplastic composite structural applications. Additional areas of impact using this technology include migration of these processing advantages to fabrication of components from other lightweight high performance materials such as aluminum and titanium (including affordable titanium powder). Again, the core capability of induction heating with smart susceptors to create an optimized thermal cycle for each material/process, thereby, maximizing the overall efficiency, affordability, and performance of these broad benefits. In summary, this technology supplies the nation with an opportunity to establish an energy efficient, affordable and effective manufacturing capability for light weight recyclable thermoplastic composite components. Moreover, it provides the basis for migration of these advantages to multiple material types and over multiple industries. In summary, this process has a broad and significant positive impact on efforts to establish unique and highly competitive manufacturing capabilities in the United States that benefit existing and emerging manufacturing related commerce.

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Glossary

Prepreg: Ready to mold sheet material of cloth, mat, or unidirectional fiber, typically impregnated with resin. The material is cut or kitted prior to molding.

Preform: A pre-shaped fibrous mat or cloth formed to the desired shape before being placed into a mold or press.

Curie point: The temperature at which a magnetic material becomes nonmagnetic.

Smart Susceptor: The molding surfaces of the induction molding tool composed of thin ferromagnetic material which is heated via induction coils with the susceptor controlling the temperature by the intrinsic properties of the alloy. This intrinsic property is the change from the magnetic to non-magnetic state at the Curie point. Once one section of the ferromagnetic material is heated to the Curie point and becomes nonmagnetic, it automatically becomes the less preferred path for the magnetic flux to reside. This automatically directs heating to the cooler areas of the material that is still ferromagnetic. The process continues until all of the susceptor is at the Curie point.

1. Introduction and Background

This project has focused in the area of energy efficient induction consolidation and molding of reinforced thermoplastic composite components. During this project an increased understanding of the use of induction heating with smart susceptors applied to consolidation of thermoplastic has been achieved. This was the result of the establishment of processing equipment and tooling and the subsequent demonstration of this fabrication technology by consolidating/molding of entry level components for each of the participating industrial segments, wind energy, aerospace, and automotive.

Induction consolidation and molding of thermoplastic composites using smart susceptors can significantly reduce energy use by eliminating the need to heat the tooling and surroundings, as is done in other conventional composite manufacturing methods, such as autoclave or oven processing. Thermoplastics do not require an extended cure at elevated temperatures and enable rapid component manufacturing cycles, as compared to thermoset materials. Thermoplastic resins can also be melted and consolidated repeatedly with minimal degradation, making them excellent candidates for recycling.

Induction consolidation/molding of thermoplastic composites using smart susceptors can significantly reduce the cycle time and energy used for manufacturing and will increase the performance of the resulting components. The characteristic rapid processing cycle of induction consolidation of thermoplastic composites not only saves energy, but may also holds the potential to improve component affordability. In addition, integrating these lightweight components into aerospace and automotive vehicles will reduce the vehicles' fuel consumption and carbon emissions.

The induction consolidation/molding of thermoplastic composites using smart susceptors enables a number of advantages over existing composite processes. Potential for significant energy savings exists due to the fact that very little mass is associated with heating the tooling during the molding process. This is due mainly to the fact that only the smart susceptor tooling faces are heated inductively and the remainder of the tooling is not. The smart susceptor is a relatively thin layer of ferromagnetic material that heats quickly, and thereby, heats the component for processing. The smart susceptor is made from a ferromagnetic alloy possessing a Curie point at or just above the processing temperature of interest. Furthermore, by balancing the thickness of the susceptor and the frequency of the induction power supply, the susceptor intrinsically controls the temperature at the processing temperature of interest. Therefore, a rapid low energy consolidation/molding process is enabled.

Figure 1 shows the typical tooling and coil design used for the tools under construction in this project. The tooling surfaces consist of .125" ferromagnetic sheets that are machine to the contour of the part. This surface forms the molding surfaces of the tooling. These contoured smart susceptor sheets are attached to non-magnetic stainless steel laminations forming the body of the tool to provide rigidity and resist the press pressure during consolidation/molding. The induction coil provides the oscillating magnetic field (2KHz is typical for .125" smart susceptor) that drives the induced current in the part. The current path in each of the smart susceptors is a loop along the back surface of the susceptor then up across the front or part surface of the susceptor then again along the back surface thereby forming the needed loop for heating. A close-up look at the susceptor cross-section cut across the length of the coil turns, when it is in the magnetic state, would reveal separate and distinct high intensity current running in this loop (as shown in figure 2) and then a diffuse low intensity current levels when the smart susceptors are non-magnetic (figure 2).

An additional, analytical view of the susceptor cross-section cut across the length of the coil turns, when it is the magnetic state (see figure 3), reveals separate current paths and high current values on both the top and bottom surface of the susceptor. Furthermore, when the smart susceptor is the non-magnetic state this same analytical view shows significant current overlap and hence current cancellation between the current along the top surface of the susceptor and the current running along the bottom surface of the susceptor (as shown in figure 4). The induced current level and therefore the power to an even greater degree, falls dramatically as the material shifts from a magnetic to a non-magnetic state. This change in power input forces thermal equilibrium at the temperature where this induced current overlap occurs. In figure 5 a picture of a typical induction tool along with an infrared image of the tool in operation shows the isolation of the heat to the surface of the tool with very limited to no heating of the tool body as well as the very even heating at the tool surface.

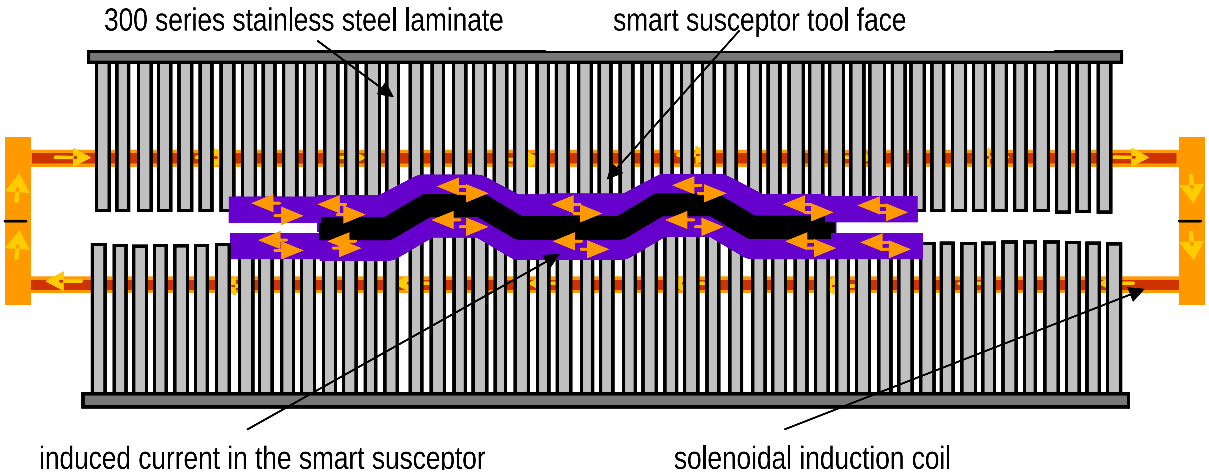


Figure 1. Typical tooling construction concept associated with the tool designs being developed

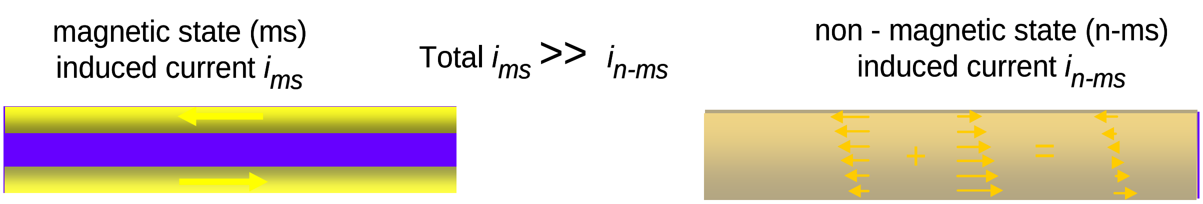


Figure 2. Depictions of the induced current distributions in the smart susceptor, with the magnetic state shown on the left and the non-magnetic state shown on the right

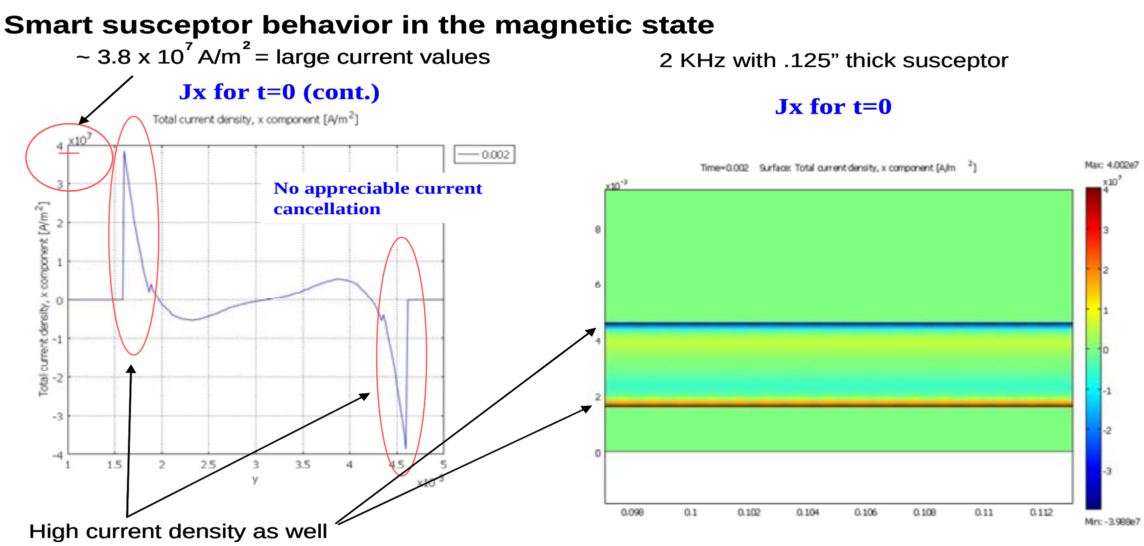


Figure 3. Depictions of the induced current distributions in the smart susceptor, with the magnetic state depicted on the left and the non-magnetic state shown on the right

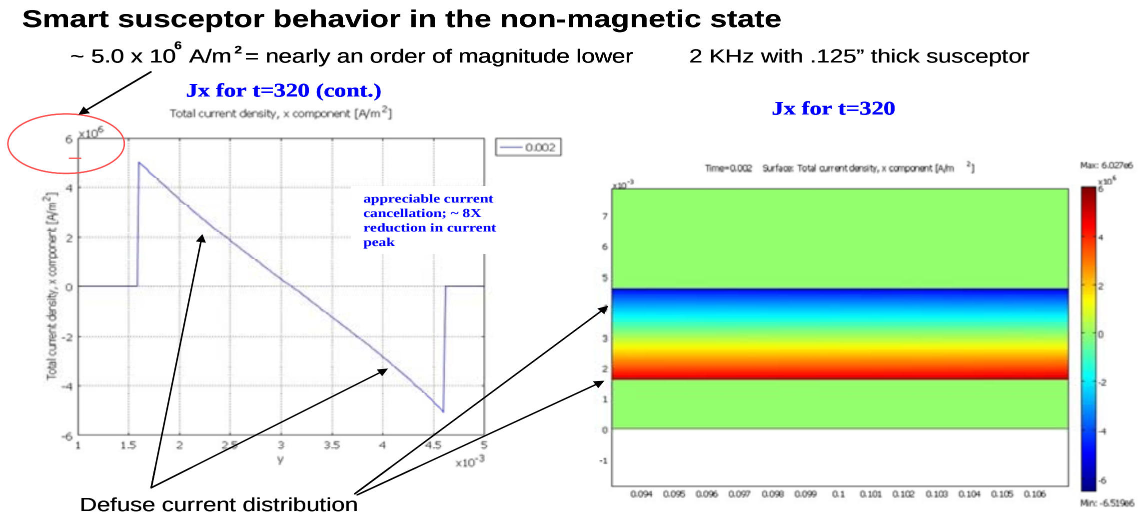


Figure 4. Depictions of the induced current distributions in the smart susceptor, with the magnetic state shown on the left and the non-magnetic state shown on the right

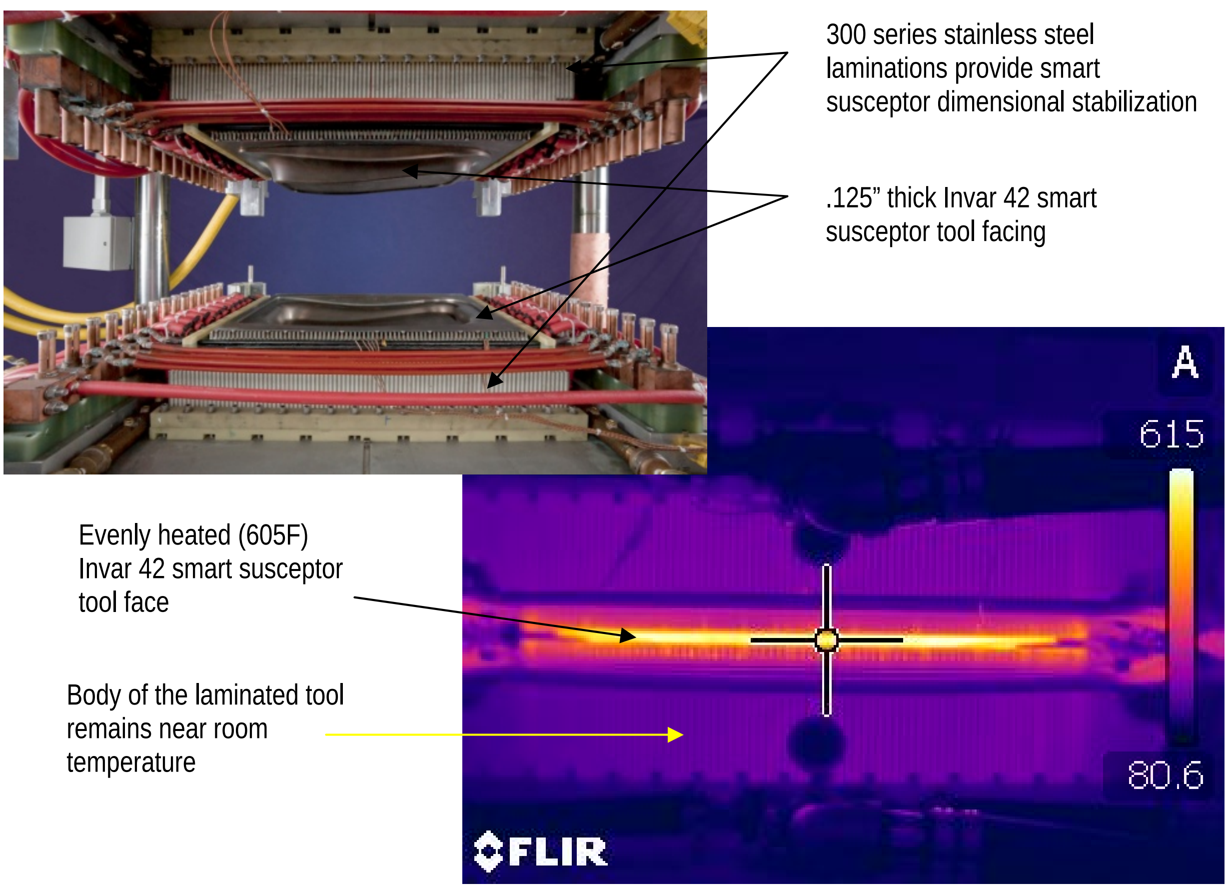


Figure 5. Typical induction consolidation tooling design on the left and then on the right an infrared picture of the tooling in operation showing the even heating of just the smart susceptor with the body of the tool remaining near room temperature

As shown in the previous figures, smart susceptors are key to the process control of the induction consolidation process. The alloy compositions of these smart susceptors are crucial to achieving the correct results for a specific task. The Ni/Fe alloys are of particular interest for composite molding. This is due to the fact that these alloys have useful Curie points and subsequent temperature leveling temperatures that are applicable to current thermoplastic resins of interest plus they possess low thermal expansion characteristics. The low thermal expansion characteristics improve dimensional compatibility with the graphite reinforced thermoplastic resins during thermal processing. The leveling temperatures were assessed by performing induction heating tests on small 1" by 1" by ~ .050" thick samples of candidate smart susceptor materials. The thermal traces for Invar 42 and Moly-Permalloy are shown in figure 6. Theses samples were heated at 3 different current levels in the coil. In each of the power input levels, there was no adjustment to the power level once to the molding temperature was achieved. The same current was applied throughout the test and only the magnetic to non-magnetic transition accounted for the leveling of the sample temperature. As one can observe in figure 6, the samples leveled at virtually the same temperature regardless of the power level imposed, with the Invar 42 leveling at 615F and the Moly-Permalloy leveling at 705F. The power level changes basically only impacted the time it takes to arrive at the leveling temperature and not the leveling temperature itself. This behavior exhibits the foundation of the processing benefits by enabling very rapid and tailored thermal cycles that exhibit excellent thermal control while enabling minimal energy to be used. This leads to important processing advantages both from cost and performance along with providing significant energy savings.

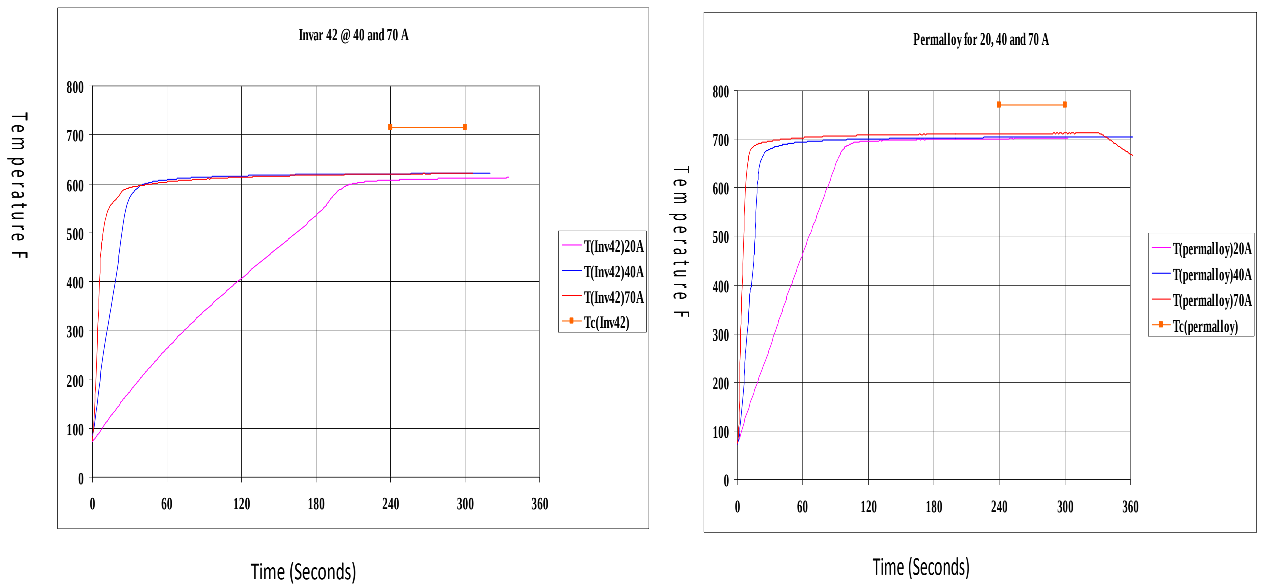


Figure 6. Induction heating test results for Invar 42 smart susceptor on the left and for Moly-Permalloy on the right. Each figure shows the insensitivity of the smart susceptor leveling point to the applied current and the effectiveness of the thermal control even with constant current being applied throughout the test.

A team consisting of both end users and infrastructure based companies were assembled to develop the technology associated with project (see figure 7). The end user companies consisted of one company from each of the automotive, aerospace, and wind energy industrial segments. These companies were responsible for describing the business requirements along with the type of composites that should be used to close the business case for each of these segments. Ford represented the automotive sector, Boeing represented aerospace, and Vestas was responsible for the wind energy segment. Cytec Engineered Materials provided the materials related information expertise and acted as the source of most of the materials used on the program. TEMPER, Inc. provided tool design and thermal/mechanical/fluid-dynamics anlaysis, specifically as applied to the press and the tooling along with providing coordination of the infrastucture participants. AjaxTOCCO provided the induction heating expetise along with electromagnetic modeling of the coil and its interaction with the electromagentic field. Steeplechase Tool and Die provided tooling and press fabrication expertise. In addition, Boeing provided the overall project management of the effort.

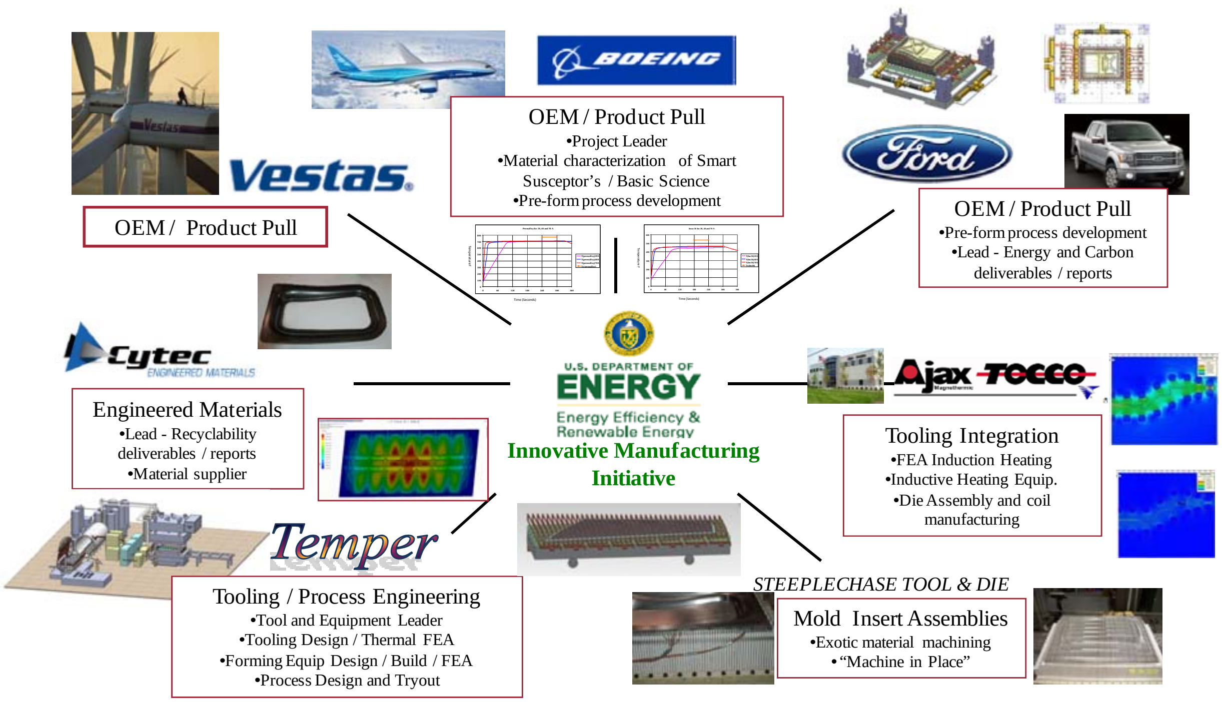


Figure 7. GO-18135 "Induction Consolidation/Molding of Thermoplastic Composites Using Smart Susceptors" development team

The following document describes the accomplishments of the project and how they relate to the initially proposed goals and objectives. The results of the development show how the project compares to the initial goals of validating the process, process scalability, energy efficiency, and process characterization. Also, business related information, developed during this project, was used to develop a cost baseline for the process and scope of application.

2 Compare Accomplishments to Initial Goals and Objectives

The objective of this project was to explore and define the technical and economic viability of the induction consolidation process to fabricate a wide spectrum of thermoplastic composite components in an energy efficient, sustainable, and affordable manner, thereby enabling enhanced automobile, air vehicle and wind turbine performance. The following objectives and goals were articulated at the inception of this project. The summarized assessment of the progress made on each of these goals is provided in the text directly after the goal statement. Subsequent pages of this report will document the detailed progress made on these initial goals and objectives.

A. *Process characterization* - Utilize predictive modeling and/or simulation of the processes and equipment this will include system scalability along with bench testing

- *Extensive use of predictive modeling was utilized to guide the design of the tooling. These models included electromagnetic, thermal, mechanical, and computational fluid dynamics. Please see section 3.1.2 for more information.*

- *Process scalability was studied and the results are described in section 3.1.3. Significant progress was made in defining the approach to both large scale part processing for both aerospace and wind energy components and methods for reaching the 1 minute cycle time required by automotive.*

- Summary comments: *Significant understanding was developed concerning the tooling design, the ability to scale this process, along with the smart susceptors behavior and customization. This objective is viewed as met.*

B. *Process validation* - prototyping will be conducted of technology applications to candidate components from each of the three large market segments. Entry level candidate components will be chosen and developed for this validation objective.

- *Three candidate entry level component designs were selected for demonstration.(3.2.1.1)*

- *The induction consolidation/molding facility was designed, fabricated as needed, and installed (section 3.2.2).*

- *Tooling designs and fabrication for the Boeing seatback inner was completed. Subsequent successful consolidation of over 20 seatback inners was completed along with component evaluations (section 3.2.3.1).*

- *Tooling designs and fabrication for the Vestas flat test panel was completed. Subsequent successful consolidation of over 10 flat panels was completed along with component evaluations (section 3.2.3.2).*

- *Tooling designs and fabrication for the Ford seat pan outer was completed. Subsequent successful consolidation of over 50 seat pan inners was completed along with component evaluations (section 3.2.3.3).*

- Summary comments: *Successful component demonstrations for each of the 3 industrial segments were accomplished showing the viability of the process. This goal is viewed as met.*

C. *Energy Efficiency* - Quantify the existing energy used in autoclaves and heated tooling and compare these values to the new process. Also, quantify the lifecycle energy costs of existing materials being replace by the composites to provide values for improvement in the sum value due to material/process implementation.

- *Existing processing energy uses was documented. Potential for the energy savings using the induction consolidation using smart susceptors was estimated (section 3.4).*
- *The energy utilized in the current laboratory induction processing system was measured. Methods for further reduction of the energy used by the induction process are identified (section 3.4)*
- *Recycling streams for the thermoplastic composite components are identified and an example part fabricated (section 3.4.5).*
- Summary comments: *More work is needed to reach the potential of this process for saving energy. However, the feasibility of reaching those goals has been established. This objective is viewed as met.*

In addition, the following enabling technologies were explored

D. Demonstrate advanced material placement and pre-form fabrication techniques that prove to be enabling companion technologies

- *Boeing has demonstrated the basic system for enabling the preform fabrication ability needed for aerospace applications (section 3.3.1).*
- *Ford has fabricated over 70 preforms using the method outlined in (section 3.3.2).*
- Summary comments: *This goal is viewed as met.*

E. Demonstrate smart susceptor technology and associated tooling

- *Small scale testing of various smart susceptor commercially available alloys was conducted and documented (section 3.1.1.1).*
- *Further additional tests were conducted on custom fabricated alloys made with laser engineered net shaping (LENS) methodology (section 3.1.1.2).*
- *Initial viability of large scale induction joining was established (section 3.1.1.3).*
- Summary comments: *With the items mentioned above and the work done on the demonstration components this goal is viewed as met.*

Also, below are the main economic objectives of the proposed project.

F. *Create process cost baseline* - Characterize the cost of tooling, equipment, and processing

- *Cost of tooling, equipment, and processing benefits are listed in section 3.5*

- Summary comments: *This objective is viewed as meet.*

G. *Create part application database* - Study applicability and define scope of applicability to the 3 main market segments.

- *Scope of application is outlined in section 3.6*
- Summary comments: *This objective is viewed as met.*

3. Project Summary

This section will provide a summary of the project activities over the entire period of funding.

3.1 Process Characterization

Several of the key characteristics of the induction consolidation/molding using smart susceptors process were analyzed and tested. The 2 main areas were the behavior of the smart susceptor and the complexity of the smart susceptor surface contours and its interaction with the electromagnetic field produced by the coil.

3.1.1 Smart Susceptors

Smart susceptors with specific chemistries will level at a given temperature based on the Curie point of the specific alloy chemistry and the reduction of the associated magnetic properties as it nears the Curie point. There are a number of commercially available ferromagnetic alloys that have useful properties as related to this application. Also, it would be advantageous to utilize net shaped fabrication methods for producing the smart susceptor tool face shell not only to reduce costs but also to allow the creation of customized alloys specifically designed to perform well in this application.

3.1.1.1 Candidate Alloys

Several commercially available alloys were selected for testing. The Ni/Fe alloys are of particular interest for composite molding. This is due to the fact that these alloys have useful Curie points and subsequent temperature leveling temperatures that are applicable to current thermoplastic resins of interest. In addition, they possess low thermal expansion characteristics. The low thermal expansion characteristics improve dimensional compatibility with the graphite reinforced thermoplastic resins during thermal processing. A solenoidal test coil was constructed (see figure 8) to provide a very uniform axial fields when the AC current was applied. The leveling temperatures were assessed by testing 1"by 1" by ~ .050" thick samples of candidate smart susceptor materials. The sample was positioned in the coil so the axial electromagnetic field was parallel to the plane of the sample. This field to sample orientation creates the condition where current cancellation occurs and exacting thermal control is achieved. The thermal traces for Moly-Permalloy and Kovar (figure 9), Invar 42 and Invar 39 (figure 10), Invar 36 and DK510 (figure 11) using 10KHz and 3 separate current levels. Theses samples were heated at 3 different current levels in the coil. In each of the power input levels, there was no adjustment to the power level once the molding temperature was achieved. The same current was applied throughout the test and only the magnetic to non-magnetic transition accounted for the leveling of the sample temperature. As one can observe in figures 9, 10, and 11, the samples leveled at virtually the same temperature regardless of the power level imposed, with the Invar 42 leveling at 615F, the Invar 36 leveling at 460F, and the Moly-Permalloy leveling at 705F. The power level changes basically only impacted the time it takes to arrive at the leveling temperature and not the leveling temperature itself. Table 1 provides a listing of candidate smart susceptors available off-the-shelf with their associate chemistries, Curie points, and assessed leveling temperatures.

Figure 8. Test coil used for evaluation of candidate smart susceptor alloys.

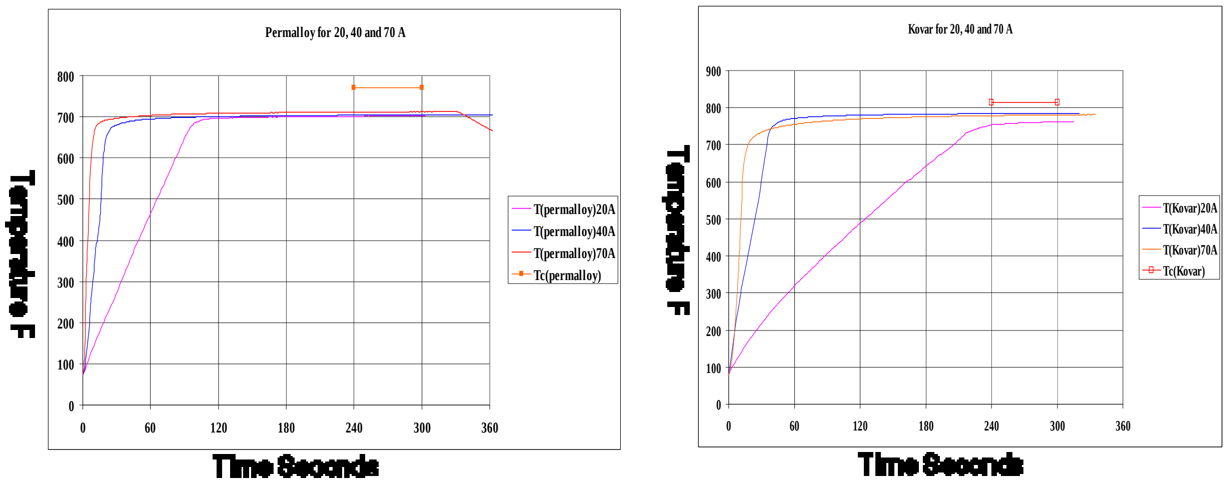


Figure 9. Thermal leveling test results for Moly-Permalloy (HyMu80) on the left and Kovar on the right

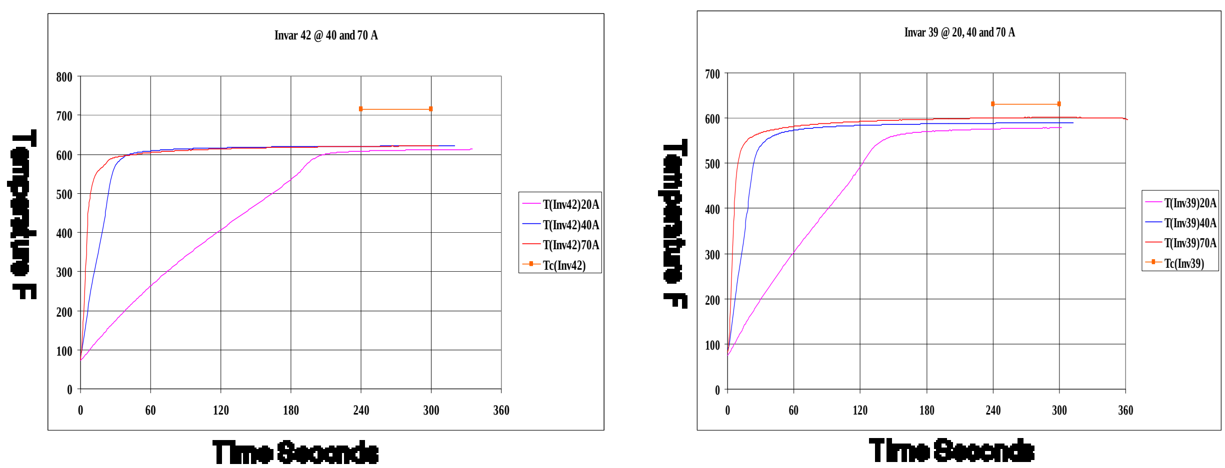


Figure 10. Thermal leveling test results for Invar 42 on the left and Invar 39 on the right

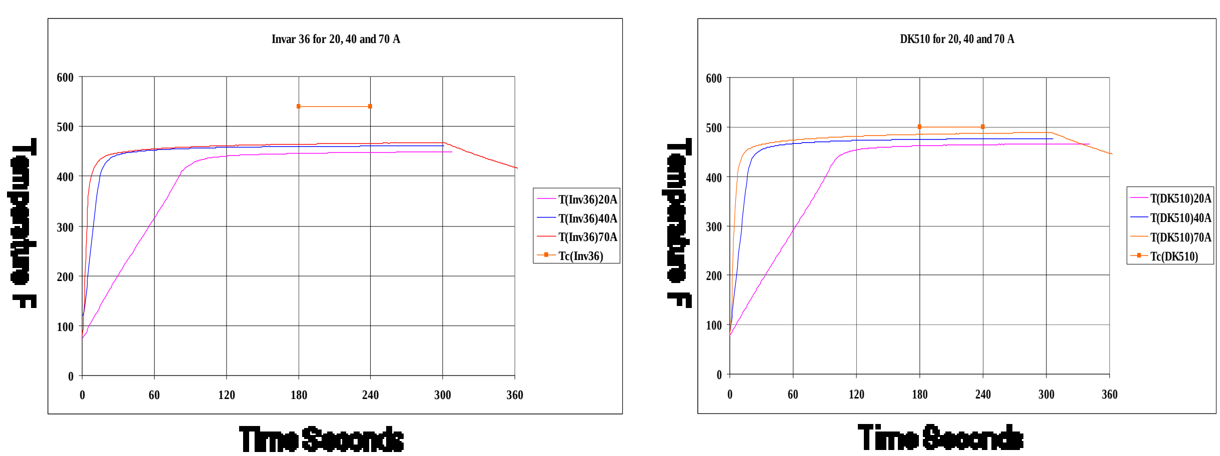


Figure 11. Thermal leveling test results for Invar 36 on the left and DK 510 on the right

Table 1 List of candidate smart susceptors with applicability to the thermoplastic resins and their processing (testing done at 10khz)

Material	Composition	Thickness	T (Curie) deg. F	T (level) deg. F
Kovar 29-17	54% Fe; 29% Ni; 17% Co; 0.3% Mn	.051”	815	780
Moly-Permalloy	80% Fe; 15% Ni; 5% Mo	.053”	770*	705
Invar 42	58% Fe; 42% Ni;	.050”	716	620
Invar 39	61% Fe; 39% Ni;	.063”	630	600
Invar 36	64% Fe; 36% Ni;	.052”	539*	460
DK510	40% Fe; 50% Ni; 10% Cr	.070”	500**	475

3.1.1.2 Near Net Shaped Smart Susceptor Fabrication

In addition to the commercially available alloys, the ability to create custom alloys via laser engineered net shaping (LENS) (see figure 12) was explored. Small 1” by 1” by .050” samples were created from the custom alloys (see table 2). The samples were tested via the methods developed earlier to evaluate the leveling temperature of the commercially available alloys. A steel plate was used as the base material and the sample was then built up using the surface of this material. The final test samples were then machined from this rough sample. These tests show that customized chemistries made from powders can be made using near net shaping process. In addition to the LENS process, a number of other thermal processes such as, plasma spraying, detonation spraying, wire arc spraying, flame spraying, high velocity oxy-fuel coating spraying (HVOF), warm spraying, and cold spraying are available to create customized chemistries and/or provide a more cost effective method of producing the smart susceptor tooling shells needed to fabricate the tools. These near net shape methods would provide significant cost savings due to the potential large reduction in material and machining costs in the fabrication of the tools needed to utilize the induction consolidation process.

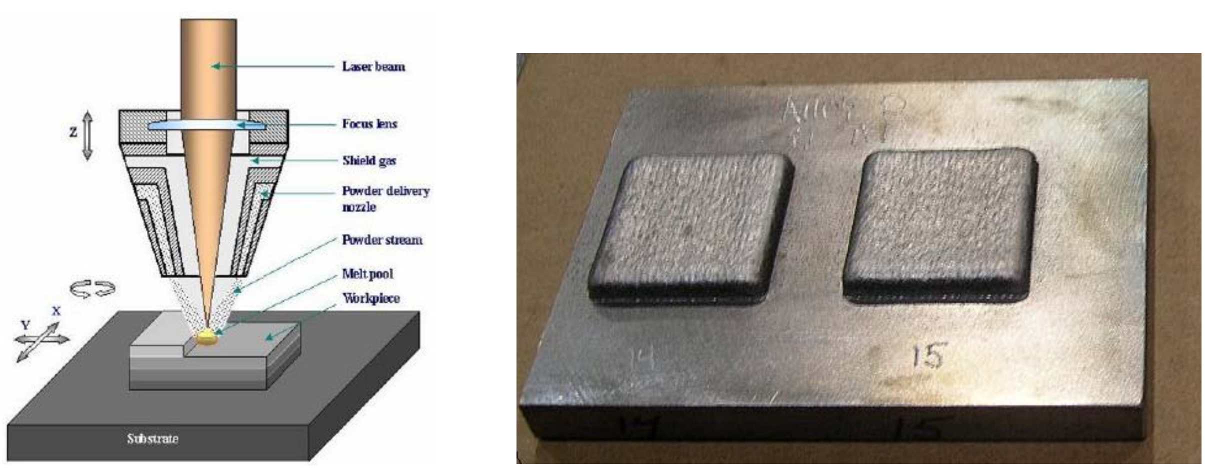


Figure 12. Depiction of the laser engineered net shaping (LENS) process in operation and a picture of the one of the custom alloy samples produced for evaluation

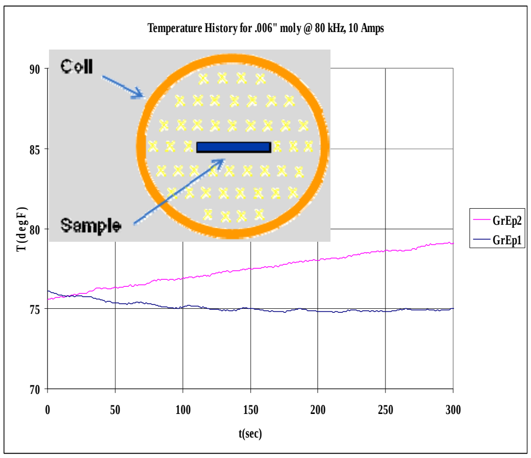
Table 2 List of smart susceptor chemistries that were used to make thermal leveling test samples via the lens process

Elements	Fe (plus) w/o	Ni w/o	Cr w/o	Co w/o	V w/o	Si w/o	T (eq) deg F
Alloy A	45	42	0	10	3	0	776
Alloy H	10	49	3	30	8	0	508
Alloy G	14	50	4	25	5	2	491
Alloy B	35	33	2	20	7	3	437
Alloy C	27	25	3	35	10	0	374
Alloy I	30	30	8	26	3	3	348
Alloy D	25	30	7	30	3	5	317
Alloy F	15	35	3	35	7	5	316
Alloy E	10	35	7	40	8	0	300
Alloy J	15	50	9	20	4	2	243
Alloy K	15	42	10	25	5	3	152

3.1.1.3 Utilization of Smart Susceptors for Joining (this section contains patentable material)

Further investigation of smart susceptors and their utilization was conducted. One particular area of interest is the ability to use the smart susceptor as an aid in joining thermoplastic composite structures. The ability to rapidly and reliably join thermoplastic composite components is an important enabling feature for integration of the material into production. This rapid reliable joining capability will provide the advantage of the integrated composite structure for enhance affordability and performance.

One key enabling condition that allows this induction joining with smart susceptors method to operate correctly is for the electromagnetic field to be parallel to the plane of the graphite fiber containing composite. Figure 13 shows the results of tests on a graphite composite sample and a sample containing moly-permalloy wires of 3 different diameters. The graphite composite does not heat even though the frequency of the test is 80KHz. The reason is that the only current path available is circumferentially around the graphite fibers. These fibers are too thin to allow significant heating due to current cancellation. The wires run parallel to the field, and therefore, the induced currents want to travel circumferentially here as well. Here again the smart susceptor is highly magnetic and has thin current depths when ferromagnetic and heats rapidly to the Curie temperature and then levels off at the leveling temperature (see figure 13). Figures 14 and 15 depict the test component to be fabricated. Five graphite fiber reinforced PEKK thermoplastic T's were welded to a graphite fiber reinforce PEKK thermoplastic flat panel. As shown in figure 14, the smart susceptor wires will be placed between the T and the flat panel. When exposed to an 80KHz electromagnetic field running parallel to the wire axis, the smart susceptor wires heat rapidly and evenly and melts the resin at the joint and forms a weld between the T and the flat panel. An elastomeric caul was used to hold the T' in place and provide tooling force to the hold the T and panels together during the welding process (see figure 16). Figure 17 depicts the tooling used to perform the welding. The tooling is reinforced cast ceramic tool with the induction coil cast into the tool. Figure 18 shows the smart susceptor wires imbedded in the resin for welding and the tooling used to fabricate the smart susceptor wire welding strip. Figure 19 shows a close-up photo of the subsequent weld joint. Figure 20 shows the completed panel after welding.



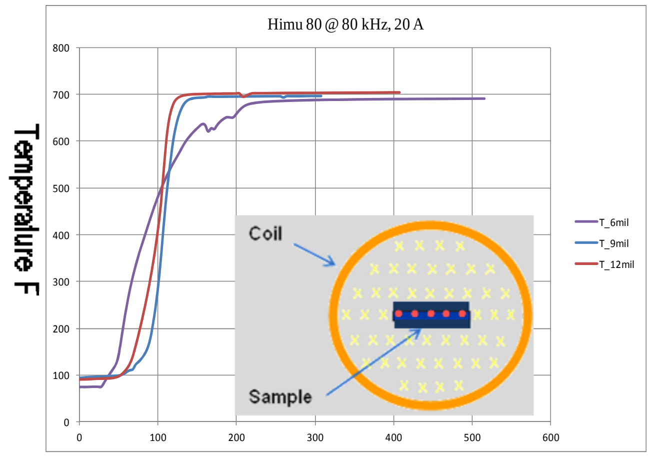


Figure 13. Graph on the left shows the heating behavior of the graphite reinforce composite material while the graph on the right shows the heating behavior of the composite with HyMu 80 smart susceptor wires imbedded in it.

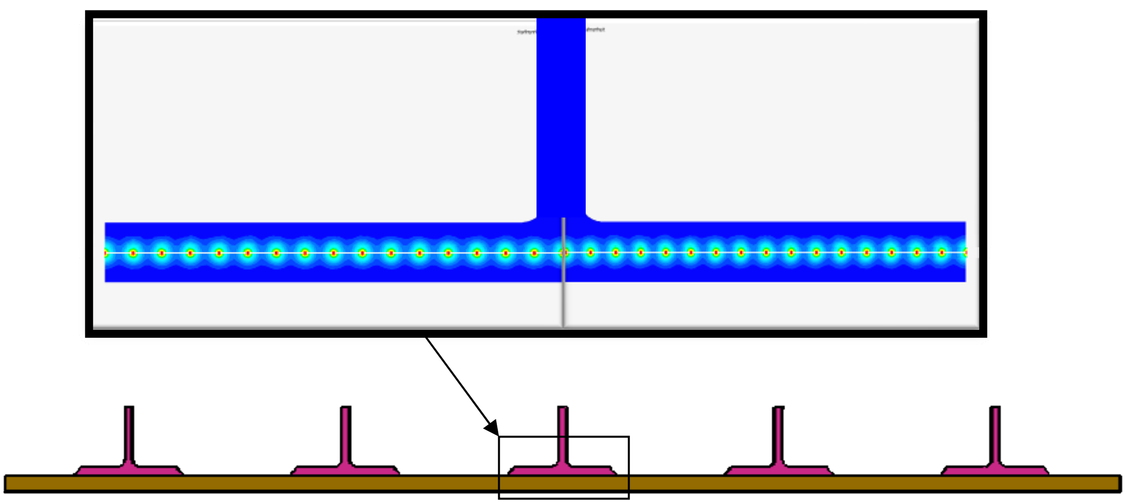


Figure 14. Depiction of the weld joint for the demonstration panel that was fabricated - note the location of the smart susceptors in the weld joint.

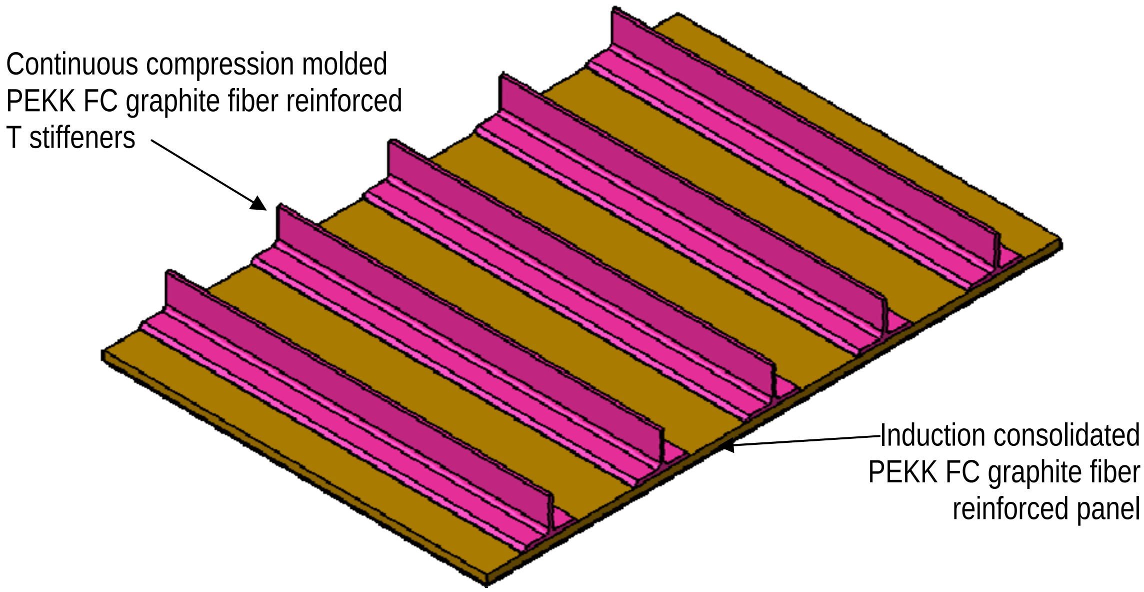


Figure 15. Depiction of the demonstration panel that was fabricated with 5 T stiffeners welded to the flat panel

Figure 16. Photo of the elastomeric caul that will hold the T stiffeners in place and provide the pressure to hold them in intimate contact during the welding process

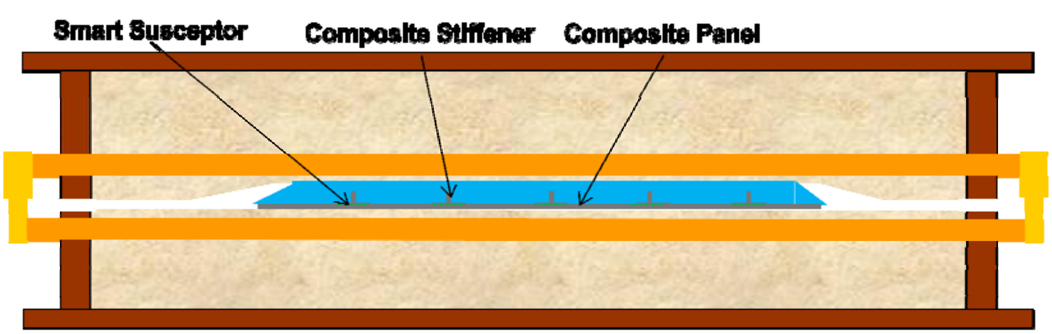


Figure 17. Depiction of the elastomeric caul holding the T stiffeners to the flat panel via pressure from the ceramic-tool/press during the welding process

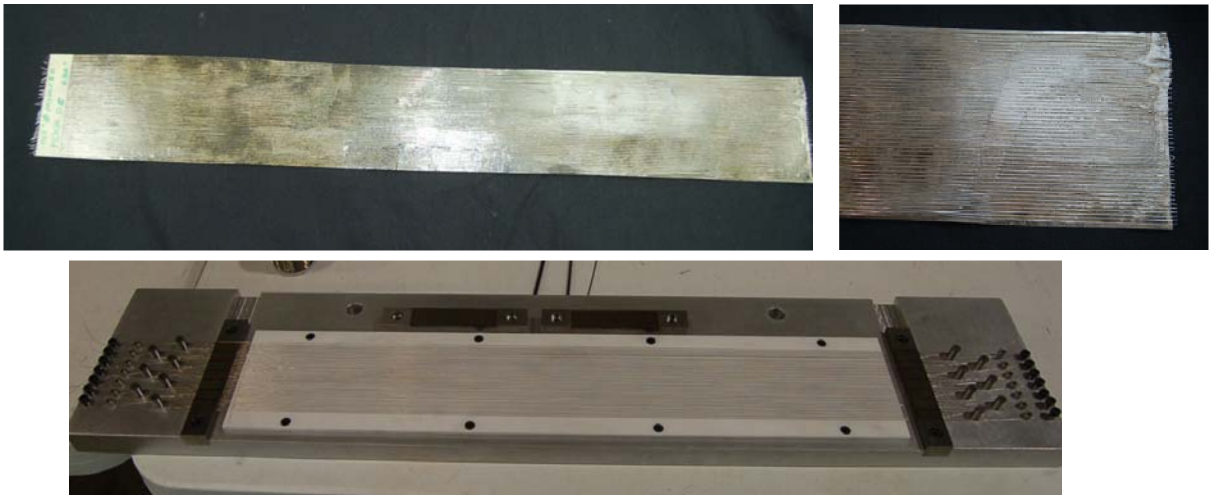


Figure 18. Photos of the tool for imbedding the smart susceptor wires in the thermoplastic resin and the strip of material produced

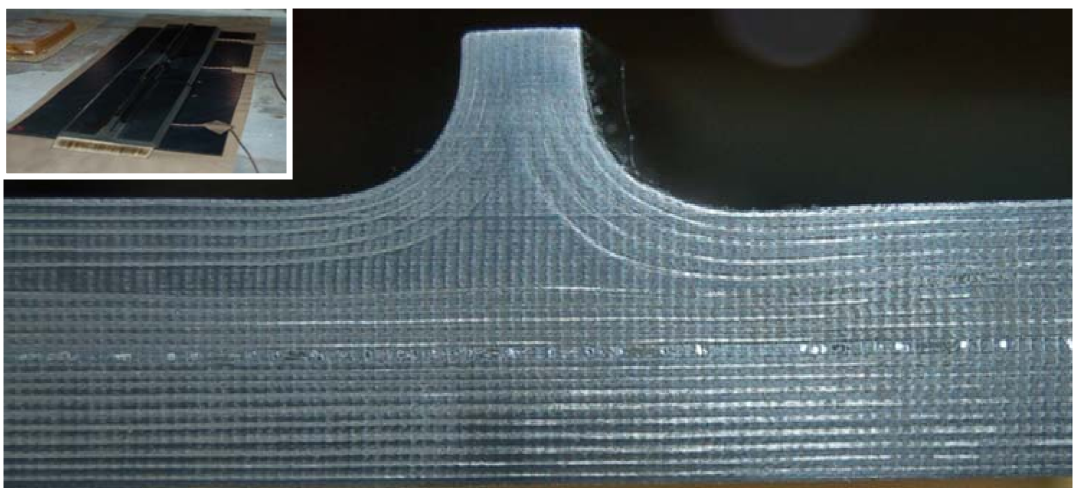


Figure 19. A close-up photograph of a typical joint in the welded panel

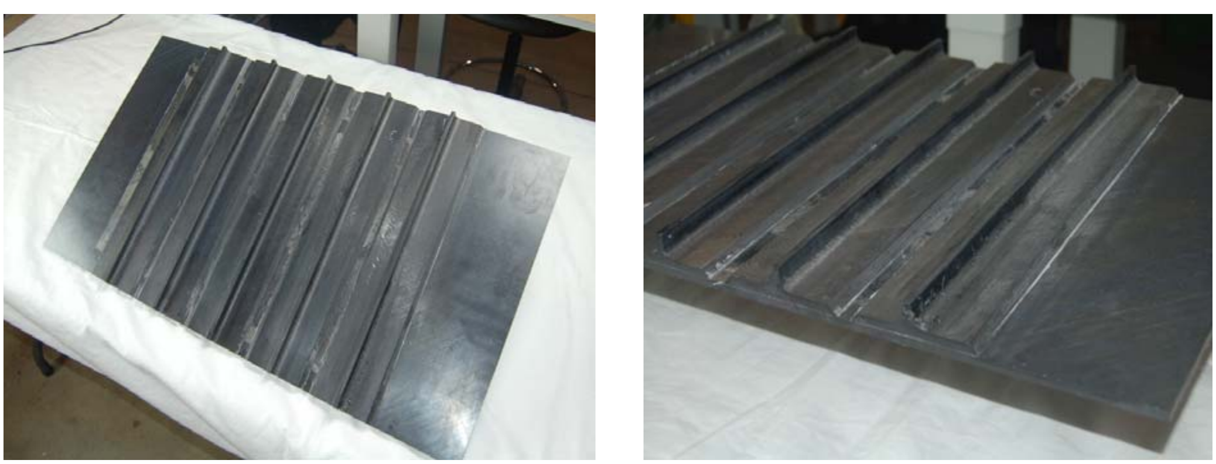


Figure 20. Photo of the completed integrated/welded structural panel

3.1.2 Modeling of Induction Heating with Smart Susceptors

Electromagnetic, thermal, mechanical, and computational fluid dynamic modeling was performed to establish the best tooling designs, press designs, coil design, cooling gas system design, and stainless steel laminations design.

3.1.2.1 Electromagnetic Analysis

The following is representative of the electromagnetic analysis procedures used for determining the best coil configuration and optimum heating parameters. Infolytica software was used to calculate the reaction of the smart susceptor tooling shells to the proposed coil designs. The Boeing seat back tooling (see figure 21) is used as an example of the analysis procedure, and how it guided the tool design. The induced currents in the smart susceptor when it is ferromagnetic are shown in figure 22. The magnetic field lines are parallel to the surface of the smart susceptor and therefore, the currents are traveling on the outside of the smart susceptor as desired, as shown in figure 22. When the smart susceptors reach the temperature where its magnetic properties begin to significantly decay, the magnetic fields are released and the flux lines across the thickness of the susceptor (see figure 23). This transverse flux condition or flux that intersects the plane of the susceptor can be problematic. Figure 23 shows the predicted temperature of the susceptor at given power levels. The areas of the susceptor where the condition of transverse flux was prevalent show the temperature exceeding the leveling temperature of the smart susceptor. This is due to the fact that the transverse flux induces currents that are not controlled by the smart susceptor. This type of heating is typically at much lower levels and hence the drifting of the temperature upwards instead of a sharp rise. Analysis provided methods to deal with it in the near term. These methods, such as specific coil designs, were used to minimize the degree of the transverse flux and also provided guidance on the sensitivity of the condition for various power levels. The data from the models are shown in figure 23. The sensitivity to power level is shown by the higher degree of transverse flux in the case of the 1200 amp setting along with the more divergent thermal condition when the current is held at that higher setting. Therefore, 1200 amps was used to heat up until the susceptor reaches the leveling temperature and then the lower 600amp or lower setting was used to hold the part at the leveling temperature. This not only allowed the development of a successful setting, it also provided energy savings due to the less power used during the elevated temperature hold portion of the cycle. This information was used to successfully demonstrate the process for each of the 3 components.

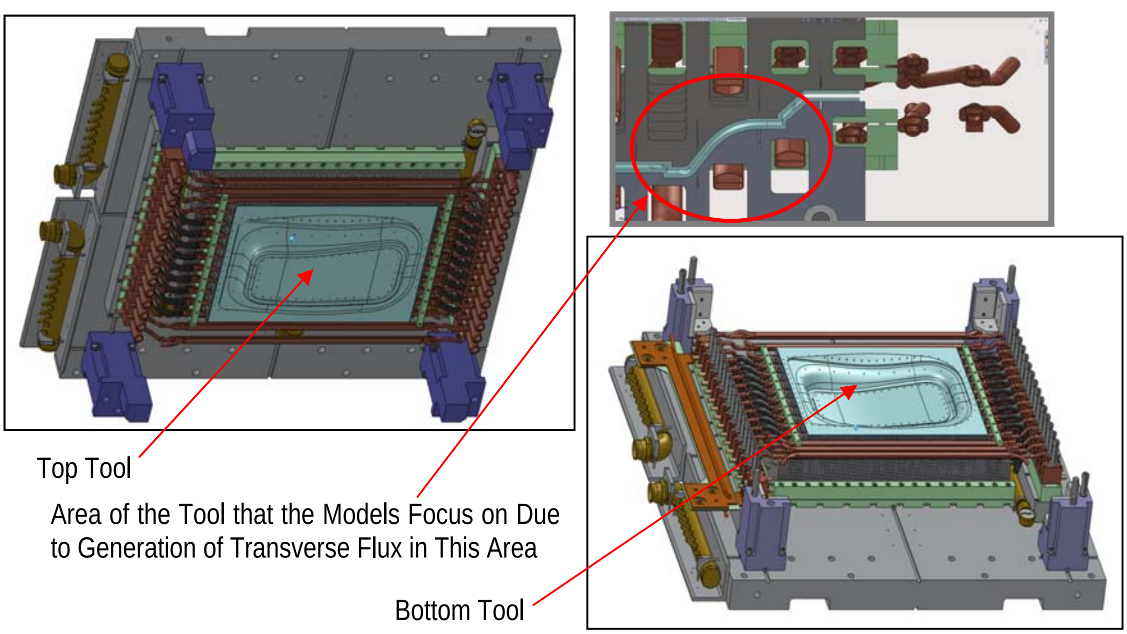


Figure 21. Boeing seat back tool design using the smart susceptors "shells" as the tool faces and the solenoidal shaped coil that surrounds these shells

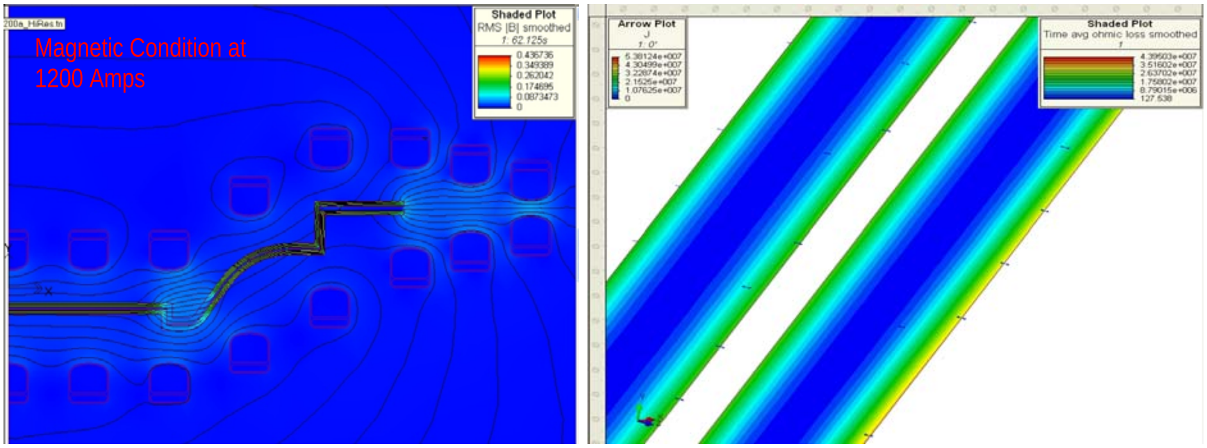
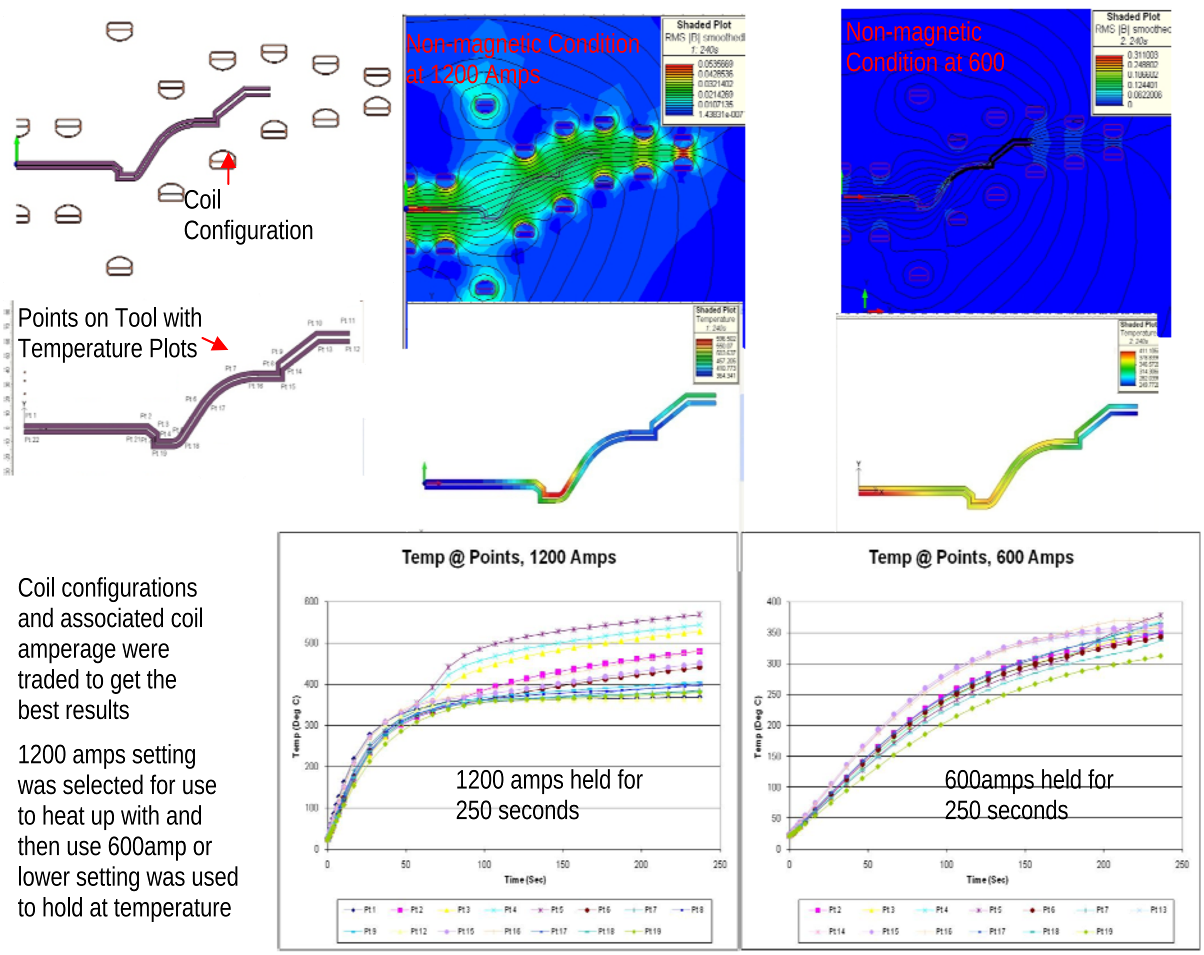


Figure 22. Boeing seat back with initial magnetic flux line shown when the smart susceptor is still non-magnetic on the left and the resulting current distribution (with currents either going into or out of the page) in each of the smart susceptor shells on the right



Coil configurations and associated coil amperage were traded to get the best results

1200 amps setting was selected for use to heat up with and then use 600amp or lower setting was used to hold at temperature

Figure 23. Electromagnetic analysis with resulting thermal condition showing the results of lowering the amperage once the smart susceptor shells reach the leveling temperature

3.1.2.2 Thermal/Mechanical/CFD analysis

Thermal, mechanical, and computation fluid dynamics (CFD) analysis was conducted on the tools along with the electromagnetic analysis just discussed (see figure 24). The Ford tool is used as the example of the analysis conducted and how it impacted tool design. Again, the coil configuration was set using a combination of thermal and electromagnetic analysis. Then, the impact of the thermal conditions to both the stress on the tool and the impact of the molding pressures on the tooling (see figure 25). CFD was used to predict the best location and size of the ports in the induction lines providing cooling to the back side of the smart susceptor, and therefore, the part (see figure 26).

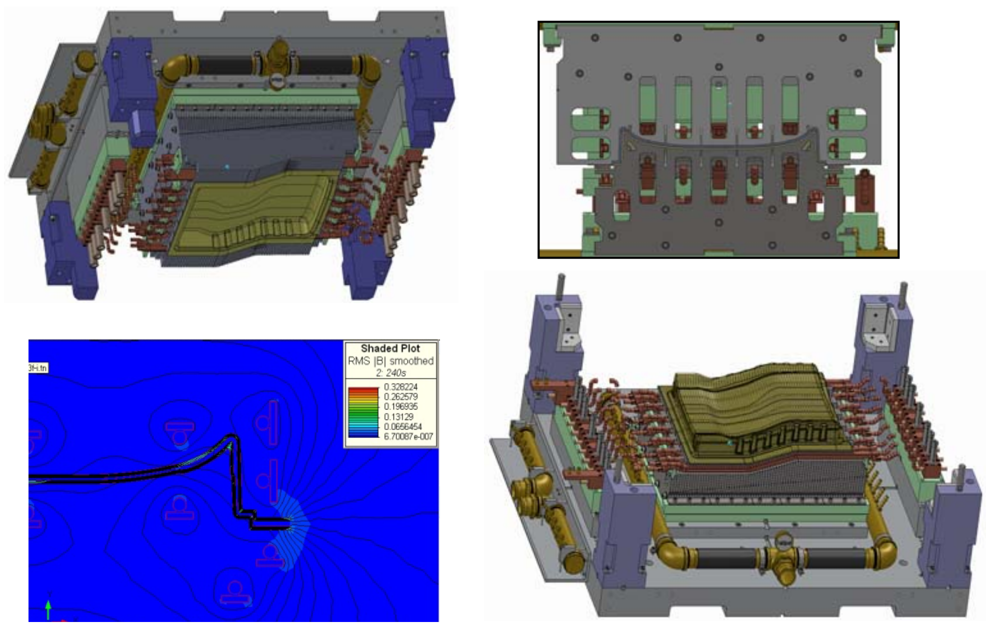


Figure 24. Depictions of the Ford tooling design and the associate electromagnetic analysis

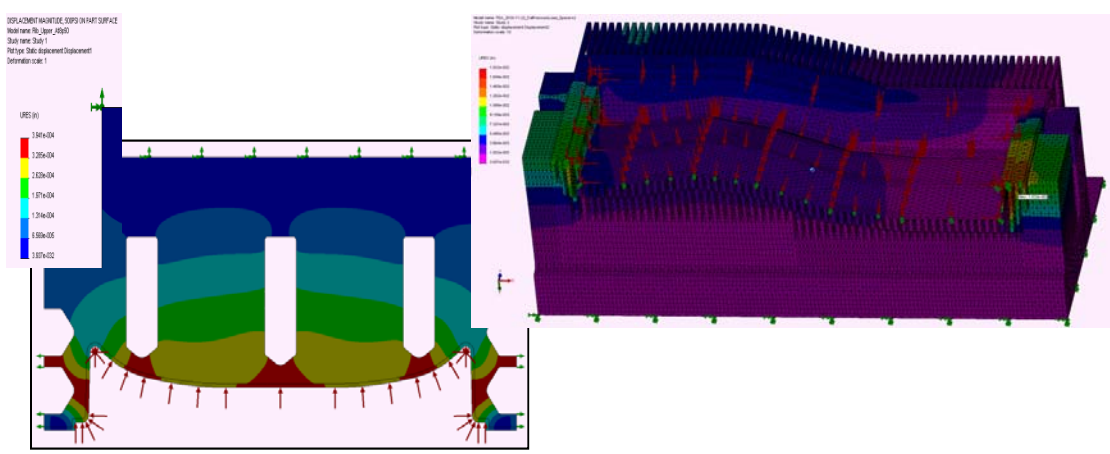


Figure 25. Stress analysis of the stainless steel laminations on the left and loading map of the smart susceptor on the right used to refine and optimize the tool design

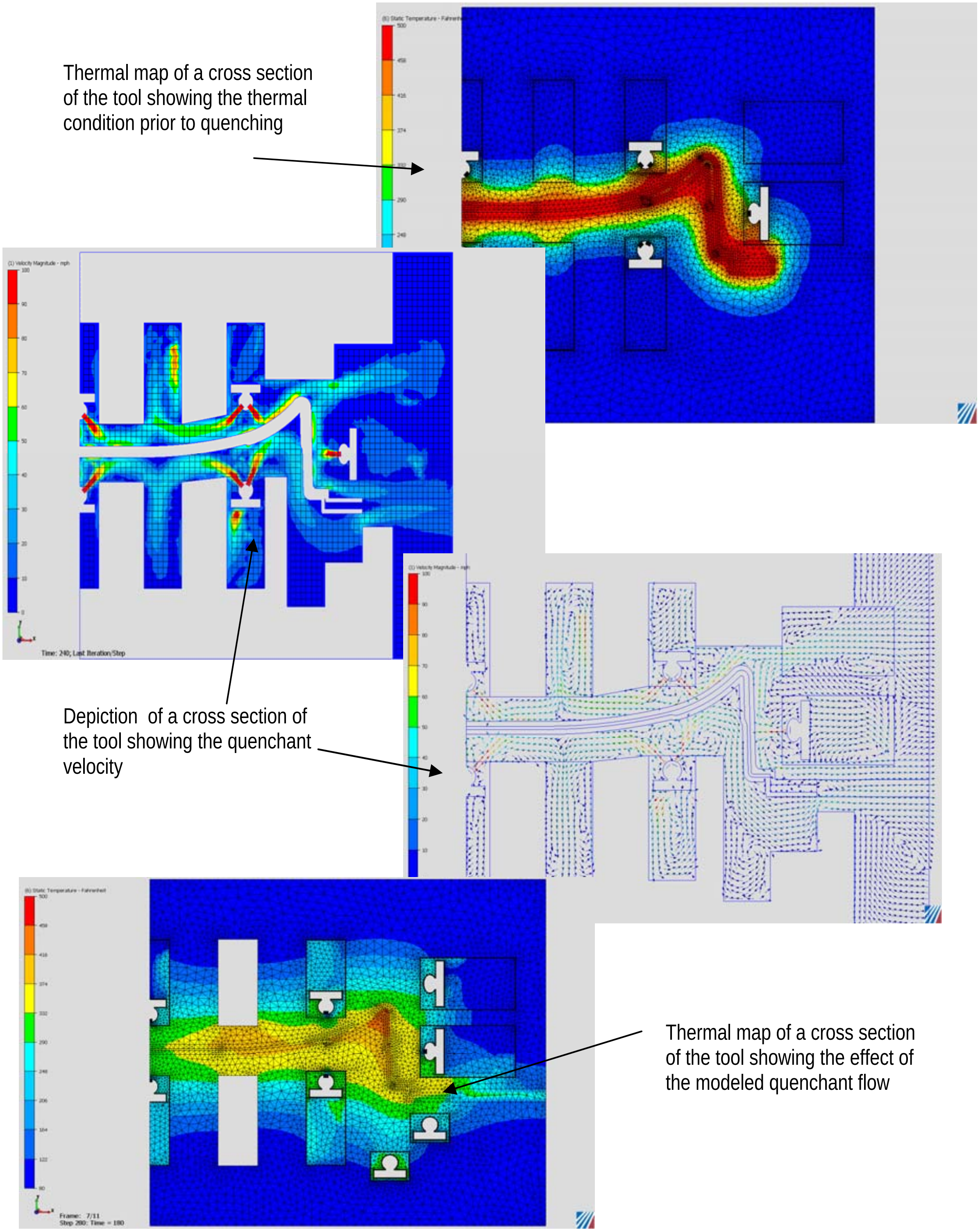


Figure 26. Depictions showing the utilization of the thermal and CFD analysis of the Ford seat pan tool to refine the placement of the active cooling medium for quenching

3.1.3 Process Scalability (this section contains patentable material)

There are two main issues regarding scalability of this process. One is the fabrication of larger scale parts, and the other is (automotive) high rate production. Large scale components are important for both the aerospace and wind energy. The utilization of smart susceptors appears to solve another issue with induction heating in regards to scale-up. Typically, when utilizing induction heating for large relatively complex components, it would be required to use one coil. This is to insure that the same current and hence the same field intensity existed at each location along the length of the coil. An example of processing a component without using a smart susceptor as the tooling face is shown in figure 27, where the differences in the resistance of each coil causes differences in current which then causes thermal differences. This poses an issue for very large coils due the large resistance associated and therefore large voltages required. Large voltages past approximately 1200volts on the coil are impractical due to propensity for arcing.

V=I*R therefore when R is large and I is given to achieve a certain heating rate then V is also large

Furthermore

$1/R_{total} = 1/R_1 + 1/R_2 + 1/R_3 + 1/R_4 + 1/R_5 +$ ………………

So large coils can be designed to have reasonable R_{tota} and hence practical voltage requirement values by the proper designation of the number of parallel coils (see figure 27). When using the smart susceptors multiple parallel coils are allowed and actually will provide further ability to control the temperature even more effectively. This is due to the fact that when an individual coil reaches the leveling temperature that particular coil will detune and develop significant additional impedance cause by the fact that it is out of phase with the driving current. Therefore, current is shunted away from each coil as it reaches the Curie point and driven to the remaining magnetic materials. This results in the anticipated behavior shown in figure 28.

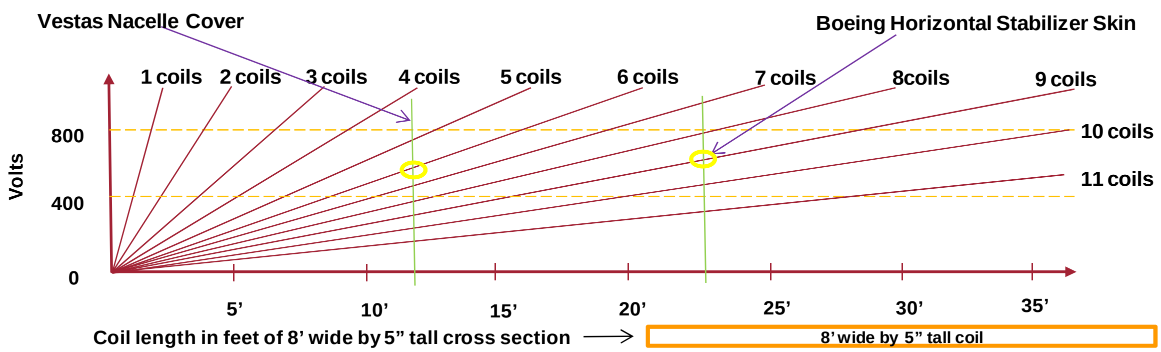


Figure 27. Graph showing the required number of coils connected in parallel to keep the required circuit voltage at practical levels (between 400 and 800 volts) for a given length of coil having 8 foot by 5 inch cross sectional area

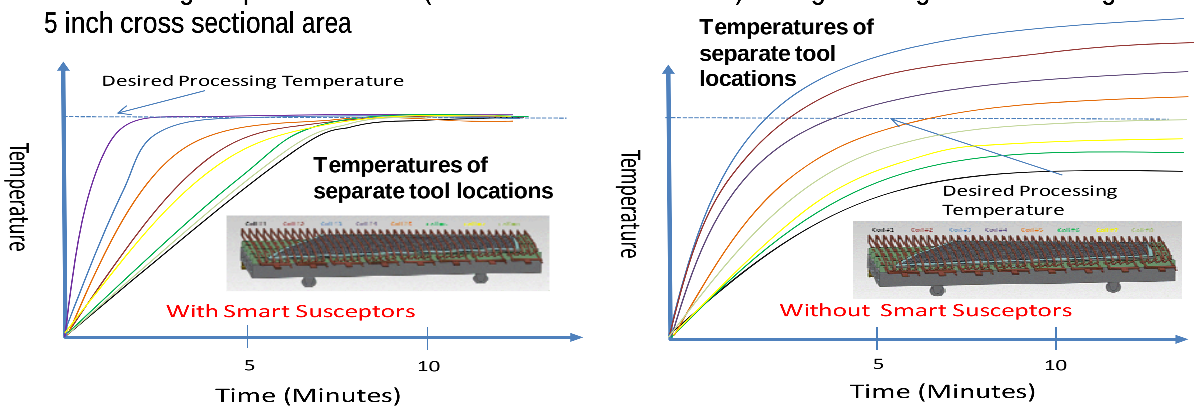


Figure 28. Depiction of the effect of the use of smart susceptors (see chart on the left) on large coils having multiple coils connected in parallel as opposed to no smart susceptors (see chart on the right)

These series parallel coil arrangements now allow the practical use of much larger coils. This is fundamental to addressing the larger scale components needed to address the needs of both aerospace and wind energy products. Furthermore, in consideration of aerospace fabrication a more cost effective tooling method and improving the practical aspects of component fabrication concept of using pneumatic pressure as the consolidation force was developed. Using pneumatic pressure in a pressure vessel should allow much less costly tooling due to the fact that the same force is required both below and above the tool surface (see figure 29). In that regard, only the tooling shell must be stabilized and does not need to resist the consolidation pressures (see figure 29). Furthermore, pneumatic pressure is a time proven method of enabling the numerous ply drops necessary to achieve the needed structural performance. These numerous ply drops can be problematic for matched tool designs. Therefore, with the series parallel combinations enabled by the smart susceptors and the pneumatic pressure applications large components such as horizontal stabilizers, wings, vertical stabilizers and fuselage sections are feasible. Plus, with the ability to join these structures to provide unitized structure the ability rapidly and affordably produce high performance composite structures is within reach.

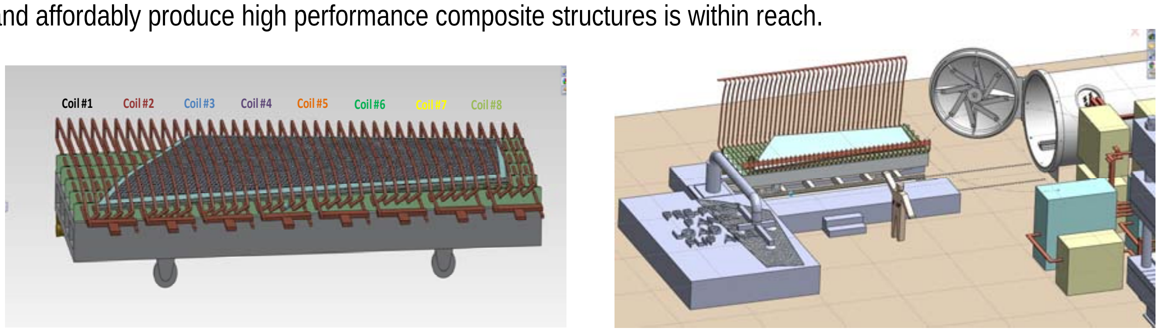


Figure 29. Depiction of a series/parallel coil for consolidating a large aircraft skin section utilizing a pneumatic pressurization facility for application of consolidation pressures

In the case of wind energy, the ability, due to smart susceptors, to utilize very large coils via the series parallel combinations to process large structures is key enabling feature. In addition, for the turbine housing panels, a press such as the one shown in figure 30 is vision for the type of equipment needed for rapid fabrication of these multi instance components. Furthermore large clam shell restraining fixtures are envisioned to the wind blades and spars. Reinforced cast ceramic tools are thought to be the best solution for the tools for both the smaller and larger components. These cast ceramic tools are much less costly to build and can be quite durable and easily repairable. Here again, the ability to effectively, rapidly, and reliably weld thermoplastic structures together to form unitized structure is very import to the wind energy business segment as well. As larger and larger wind turbines are designed, effective joining capability will become key to being able to get the structures to the installation site and then to join these sections in the field to complete the installation.

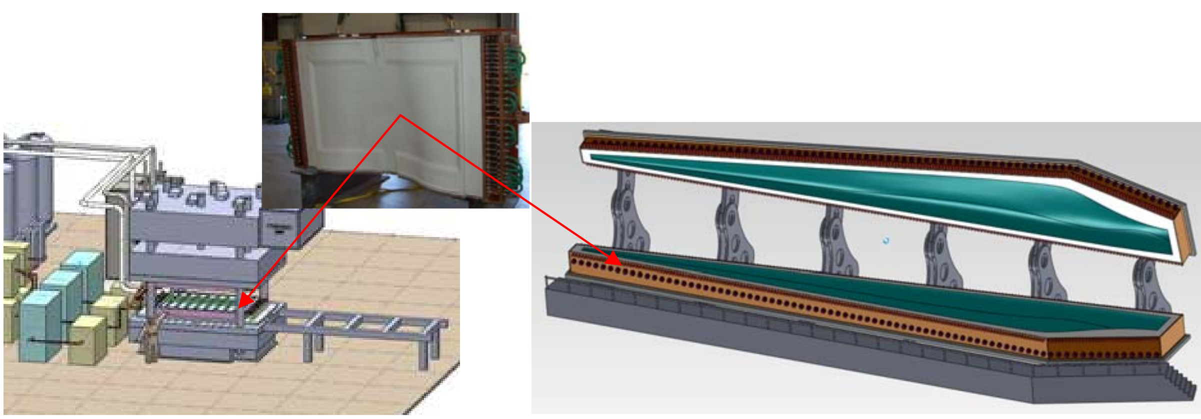


Figure 30. Depiction of the large induction consolidation facility for processing nacelle panels on the left and blade skins on the right

Another key scale-up issue is the ability to meet model production rates for the automotive industry of 200,000 to 500,000 vehicles per year. Additional concepts have been developed to facilitate the ability to meet the cycle time of 1 minute needed for effective automotive production. One step of this concept is to pre-heat the tool to the consolidation/molding temperature. This can be done by using a third component to the tool set that has a non-conductive ferromagnetic shell (see figure 31). This shell will guide the flux in the path needed to avoid transverse flux at high current levels and the uncontrolled heating it produces (see figure 31). In this concept, the tools close on ferromagnetic insert and each susceptor is heated rapidly (10 to 15 seconds) and individually to the molding temperature. The consolidation tools rise slightly and the insert is removed. This step produces a rapidly preheated tool set. To accompany this tool preheating step, the preform is preheated as well. The preheating of the preform is accomplished by using smart susceptor wires much like a pitchfork and inserting these in to lofted preform. Then the preform with the inserted smart susceptor wires is placed into a separate induction coil (see figure 32), thereby preheating the preform independently from the molding tools. By the use of smart susceptor wires throughout the thickness of the preform it can be rapidly inductively heated even though it is a very lofty material. The heated preform is then placed into the preheated tools by use of the susceptor wire structure (see figure 32). Now the molding operation is performed by closing the preheated tool set on the preheated preform. This should take about 10 seconds. Then active cooling of the back side of the smart susceptor shells on the molding tools is proposed, thereby rapidly cooling the part (see figure 33). The part is then ejected and the preheating insert is brought in to begin the preheating step and the fabrication steps for another part. This method would enable a 1 minute or less fabrication cycle and would be part of additional work in this area regarding risk reduction for implementation into the automotive industry.

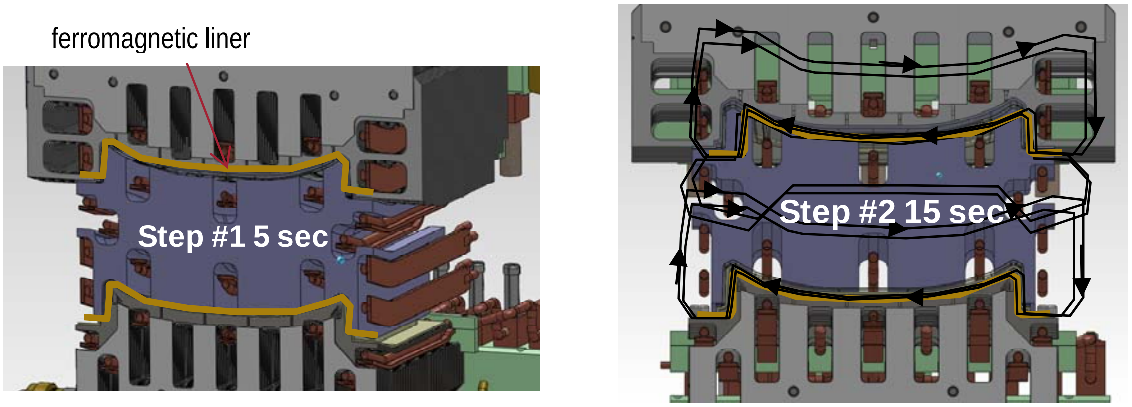


Figure 31. Depiction of smart susceptor preheating using tooling inserts with nonconductive ferromagnetic shells to reduce transverse flux issues allow very rapid preheating of the tool

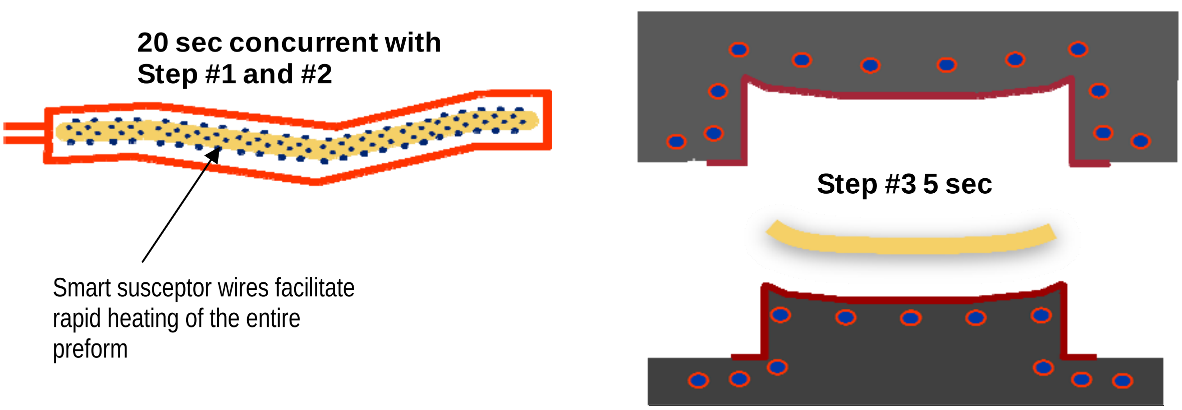


Figure 32. Depiction of a system for rapidly preheating of the preform on the left using smart susceptor wires to quickly heat the preform and then the preheated preform is loaded into the preheated tool

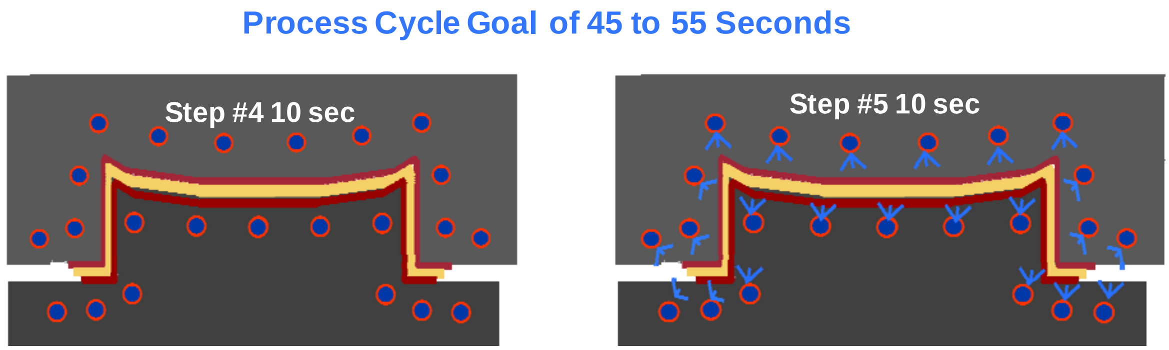


Figure 33. Depiction of the rapid molding of the preheated preform using the preheated mold with a subsequent water quench

3.2 Process Validation

As part of the process validation, there were a series of activities that have taken place. First was the selection of the 3 demonstration components used as the entry level components that when fabricated successfully would indicate initial validation of the process. Secondly, the processing system to perform the process with needed to be established. Thirdly, the tools for fabrication of the components were needed. Then the fourth and final step consisting of component fabrication and the subsequent assessment of these components was completed.

3.2.1. Demonstration Component Selection

During the course of the project three components, one from each of the three main industrial segments were selected for demonstration. These components are meant to be entry level components or components that would lend themselves to furthering the assessment of the process and thermoplastic materials produced for the application in these business segments.

3.2.1.1 Aerospace Business Segment Component

The aerospace component selected was a light weight seatback component design (see figure 34). This component represents a high instance component for interiors application. Therefore, the high rate of fabrication enabled by the induction consolidation process can be utilized for cost reductions and the thermoplastic composite materials are well suited to the interiors applications due to their excellent smoke and toxicity ratings.

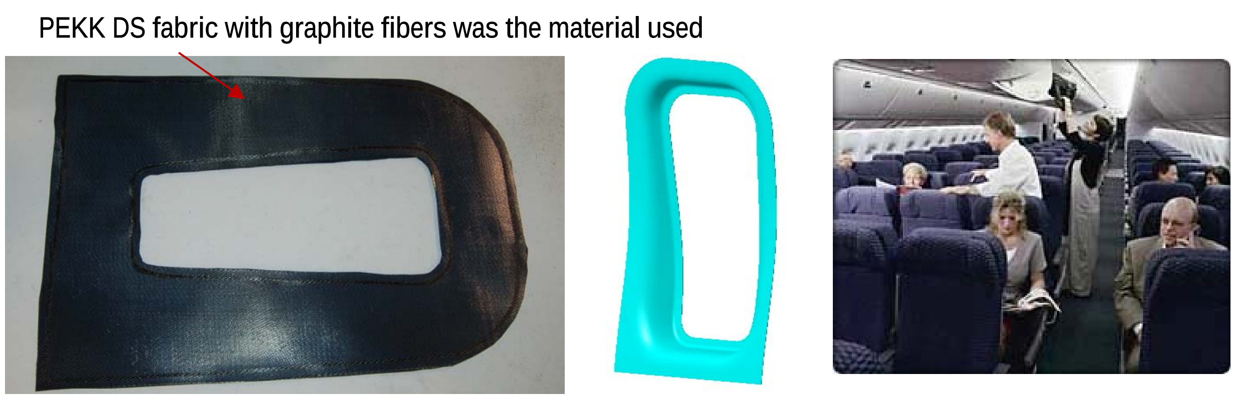


Figure 34. Boeing lightweight seat back design was chosen as the aerospace demonstration component due to its high number of instances per plane and existing composite design

3.2.1.2 Wind Energy Business Segment Component

The application of thermoplastics to wind energy is somewhat new, and it was determined that the best component would be a flat panel (see figure 35). This flat panel would provide consolidated laminates for evaluation by Vestas to enable a better understanding of the benefits of thermoplastic composites for wind energy and also provide test data that would aid in the implementation of this process and material combination.

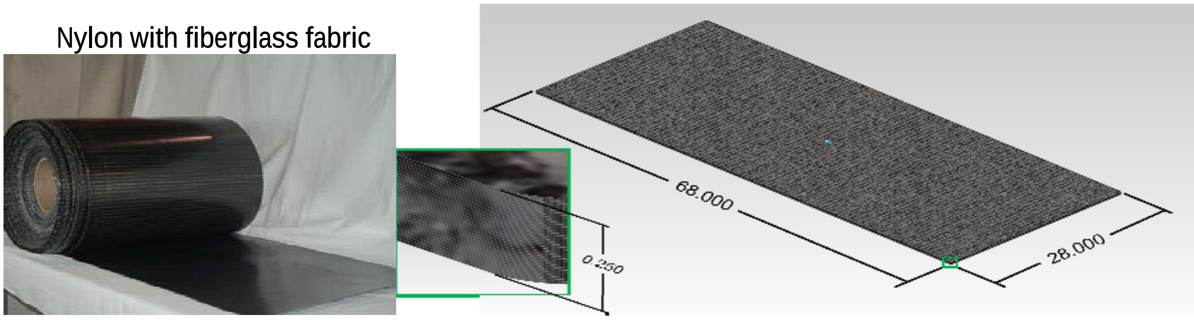


Figure 35. Depiction of Vestas flat panel demonstration panel to enable evaluation of the consolidated fiberglass/nylon materials for application to wind energy

3.2.1.3 Automotive Business Segment Component

The automotive component selected was a light weight seatback component design (see figure 36). Ford has existing information on molding of these components using compression molding, and it would allow for a convenient comparison of the competing process.

Figure 36. Depiction of Ford seat pan demonstration part for evaluation of the induction molding of random matte fiberglass reinforced polypropylene for application to automotive applications

3.2.2 Establishment of Induction Consolidation/Molding Fabrication System

The induction consolidation molding system was developed and installed to meet the needs of the process. A used press was purchased and refurbished to meet the needs of the process (see figure 37). One of the key criteria for the press was the ability to meet the need to hold the tools parallel to one another, even if there was uneven loading being experienced by the tool. A unique system consisting of a set of controls and the placement of 4 hydraulic cylinders was designed (figure 37) and installed (figure 38). This system enables the press to apply more pressure in the "higher" areas and "lower" areas as needed to evenly mold the heated composite material. Significant design modifications were needed to enable the press to accept these 4 hydraulic cylinders and significant systems and controls engineering and design effort was required to complete this task. This press was modified and assembled before subsequent shipping and installation (see figures 39 and 40). This press performed as designed and is a unique and inventive contribution to the press design field. In addition to the press, the induction power supply, the associate tuning capability, and the air quenching system needed to be designed and installed (see figures 41, 42, and 43). Finally, the induction processing system controls were integrated and the resulting operable press was ready for operation (figure 44).

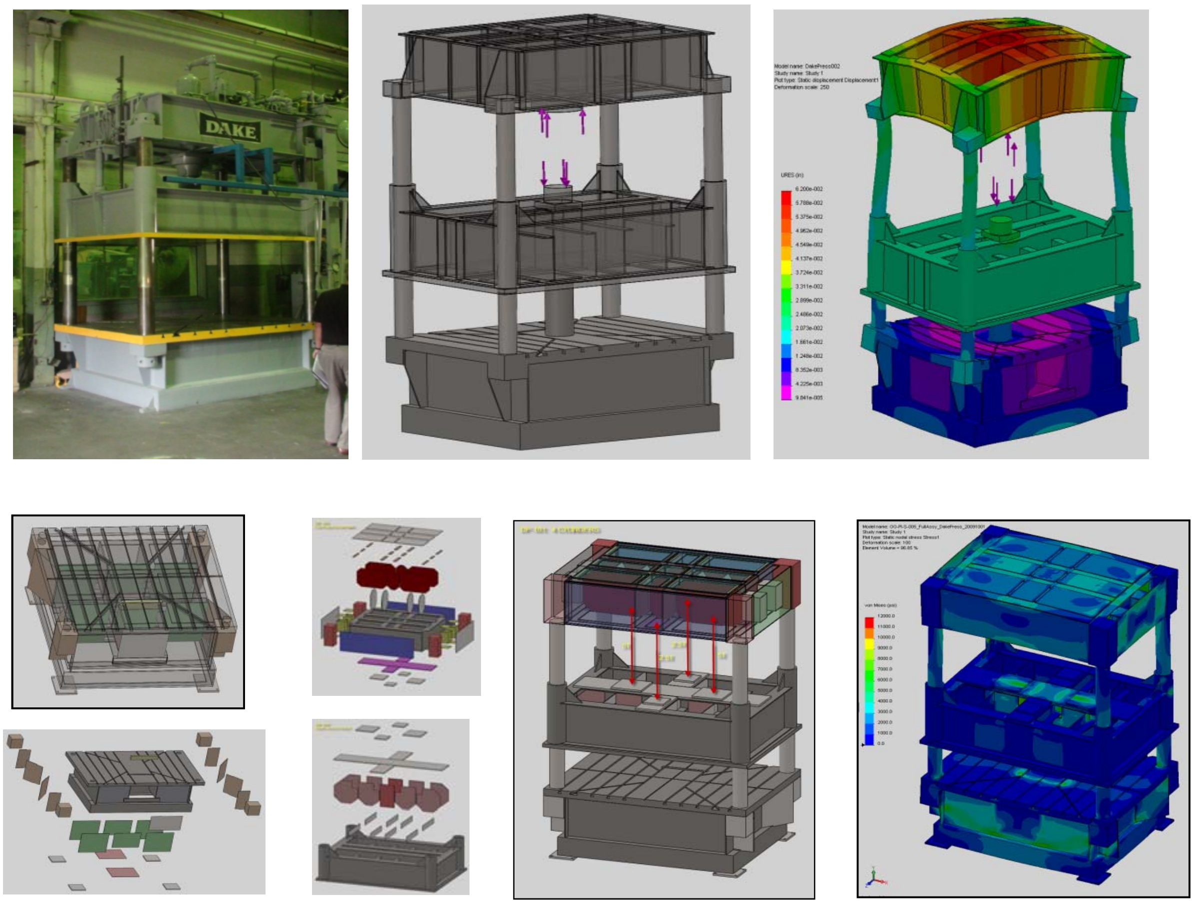


Figure 37. Picture of the used DAKE press as purchased and depictions of the subsequent analysis and redesign of the structure of the press

Figure 38. Pictures of the installation of the new hydraulic cylinders/system in the redesigned press

Figure 39. Pictures of the assembly of the refurbished components of the redesigned press

Figure 40. Delivery and set-up of the redesigned and refurbished press

Figure 41. Tuning cabinet is completed allowing the proper voltage and capacitance for matching the coils designed to the power supply

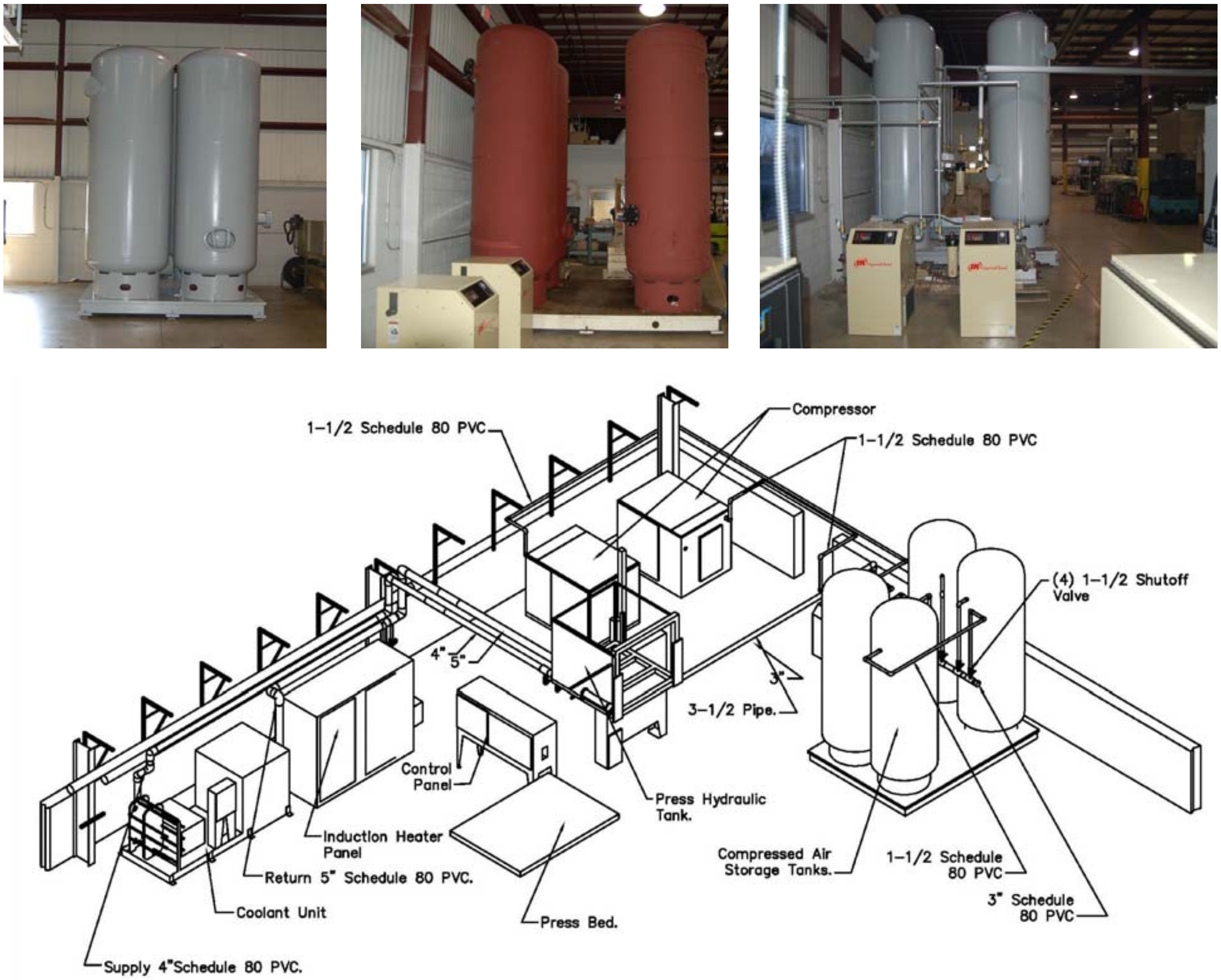


Figure 42. Induction processing system schematic showing the elements of the process plus pictures of the installed air quenching pressurized tanks

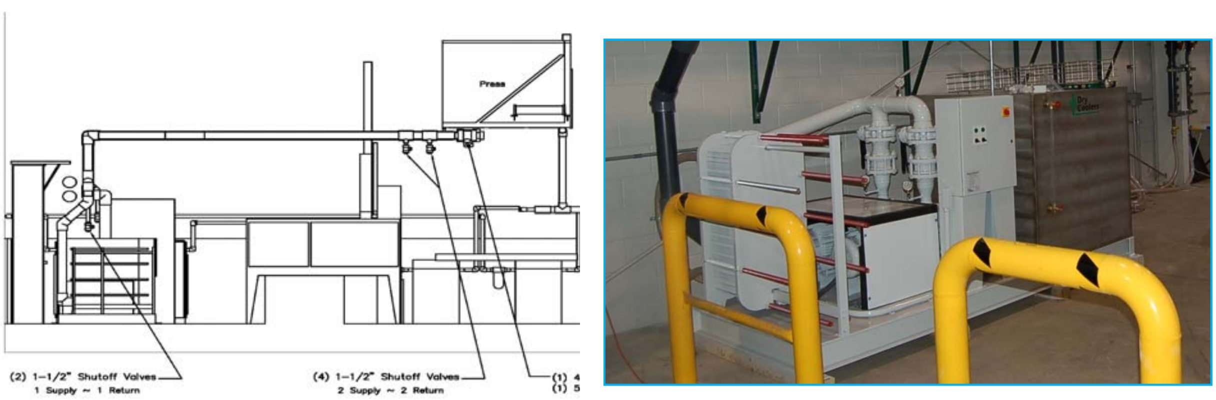


Figure 43. Schematic and picture of the coolant system for delivering coolant to the coil and the power supply

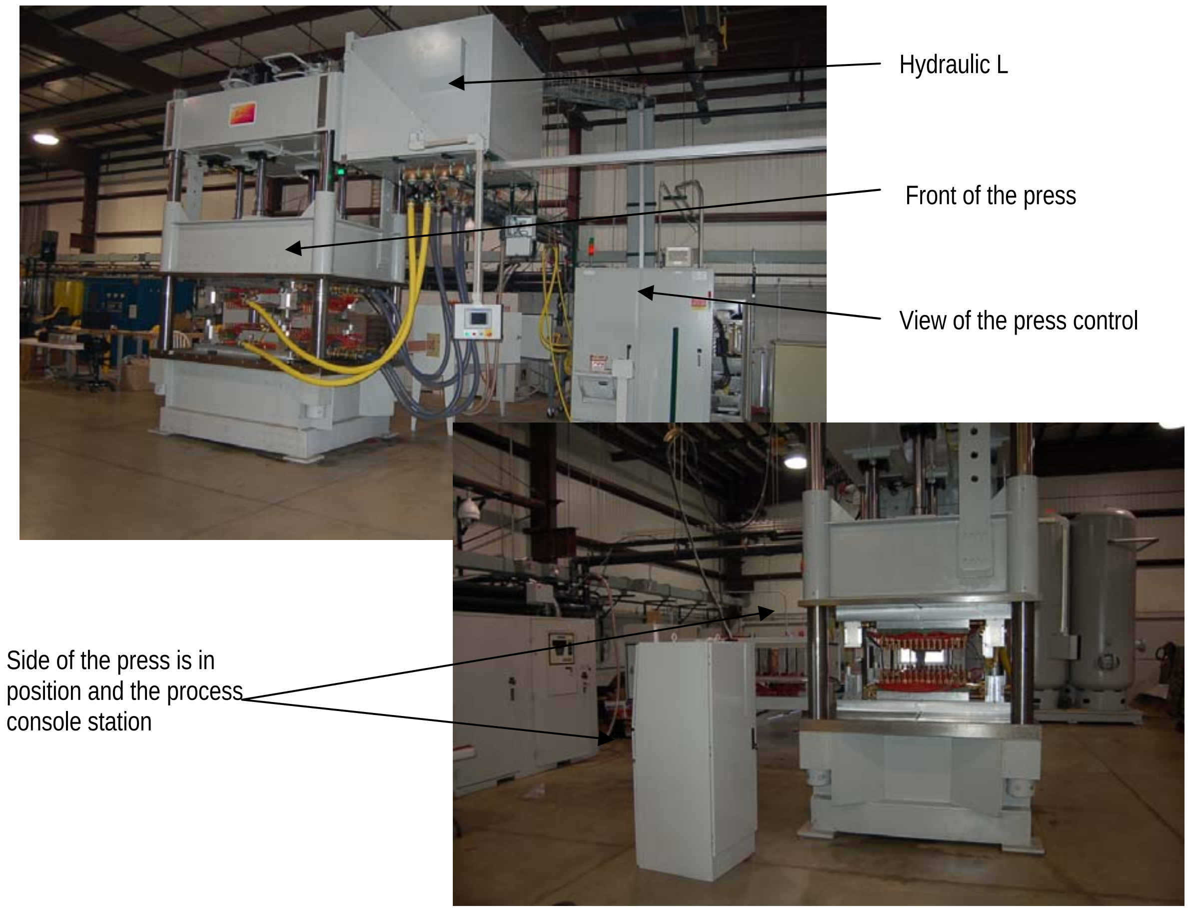


Figure 44. Completed, installed, and integrated induction consolidation/molding system ready to begin processing components

3.2.3 Design and Fabrication of Induction Molding Tools, Part Fabrication, and Part Assessment

Tools for the 3 demonstration components were designed and fabricated. These tools were then used to consolidate/mold components during the tool try-out effort. The components fabricated were then evaluated along with the processing parameters that were utilized to assess the overall performance of the process. Components produced by the process were subsequently assessed for quality and process repeatability.

3.2.3.1 Aerospace Seatback Component

As described earlier the aerospace demonstration component selected was a lightweight seatback design. This part design was used to initiate the design and fabrication of the induction molding tooling.

3.2.3.1.1 Aerospace Tool Design and Fabrication

The tooling design is shown in figure 45. Note the induction coils have an additional copper tube running along surface of the coil facing the smart susceptor shell. This tube carries the quenching gas when the cooling portion of the cycle is activated. Once the tooling design was set, the fabrication of the tooling commenced. Figure 46 shows the completed smart susceptor shell support structure made from the 3/16" thick 300 series stainless steel laminations. Pictures of the laminated support structure with the machined 1/8" thick Invar 42 smart susceptor shells installed are shown in figure 47 and figure 48. After the laminate tooling insert with the smart susceptor shells was completed then the induction coils were installed (see figures 49 and 50). During operation, the coil halves are joined by pin and socket reconnect-able junctions. This allows the tool halves to be connected for processing and then separated to load and unload the part. In addition, this tooling was designed to allow quick installation and set-up. The quick connectors for the air and water are shown in figures 49 and 50 respectively. The completed Boeing seatback tool, installed in the induction molding press, is shown in figure 51 and figure 52.

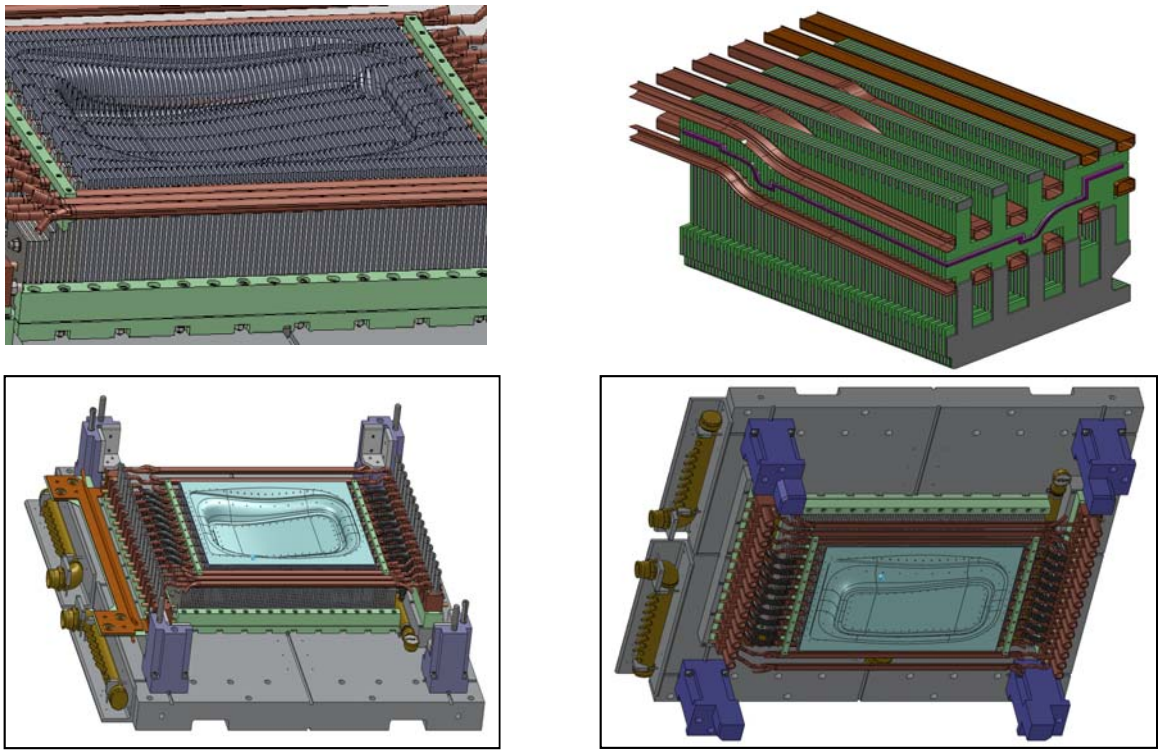


Figure 45. Boeing seatback tool design showing the induction coil, the stainless steel tool body laminations, the smart susceptor shells, and the die shoes for easy handling

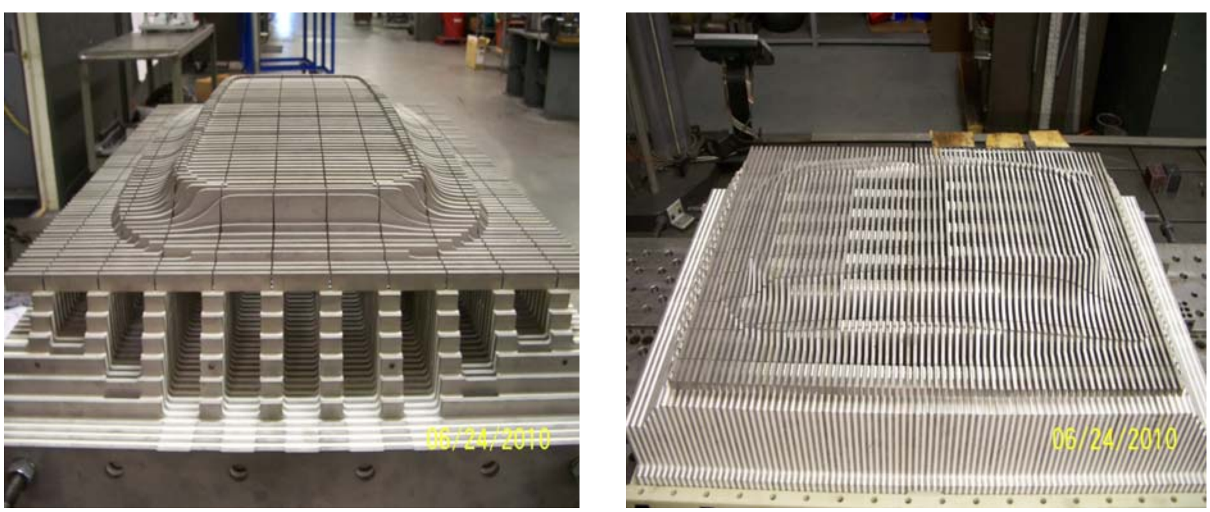


Figure 46. Picture of the assembled stainless steel tool body laminations for both the upper tool and the lower tool halves

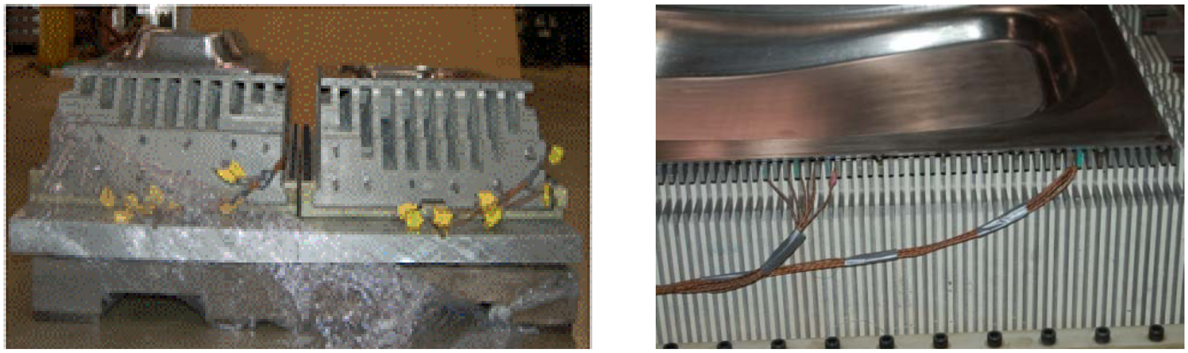


Figure 47. Side view of the stainless steel tool body laminations assembled with the smart susceptor shells tack welded on and subsequently finished machined

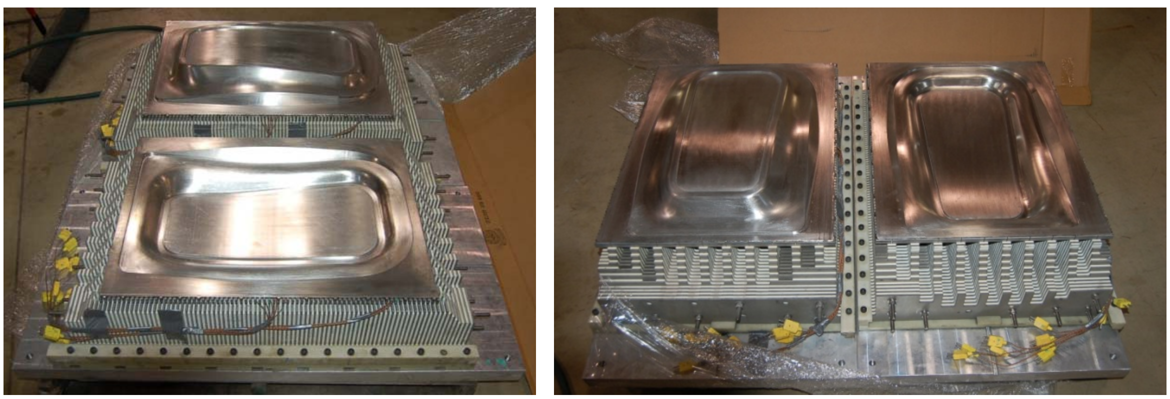


Figure 48. Side view of the stainless steel tool body laminations assembled with the smart susceptor shells tack welded on and subsequently finished machined

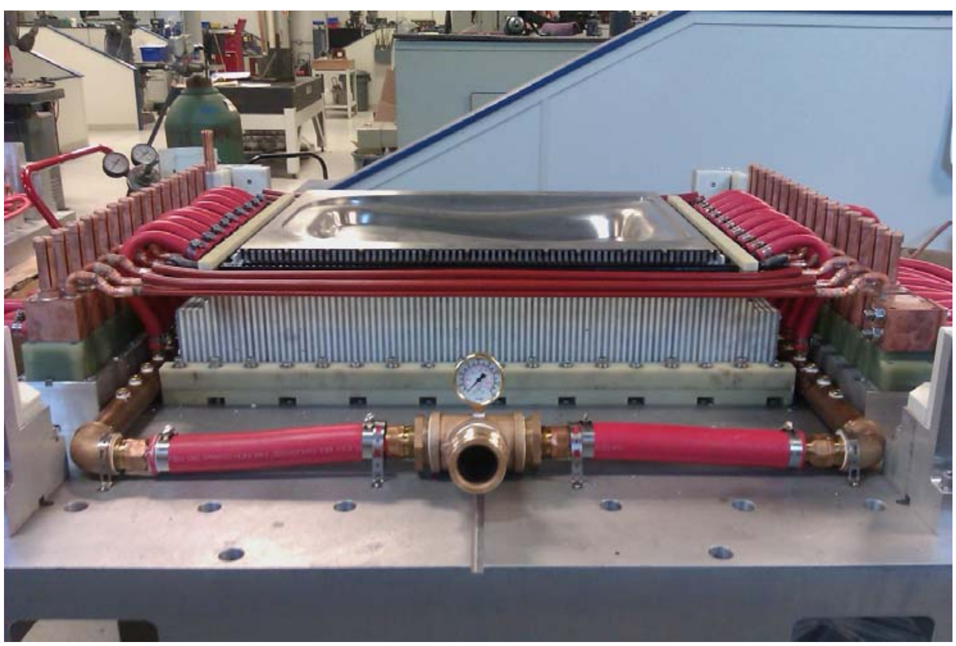


Figure 49. Front view of the completed lower tool half showing the quick disconnect for the quenching air feeding the individual quenching tubes

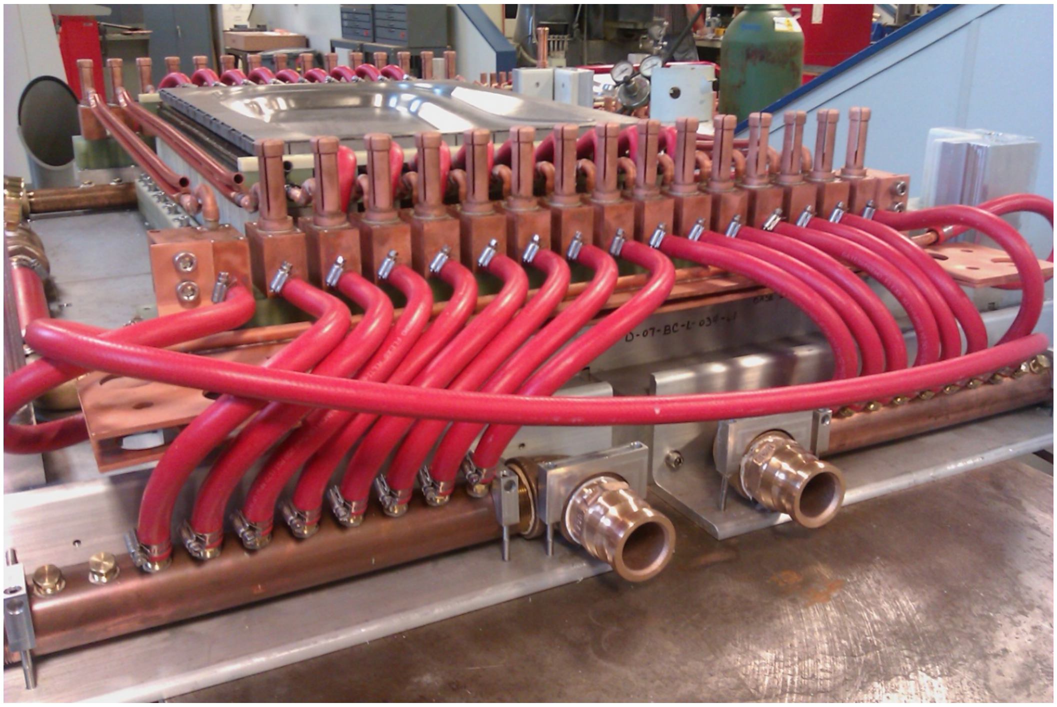


Figure 50. Side view of the completed lower tool half showing the quick disconnect for the cooling water feeding each of the induction coil turns

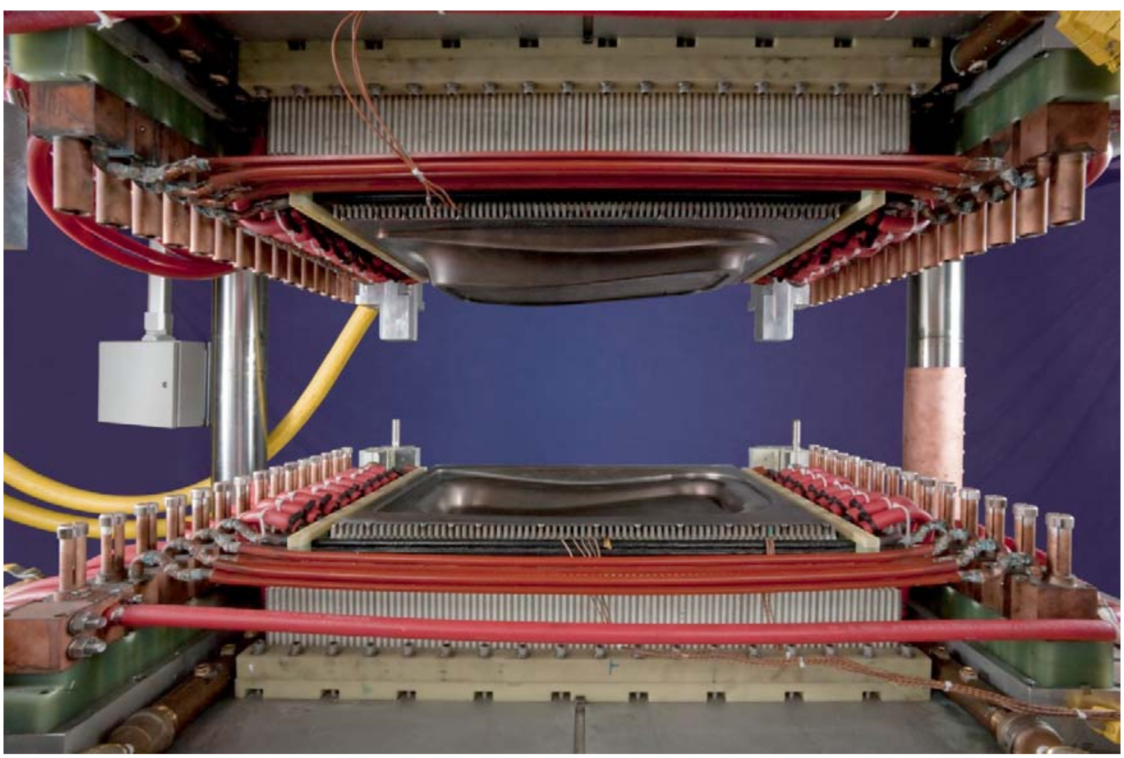


Figure 51. Front view of the completed Boeing seatback tool installed in the induction press and ready for molding

Figure 52. View of the completed Boeing seatback tool installed in the completed processing system along with the attachment of the air quenching yellow lines to the quick disconnect fittings

3.2.3.1.2 Aerospace Part Fabrication

AS4 graphite fiber PEKK DS reinforced resin plain weave thermoplastic composite fabric was used as the preforms for the fabrication of the Boeing seatback component (see figure 53). The resulting component fabricated is shown in figure 54. Also in figure 54 is the general desired thermal cycle configuration. This thermal cycle configuration consists of a rapid heat to consolidation/molding temperature, then a hold at temperature while pressure is applied, then a rapid quench to an intermediate temperature, then a hold at this intermediate temperature to build crystallinity, then finish the quench and unload the part. The recommended consolidation temperature for PEKK DS is 600 to 610F. Figure 54 shows the typical heating and hold portion of the thermal cycle for both the smart susceptor and the component. The smart susceptor heats rapidly to leveling temperature and then the heat is conducted into the preform, heating it to the consolidation temperature. Figure 55 shows the overall repeatability of the process. The measurements were made on the same location from part #37 to #46. The lines are almost identical showing excellent part to part processing repeatability.

Figure 53. Picture of the graphite fiber reinforced PEKK DS fabric preforms ready for consolidation on the right side of the picture along with the consolidated components on the left side of the picture

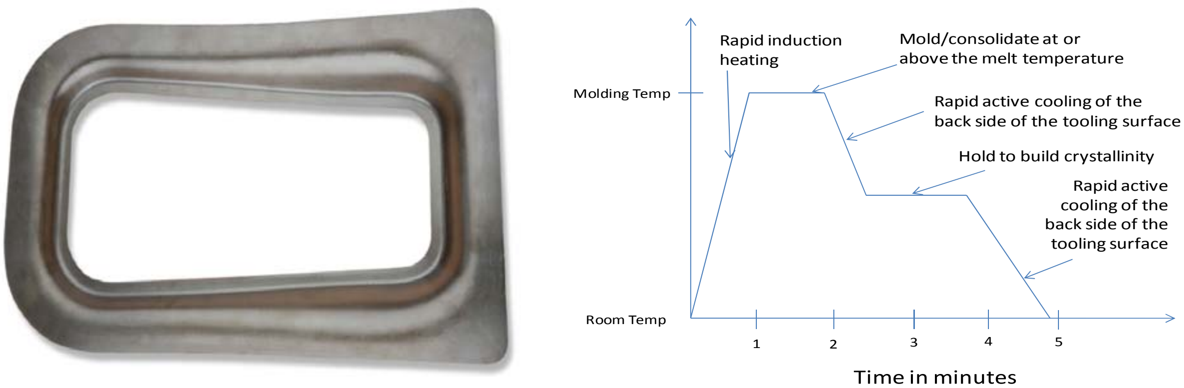


Figure 54. Picture of the typical consolidated component and the thermal cycle goal establish at the beginning of the project for the PEKK materials

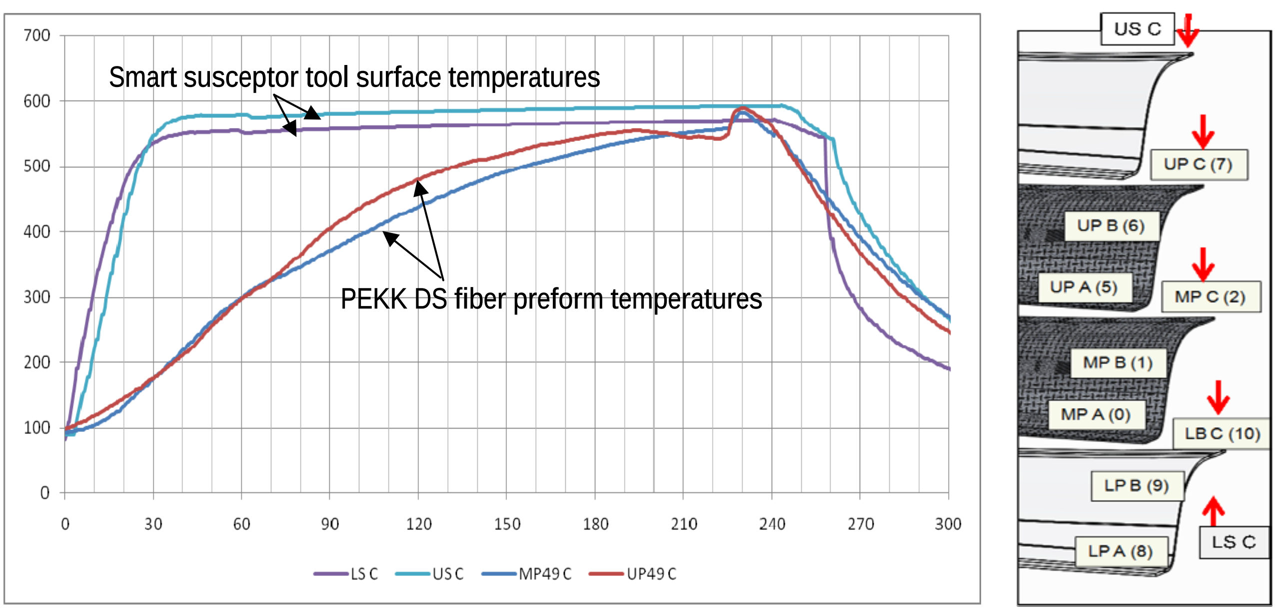


Figure 54. Graph showing how the smart susceptor quickly gets to temperature and the component takes a little longer to converge at the leveling temperature due to need for conduction of heat thru the composite material

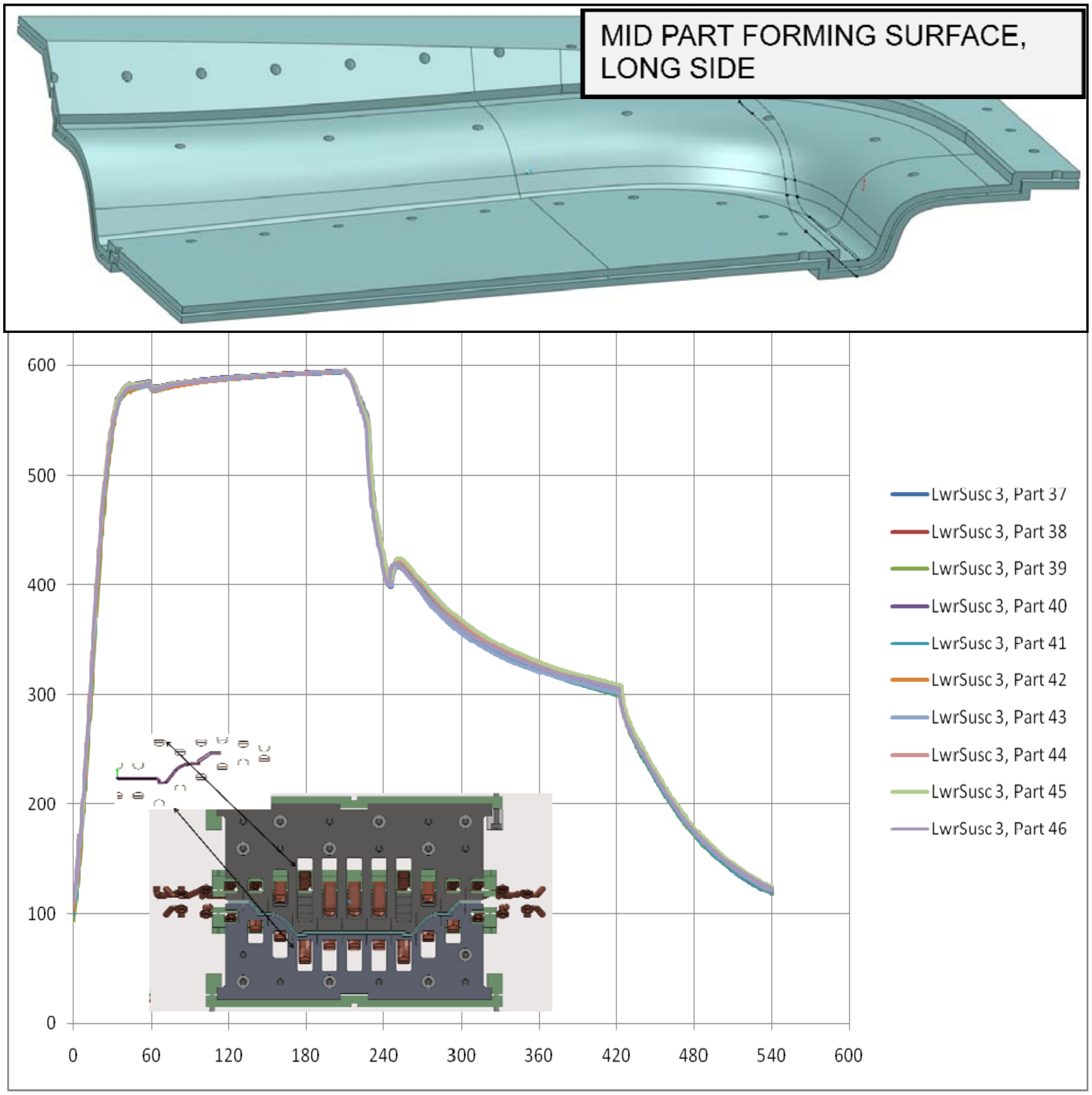


Figure 55. Graph showing the thermal repeatability of the process with the same spot on the tool over a 10 part run with almost the exact profile on each processing run

3.2.3.1.3 Aerospace Part Assessment

Several tests were conducted to assess the overall quality of the components fabricated. One of the assessments was to conduct a non-destructive test using ultrasound to assess the overall consolidation quality. To accomplish this ultrasound inspection, a through transmission ultrasonic (TTU) squirter system testing 5 MHz was used with a step matrix of 0.04 inches for each pass. Figure 56 shows the typical inspection results from the ultrasonic inspection. The data shows good consolidation and would likely pass production requirements for aerospace seatback requirements. In addition, dimensional inspection of a group of 10 components was performed and compared (see figure 57). The results of the dimensional inspection of these 10 panels are shown in figure 58. This shows that the parts fabricated exhibit very good dimensional repeatability from part to part. This is attributed to the fact that each part is subjected to the very same thermal cycle therefore imparting that same repeatability to the dimensional characteristics.

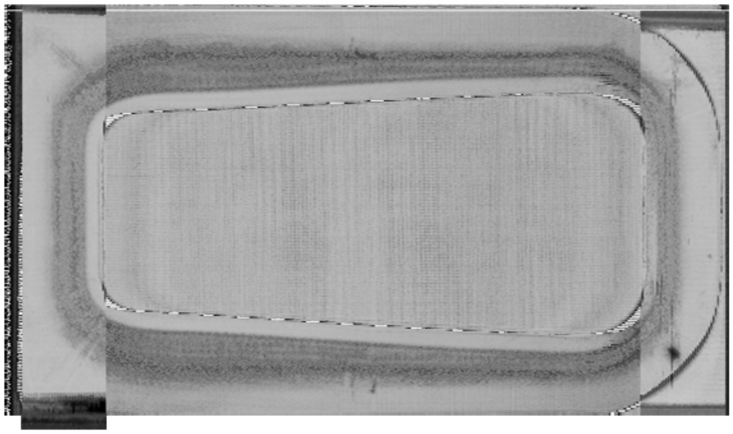


Figure 56. Typical ultrasonic inspection results for the induction consolidated Boeing seat back part showing acceptable overall quality

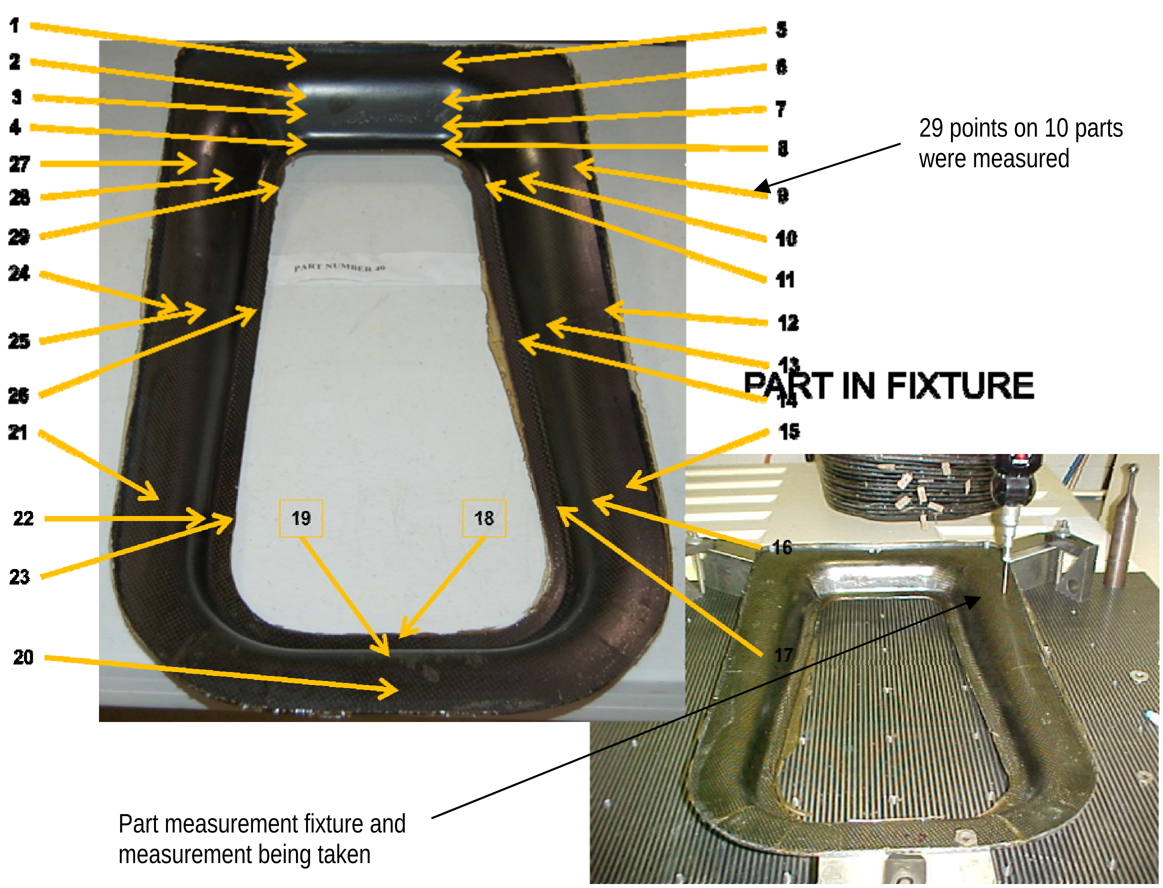


Figure 57. Picture on the left shows the points measured during the dimensional evaluation using a coordinate measurement machine (CMM) with a photo of the part set up shown on the right

DATE OF STUDY	7/6/2011						LOCATION OF STUDY:			STEEPLECHASE TOOL & DIE			
EQUIPMENT:	Attributte Check Fixture/ CMM lk												
Point	Trial										Range	Tolerance	GR
Label	1	2	3	4	5	6	7	8	9	10		Range	%
F_1	0.292	0.291	0.287	0.285	0.278	0.301	0.291	0.292	0.303	0.302	0.025	1.4	3.0%
F_4	0.108	0.106	0.134	0.134	0.133	0.135	0.134	0.132	0.137	0.135	0.031	1.4	4.4%
F_5	-0.010	-0.012	0.022	0.023	0.023	0.024	0.024	0.023	0.025	0.025	0.037	1.4	5.5%
F_8	0.221	0.221	0.221	0.257	0.266	0.269	0.267	0.227	0.268	0.269	0.048	1.4	8.6%
F_10	-0.238	-0.241	-0.239	-0.227	-0.259	-0.258	-0.259	-0.266	-0.250	-0.261	0.039	1.4	4.8%
F_19	0.197	0.205	0.195	0.207	0.227	0.227	0.222	0.216	0.214	0.228	0.033	1.4	4.7%
F_20	-0.071	-0.071	-0.072	-0.069	-0.069	-0.068	-0.069	-0.070	-0.069	-0.071	0.004	1.4	0.5%
F_22	-0.273	-0.282	-0.285	-0.257	-0.273	-0.260	-0.260	-0.280	-0.259	-0.276	0.028	1.4	4.0%

Figure 58. Data resulting from the CMM evaluation showing excellent repeatability of less than +/- .025" from part to part

3.2.3.2 Wind Energy Panel Component

As described earlier, the wind energy demonstration component selected was a flat panel design. This part design was used to initiate the design and fabrication of the induction molding tooling.

3.2.3.2.1 Wind Energy Tool Design and Fabrication

The use of analytical techniques helped to finalize the overall induction molding flat panel tooling design. The tooling design is shown in figure 59. This design enables the fabrication of a flat panel that is at maximum 28" by 68". This is near the largest panel that can be made in this press. Figure 60 shows the 300 series stainless steel laminations after they have been water jet trimmed from plates. These laminations are then stacked together for the support base for the smart susceptor shell. This support base will not heat inductively and is therefore not intimately involved in the thermal cycle. The 1/8" (plus) Invar 42 smart susceptor shell is machined from a plate. This invar 42 shell is then fitted to the laminated support base (see figure 61). Thermocouples are welded to the smart susceptor so the thermal performance of the susceptor can be monitored (see figure 61). Then the smart susceptor is welded to the laminated support (see figure 61). After welding, the smart susceptor surface is final machined. The susceptor is intentional slightly thicker than 1/8" when it is welded into the tool. This allows for a skin cut after welding thereby achieving very accurate tool tolerances (see figure 62). Then the tooling insert is ready for installation of the coil. After the coil installation, the tool was installed in the press and connected to the processing system and ready for performing processing trials.

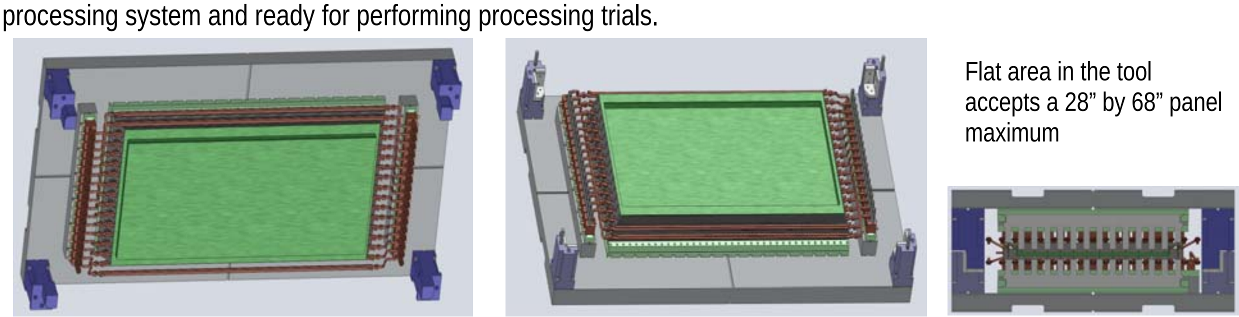


Figure 59. Vestas flat panel tooling design

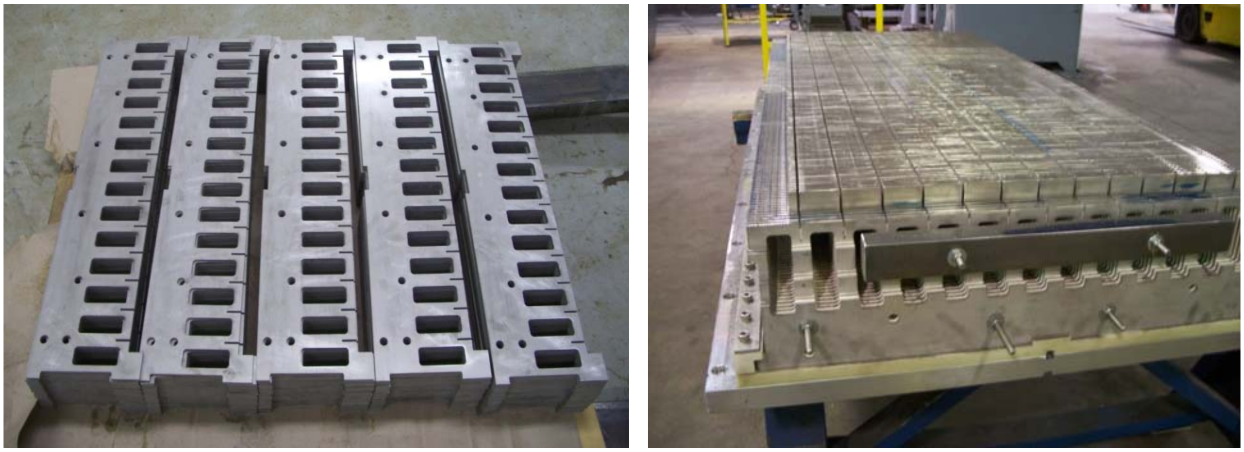


Figure 60. Trimmed stainless steel laminations on the left and subsequent assembly of the laminations making up the tool body for the Vestas tool on the right

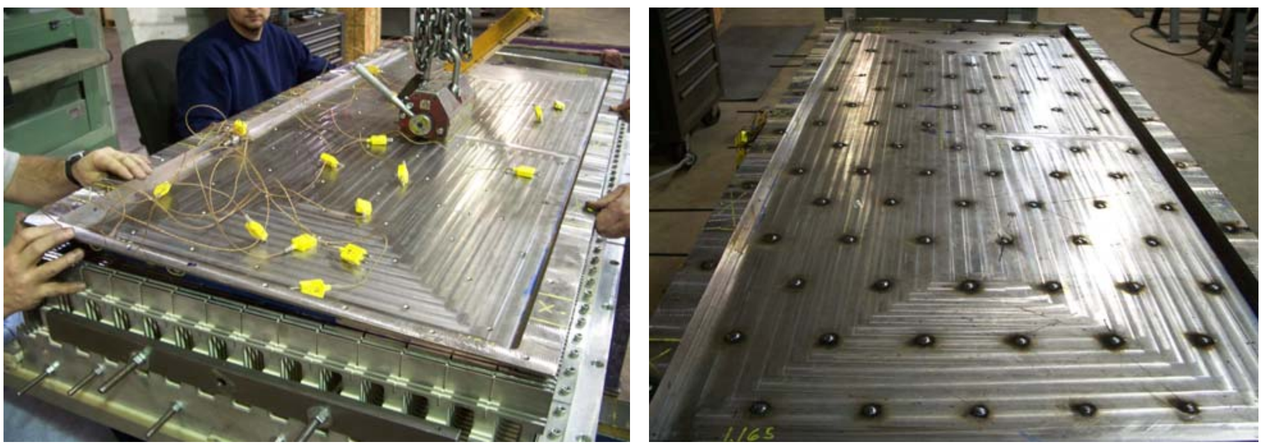


Figure 61. Machined smart susceptor being loaded onto the assembled laminations and then the subsequent tacking of the smart susceptor to the laminations

Figure 62. Final machining of the susceptor after tacking to the laminations on the left and then the completed tooling insert on the right

Figure 63. Picture showing the completed Vestas tool installed in the induction processing system and ready to begin molding trials

3.2.3.2.2 Wind Energy Part Fabrication

Fiberglass fabric reinforced nylon was the material of choice for the wind energy applications. Two types of nylon resin were use, nylon 6 and nylon 6/6. The received product was large rolls of consolidated single ply material. This material was rolled out and placed into the tool cavity (see figure 64). Armalon (PFTE and fiberglass) was used as the release film during molding (figure 64). Once the lay-up was complete, the consolidation process was initiated. Figure 65 shows the typical thermal profile for the smart susceptor during the processing of nylon 6/6. The smart susceptor heats rapidly to the leveling temperature then the temperature is held at this temperature to allow heat to soak into the composite lay-up. Then, consolidation is completed and the quenching is initiated. Figure 66 shows the typical panel fabricated. Four test panels (5plys, 10plys, 15plys, 20plys) of both the nylon 6 and nylon 6/6 were fabricated for evaluation (see figure 67). The four nylon 6 panels are shown in figure 68.

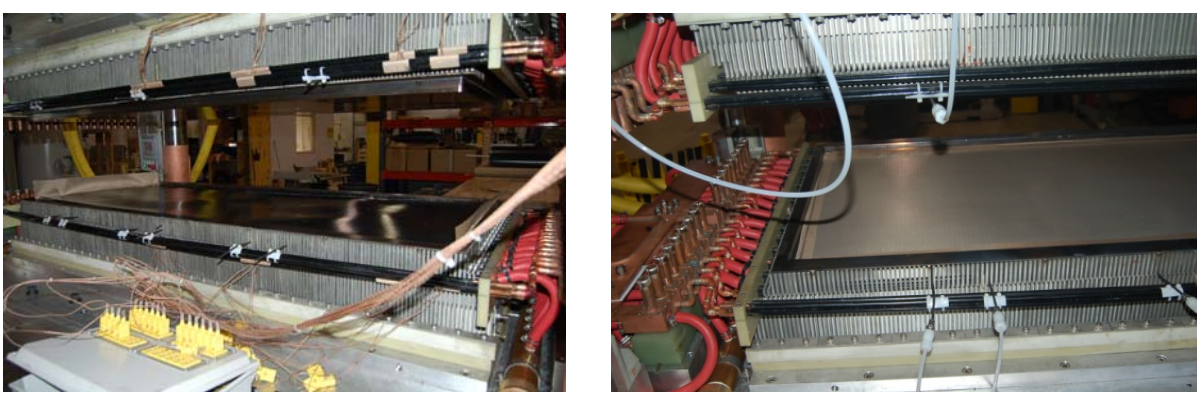


Figure 64. Pictures showing layers of the fiberglass/nylon fabric placed in the part molding cavity and the subsequent lay-up in the tool ready for consolidation

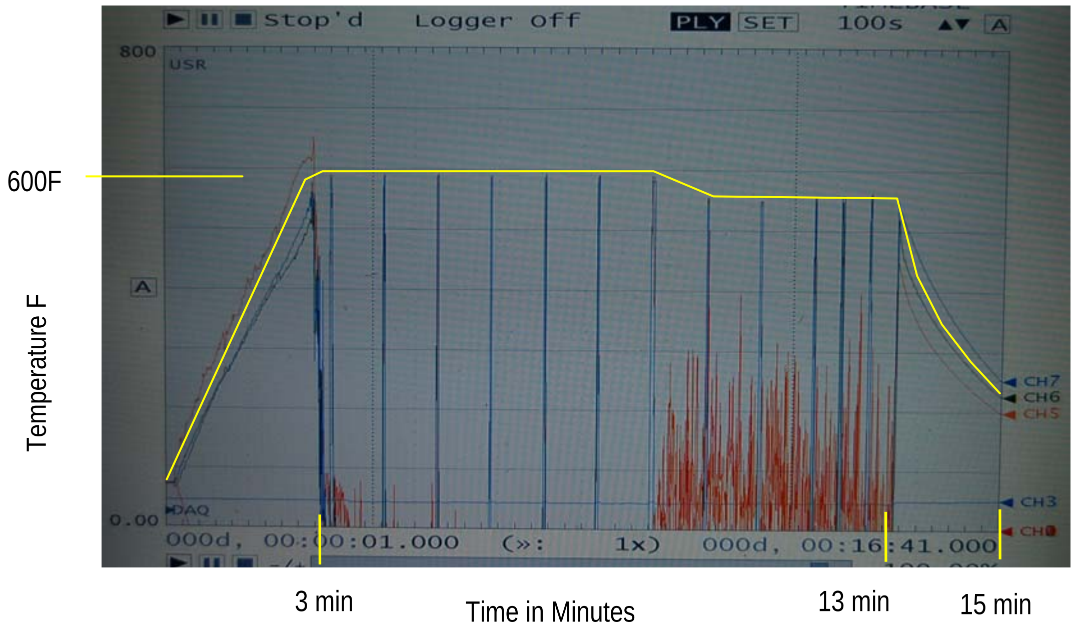


Figure 65. Typical thermal cycle for tooling surface (15 minutes) associated with the consolidation of the fiberglass/nylon 6-6 fabric laminates with the soak time associated with conduction of thermal energy into the preform

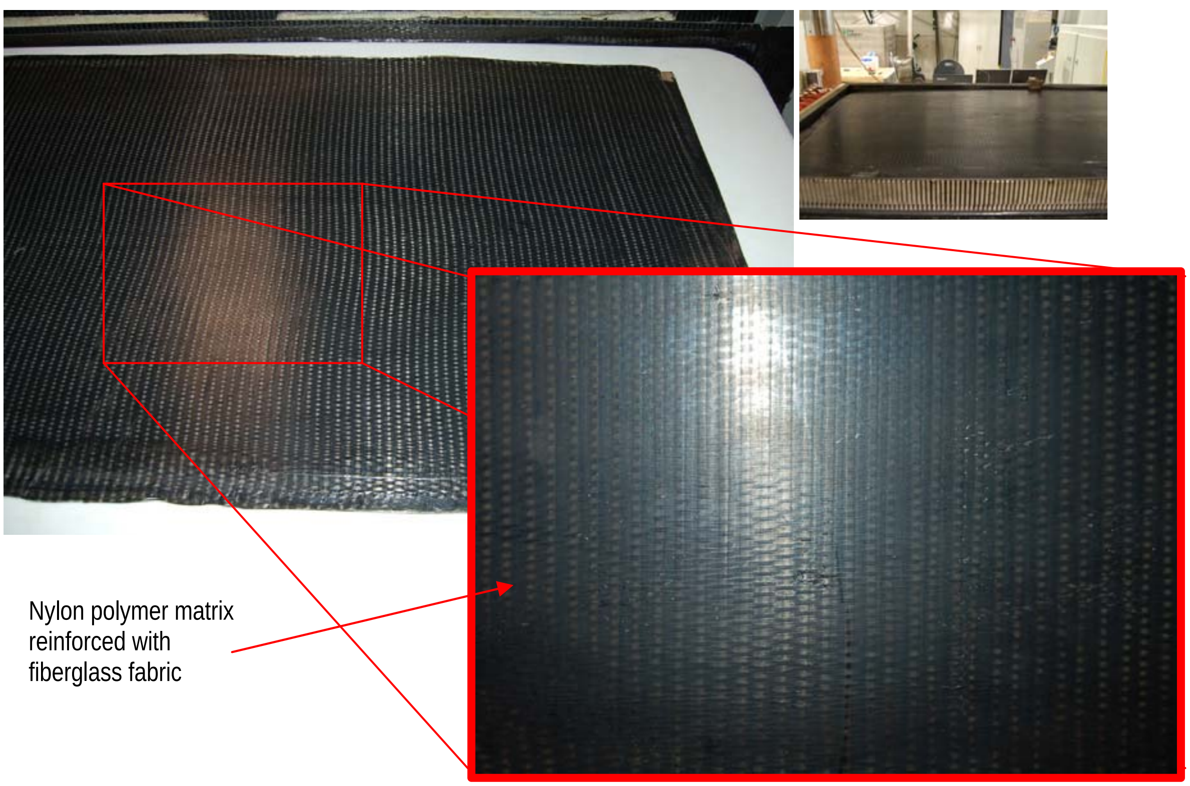


Figure 66. Picture of the as molded panel in the tool top right and then typical molded panel appear as shown in the remaining 2 pictures

Panel	Resin	Fiber/Type	# of Plys/Thickness/Orientation	Width/Length
1	Nylon 6	Fiberglass/Fabric	5 plys/0.080”/0^o - 90^o	28” x 68”
2	Nylon 6	Fiberglass/Fabric	10 plys/0.160”/0^o - 90^o	28” x 68”
3	Nylon 6	Fiberglass/Fabric	15 plys/0.240”/0^o - 90^o	28” x 68”
4	Nylon 6	Fiberglass/Fabric	20 plys/0.320”/0^o - 90^o	28” x 68”
5	Nylon 6/6	Fiberglass/Fabric	5 plys/0.080”/0^o - 90^o	28” x 68”
6	Nylon 6/6	Fiberglass/Fabric	10 plys/0.160”/0^o - 90^o	28” x 68”
7	Nylon 6/6	Fiberglass/Fabric	15 plys/0.240”/0^o - 90^o	28” x 68”
8	Nylon 6/6	Fiberglass/Fabric	20 plys/0.320”/0^o - 90^o	28” x 68”

Figure 67. Listing of the panels fabricated and sent to Vestas for testing

Figure 68. Photo of the fiberglass fabric reinforced nylon6-6 panels fabricated and ready for evaluation

3.2.3.2.3 Wind Energy Part Assessment

The primary method of assessment of these fiberglass reinforced nylon panels was to conduct a non-destructive test using sound waves to assess the overall consolidation quality. To accomplish this ultrasound inspection, a through transmission ultrasonic (TTU) squirter system testing at 1 MHz was used with a step matrix of 0.04 inches for each pass. Figure 69 shows the typical inspection results from the ultrasonic inspection. This shows good consolidation and would easily pass production requirements for wind energy requirements.

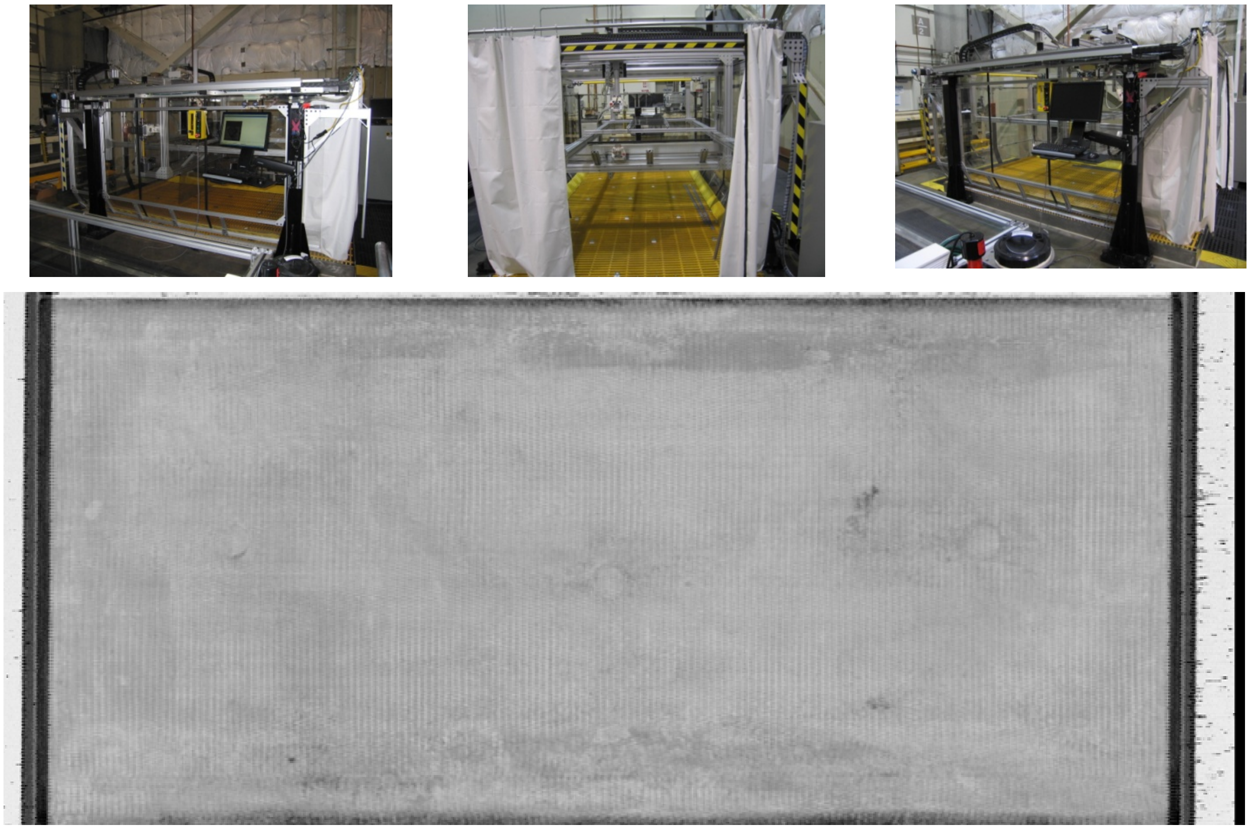


Figure 69. Three pictures situated to the top of the figure show the equipment utilized to perform the typical ultrasonic evaluation of a typical Vestas panel as shown in the lower picture

3.2.3.3 Automotive Seat Pan Component

As described earlier, the automotive demonstration component selected was a seat pan design. This part design was used to initiate the design and fabrication of the induction molding tooling.

3.2.3.3.1 Automotive Tool Design and Fabrication

The use of analytical techniques helped to finalize the overall induction molding seat pan tooling design. The tooling design is shown in figure 70. The top tool half is significantly wider than the bottom tool half (see figure 70). This is due to the additional lamination width necessary to counteract the side load developed with the appropriate stiffness and load carrying capability when consolidating the component. Figure 71 shows the machining of the DK510 smart susceptor alloy. This process produces the 1/8" thick smart susceptor shell. This shell is then installed onto the 300 series stainless steel laminations as shown in figure 72. Furthermore, this tooling insert was then installed onto the tooling "shoe". The coils were then installed and the resulting tooling set was installed into the induction molding processing system and ready for processing (see figure 74).

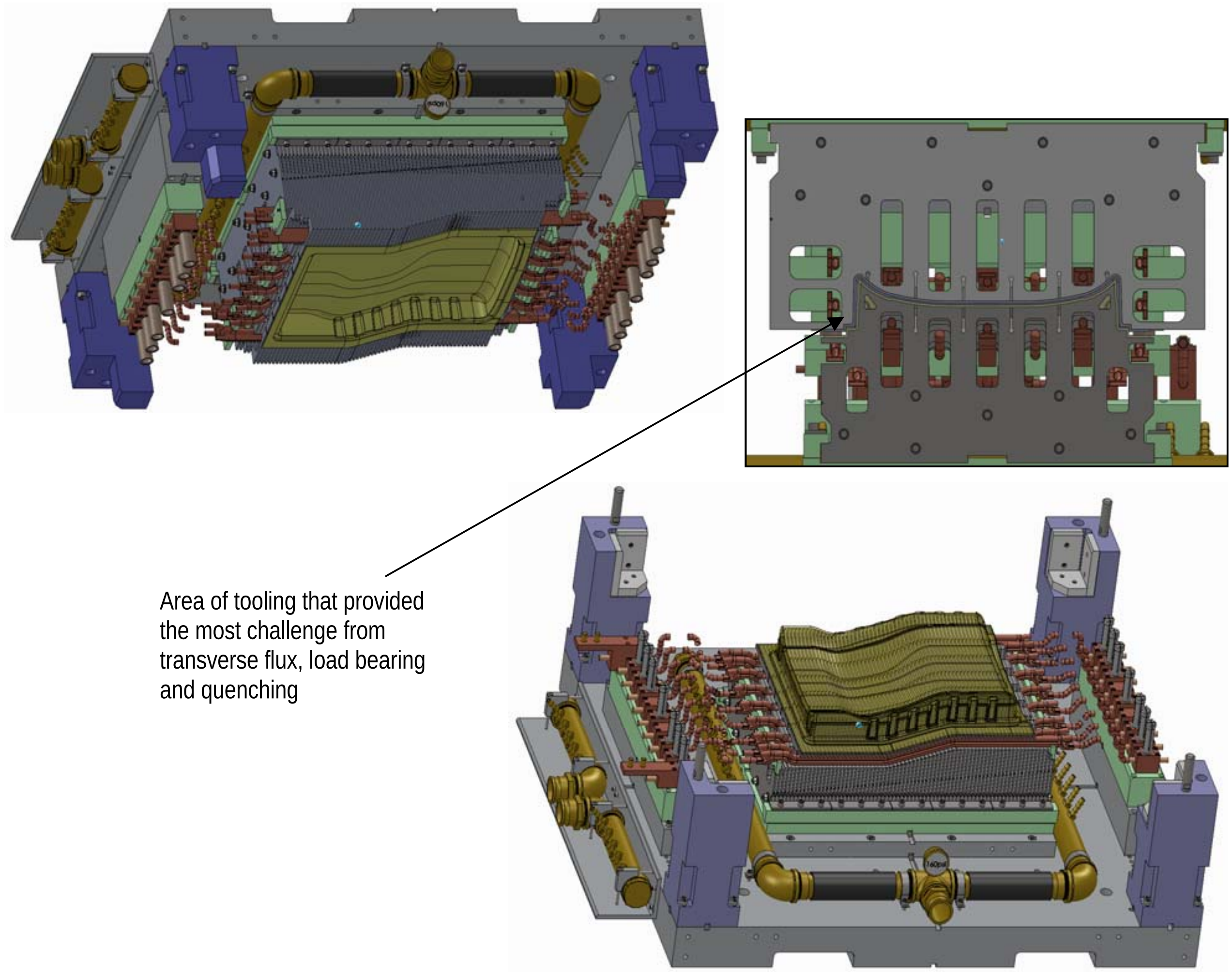


Figure 70. Induction molding tool design for the Ford seat pan is shown with the top and the bottom halves along with cross section of the tool running parallel to the stainless steel laminations

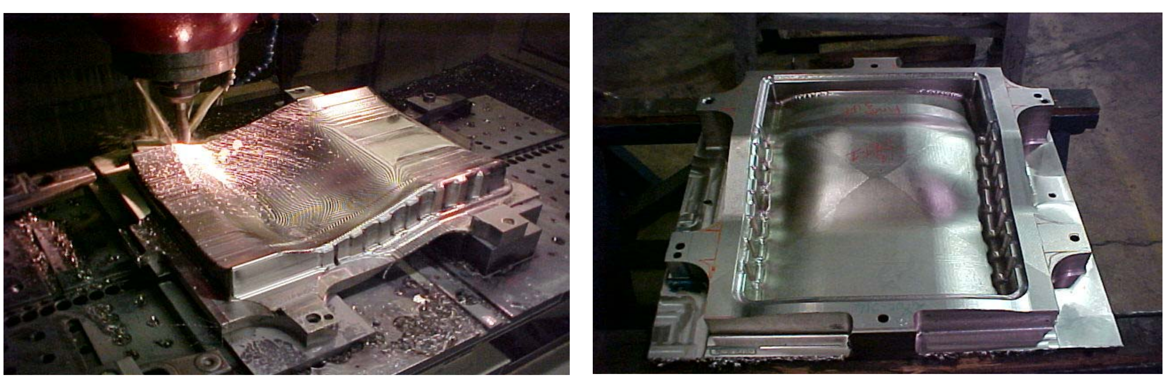


Figure 71. Machining of the smart susceptor shells from blocks of DK 510 alloy

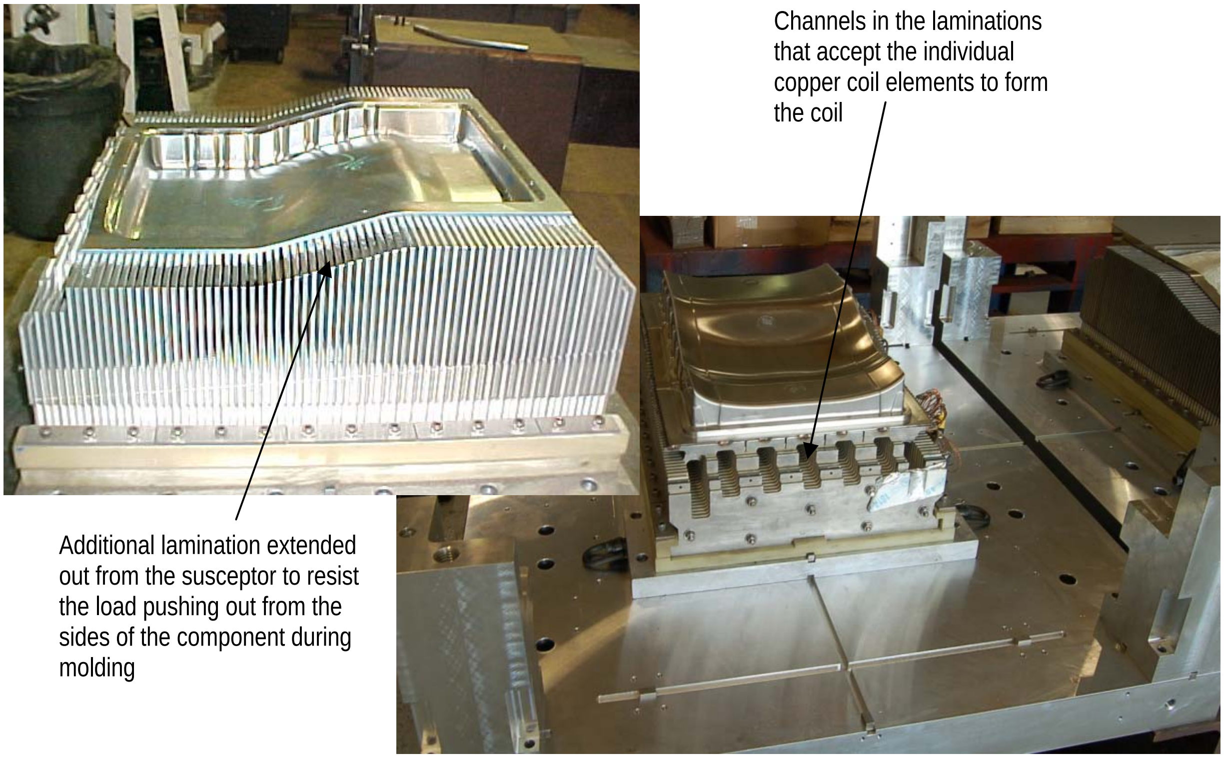


Figure 72. Completed tooling insert as shown in the upper left picture and the insert positioned on the die shown in the bottom right

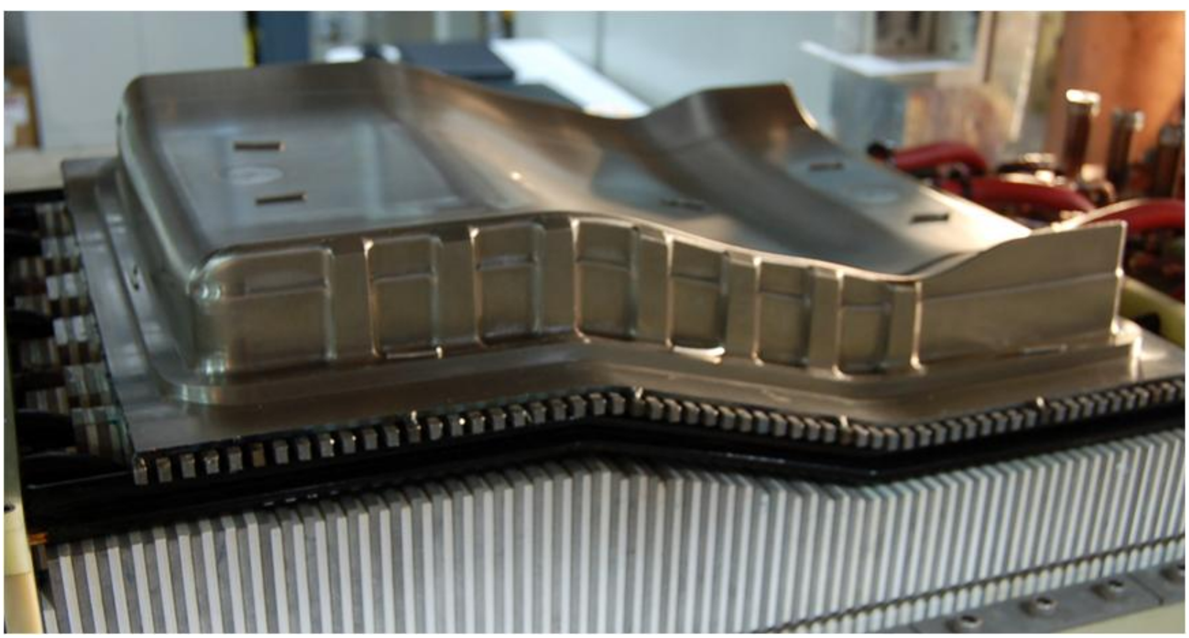


Figure 73. Complete bottom half of the Ford seat pan tool showing the detail of the machined susceptor

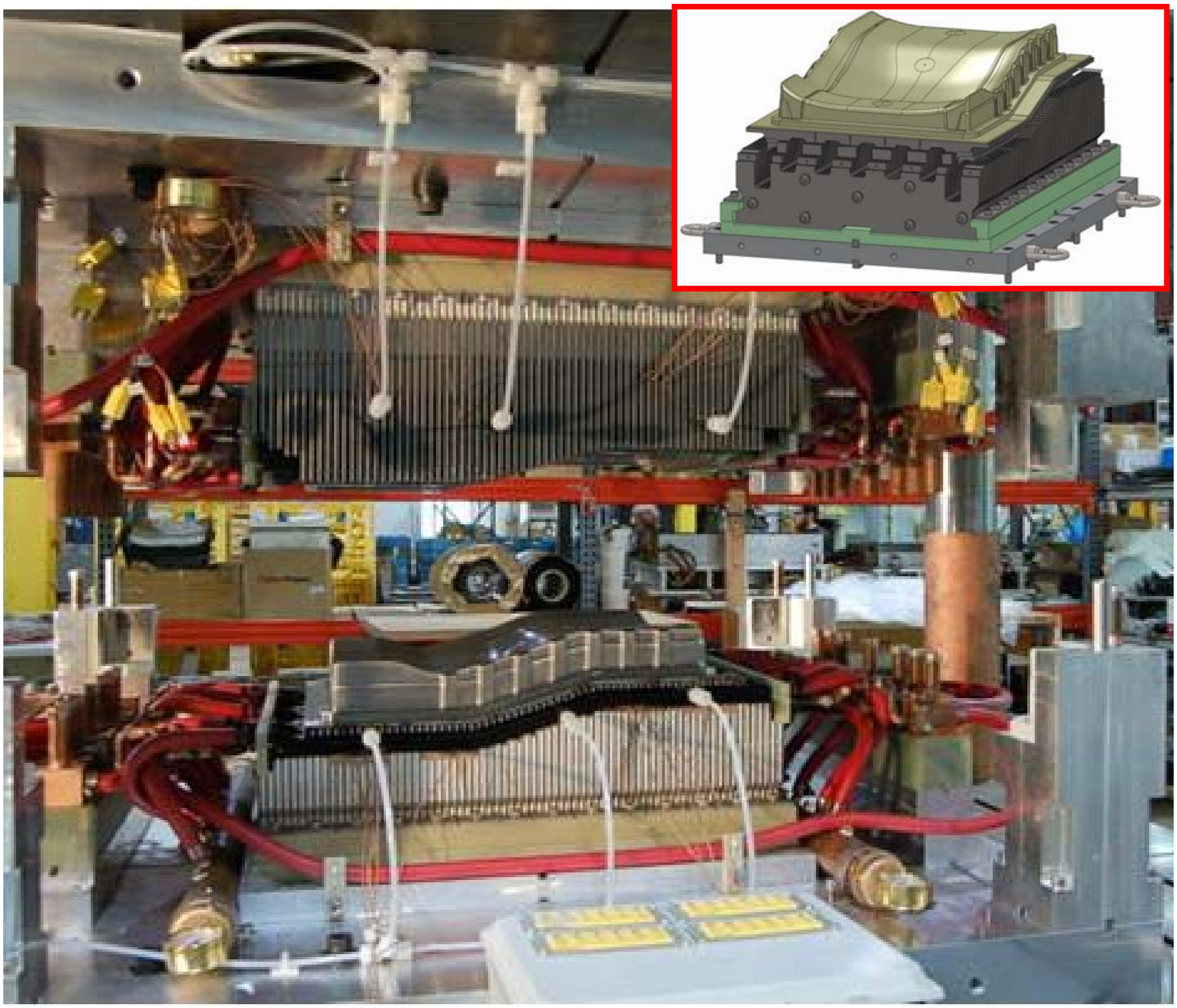


Figure 74. Ford set pan tool installed in the induction processing system and ready to begin part molding

3.2.3.3.2 Automotive Part Fabrication

Chopped fiberglass reinforced polypropylene was the material of choice for the automotive application. These preforms were produced with robotically sprayed copper guns to produce preforms. The preform (see figure 75) was placed into the tool with both preform and tool being at room temperature (see figure 76). Then heating commenced with the smart susceptors reaching processing temperature in about 3 minutes and then after another 8 or 9 minutes, the preform is at temperature and molding takes place. Once the molding is completed the quenching system is activated (see figure 77). The molding commenced rapidly (2 to 3 seconds) with applied pressures of between 250 and 300 psi even though the preforms contain nearly 20% more fiberglass fibers than in the current process. Figures 78 and 79 show the part molding characteristics. These pressures are approximately 5X less than standard compression molding due to the fact that we are above the melting temperature of the resin. Additional development along the lines described in the scale-up section (3.1.3 Process Scalability) is necessary to reduce the cycle to levels that meet automotive requirements. This development effort should include the ability to efficiently and effectively pre-heat both the tool and the preform quickly.

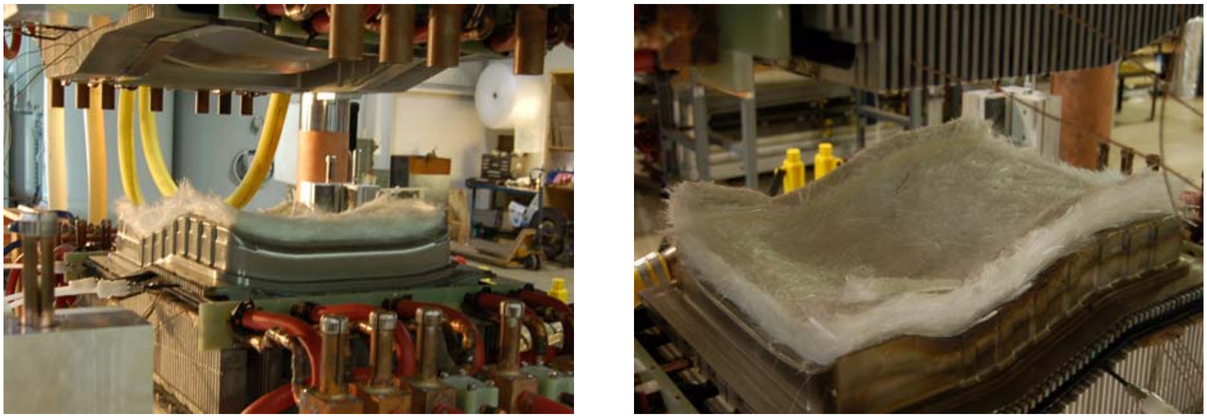


Figure 75. Two pictures of the robotically sprayed chopped fiberglass fiber and polypropylene rovings making up the Ford seatpan preforms ready for induction molding

		Melting Point				Molding Temperture					Close Tool			Hold													
Recipe Step	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	43	44				
Seconds	33	66	99	132	165	198	231	264	297	330	363	396	429	462	495	528	561	594	627	660	693	729	759	789	819	849	879
Upper																											
0	220	277	314	340	358	373	383	390	387	389	397	395	397	397	395	394	394	395	396	397	399	376	233	184	155	135	120
1	119	178	302	334	359	379	394	394	400	405	408	412	415	416	418	420	427	424	424	423	425	388	139	124	112	104	98
2	110	172	331	365	392	410	419	418	418	421	424	425	427	427	431	433	433	436	435	436	436	387	178	142	127	118	122
3	124	189	211	233	248	264	278	293	300	302	308	312	317	320	325	329	333	337	340	342	344	352	211	175	152	135	123
Pre - Form																											
0	108	115	133	150	177	210	225	260	293	312	333	347	364	378	393	403	413	421	428	437	440	400	291	198	158	125	108
1	107	112	125	143	166	183	206	228	243	257	263	279	295	300	310	317	327	342	356	367	430	395	280	195	158	127	110
2	108	112	125	143	166	184	208	230	248	263	275	287	301	313	329	349	368	381	402	409	425	383	288	211	167	140	122
3	109	115	129	149	172	194	220	245	266	283	297	310	323	343	363	381	397	410	421	439	440	395	286	203	158	130	113
Lower																											
0	218	303	392	413	424	433	435	435	436	437	438	441	444	443	443	445	446	447	446	447	447	433	247	193	154	134	113
1	186	244	303	350	391	411	417	414	417	421	428	427	428	429	431	437	433	434	433	434	435	375	302	244	200	167	143
2	139	154	188	213	237	265	283	288	299	309	319	330	337	341	347	353	356	362	365	369	369	366	193	148	122	106	93
3	162	189	213	234	256	280	297	303	317	325	339	354	378	380	386	391	395	399	403	404	407	393	212	177	146	133	113

Figure 76. Display of temperatures vs time of areas on the lower and upper susceptor and the preform during the ford seat pan induction molding process

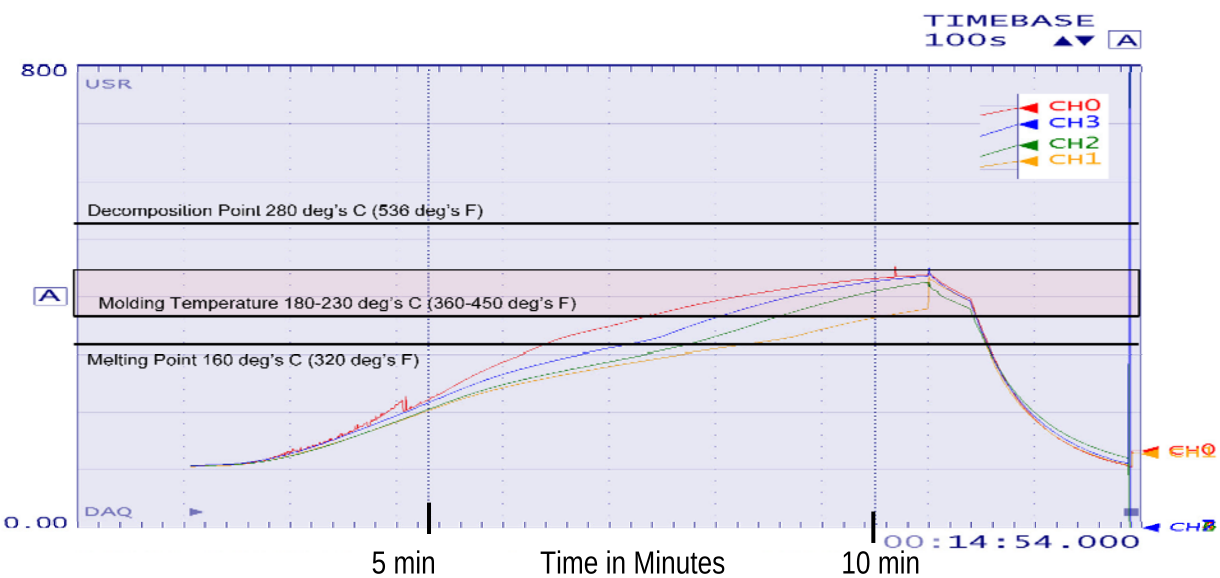


Figure 77. Temperature versus time plot for the preform during the induction molding of the Ford seat pan component

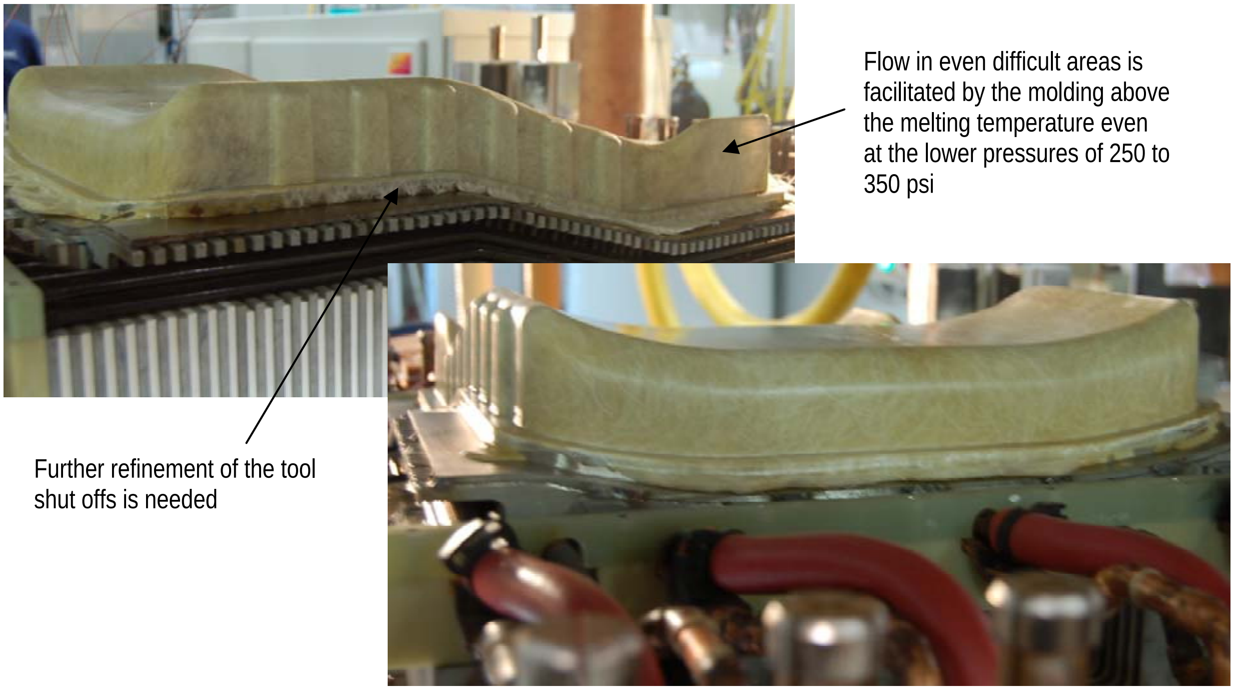


Figure 78. Initial as molded Ford seat pan component showing the complete flow of the material in all areas of the tool

Figure 79. Resulting induction molded ford seat pan components

3.2.3.3.3 Automotive Seat Pan Assessment

Figure 80 shows the pattern of samples selected from a typical molded seat pan. These samples were removed (see figure 80) and then mounted and polished. Typical images taken from these polished samples are shown in figure 81. These photomicrographs show excellent consolidation and a minimum amount of porosity (less than 1%). These components would pass automotive production consolidation requirements.

Figure 80. Candidate induction molded seat pan with sections identified for evaluation via microscopy (top pictures) and the part with the evaluation samples subsequently removed (bottom pictures)

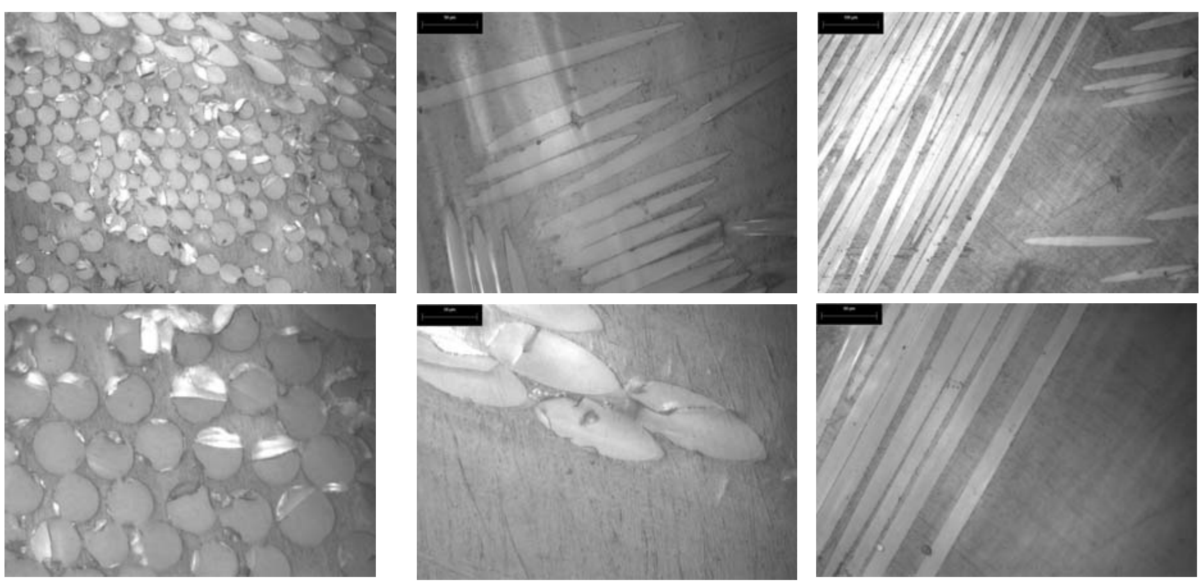


Figure 81. Pictures showing the typical microstructure of the induction molded Ford seat pan and depicting virtually no porosity

3.3 Preform Fabrication Technology

Technology is needed to support the creation of the composite fiber and resin preform or ”lay-ups”. These preforms or lay-ups provide the needed resin along with the fibers in an architecture that meets the design requirements. These preforms are subsequently induction consolidated to create the thermoplastic composite component.

3.3.1 Aerospace Preform Fabrication

Precise application of continuously reinforced thermoplastic pre-preg material is required for the aerospace sector. To create the preform for the Boeing seatback component, a system for lightly tacking slit tape using a laser was developed. Figure 82 shows the initial set-up using a 2 axis gantry to apply the precursor composite pre-preg tape. The process consists of using a low power laser system that supplies heat directly in front of the tape being placed. This enables the tape to weld to the layer below and is repeated to allow the creation of the preform (see figure 83). Figure 84 shows the preform lay-up tool with a thermoformed .010” thick neat thermoplastic resin sheet that provides the initial starting surface for the lay-up process. Furthermore, figure 84 shows the integration of the laser system onto the robotically controlled fiber placement head. This creates the system that will enable the fiber placement of preforms for induction consolidation.

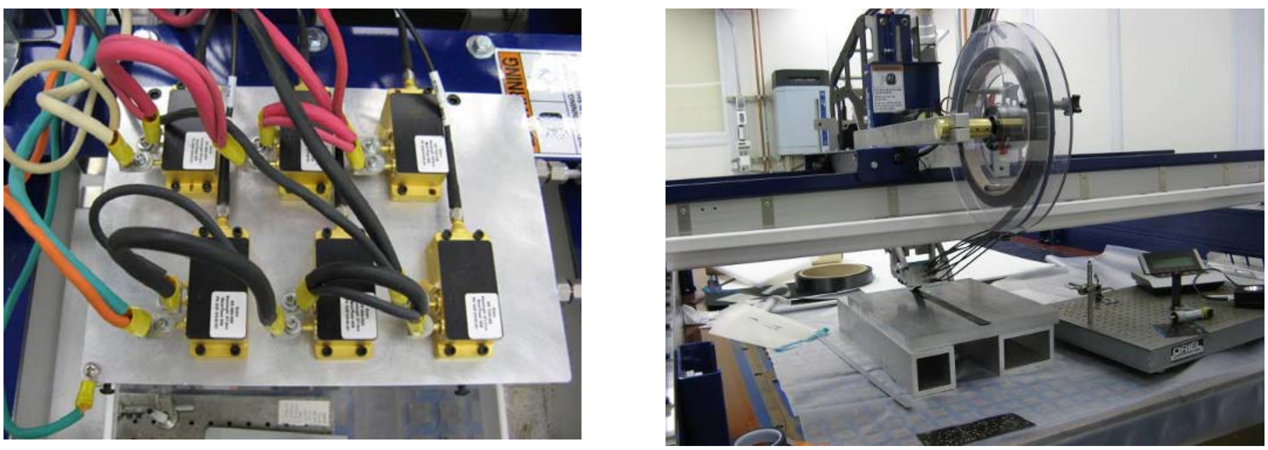


Figure 82. 2-axis initial laser set-up to demonstrate the ability to effectively tack down the thermoplastic prepreg tape

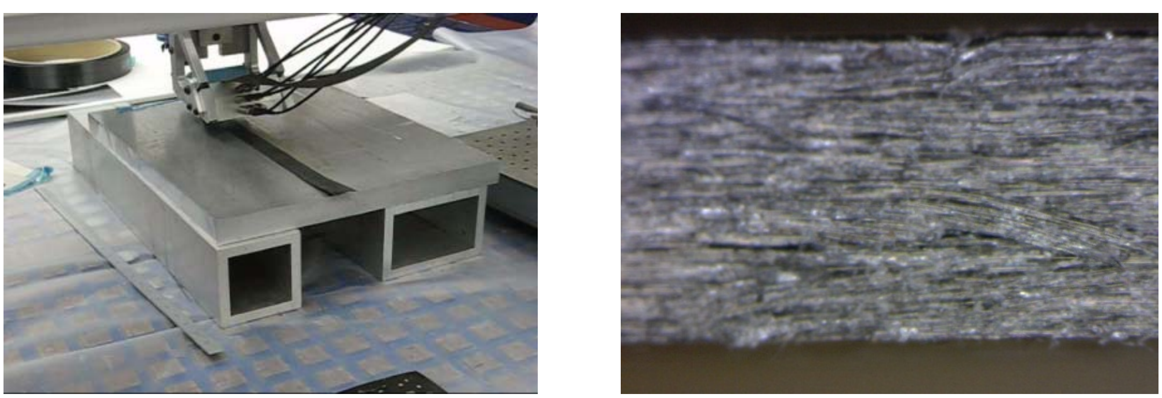


Figure 83. Resulting tacked material showed no damage from the laser due to the very controlled types of lasers and a stable lay-up of material

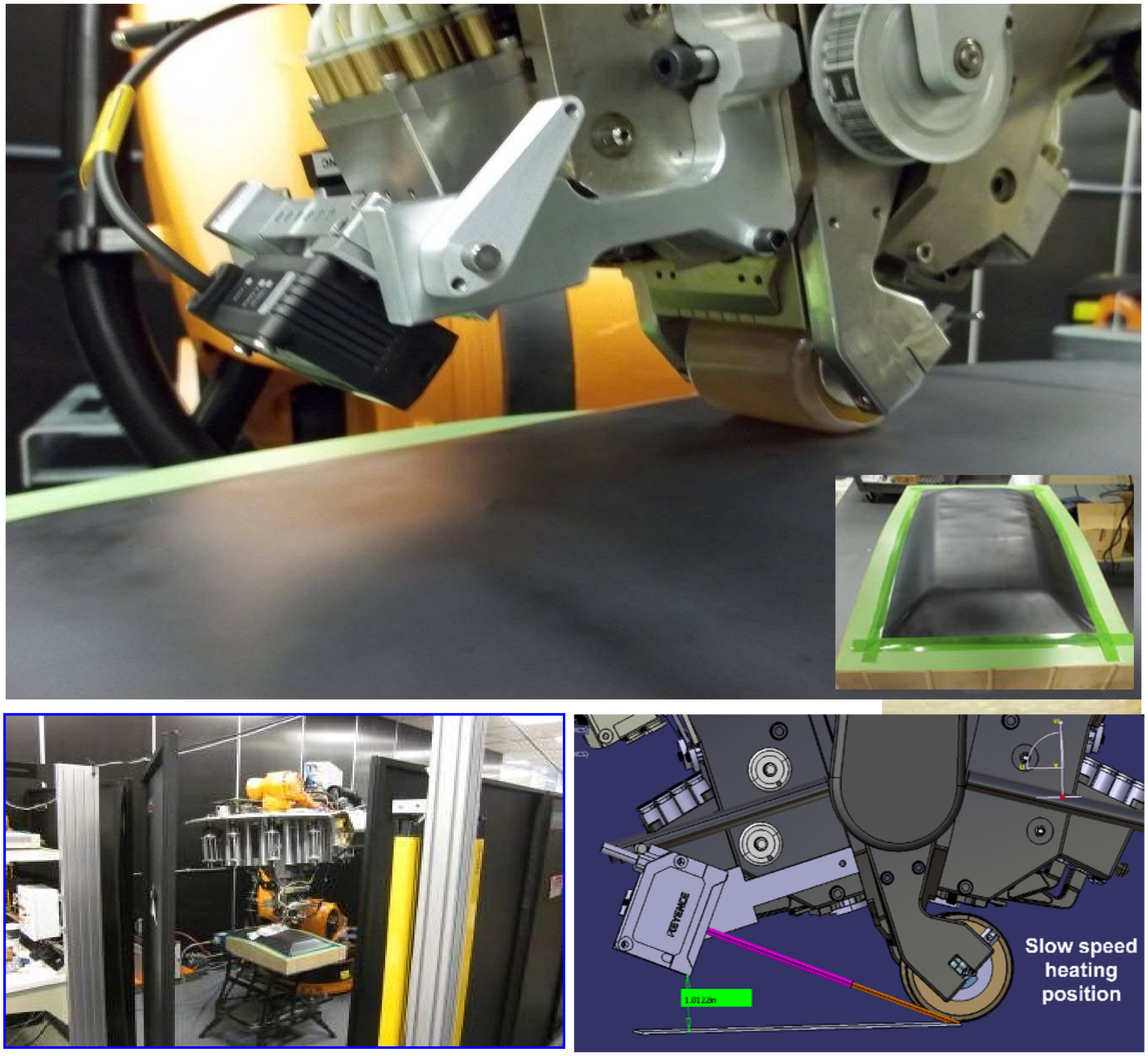


Figure 84. Pictures showing the integration of the laser system with a tow placement head for the application on slit thermoplastic tape

3.3.2 Automotive Preform Fabrication

Cost and model production rates of between 200,000 and 500,000 vehicles per year rate are key criteria for the automotive industrial segment. To those ends the method utilized to fabricate the preforms is as outlined in figure 85. There are 4 major steps to make the random matte polypropylene preform. The first step is to deposit the chopped fiberglass fibers and chopped resin rovings. This is done by the use of a chopper gun attached to a robot. The chopper gun is aimed in a specific pattern into a tool to apply the chopped fiberglass and resin rovings (see figure 86). The tool has a screen in the bottom of it to allow air to drawn down through the screen. This draft of air downward through the tool holds the sprayed material down to the tool surface (figure 85). The second step is then is to perform a light consolidation using a second mating tool with a similar screen surface to allow hot air to follow through the top tool through the sprayed material and then exiting through the bottom tool. The third step is to stabilize the heated preform. This is done by immediately flowing cool air through set-up right after the consolidation step. The final step then is the removal of the preform from the tool. The preform is now ready for the induction molding step (figure 86).

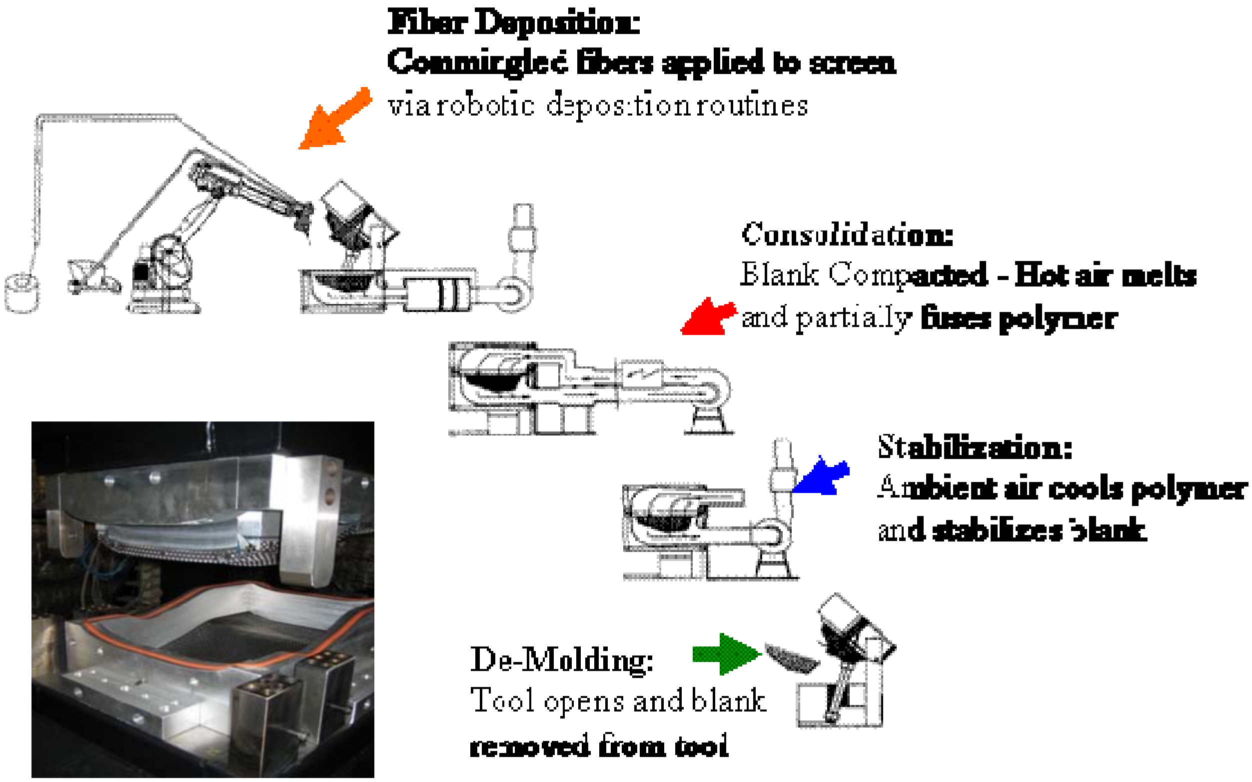


Figure 85. Process description for the Ford seat pan preform fabrication using a robotically manipulated chopper gun for spraying the fiberglass reinforce polypropylene

Figure 86. Pictures of the preform tooling, the robotically manipulated chopper gun, and a stack of completed preforms

3.3.3 Wind Energy Preform Fabrication

The emphasis for the wind energy component was to make flat panels that would facilitate the initial evaluation of the thermoplastic composites in wind energy applications. Therefore, no significant work on preform fabrication was done in the area of wind energy. If additional efforts in this area were to be undertaken then the preform fabrication effort for the wind energy components would most likely be a cross between continuous fiber aerospace system and the rapid nature of the automotive system. This is a technology area that needs further development for candidate thermoplastic components fabrication by induction consolidation with initial implementation.

3.4 Energy Efficiency

The previous sections have shown how just the surface of the induction tooling with smart susceptors is heated to enable consolidation/molding of thermoplastic components. It is this fact that only a small amount of thermal mass is present in the process that enables significant energy savings (see table 3). This characteristically light thermal mass not only saves energy but also enables a very rapid process cycle. This rapid thermal cycle can significantly improve component affordability. In addition, these lightweight components will reduce fuel consumption in aerospace and automotive vehicles and reduce carbon emissions. Also, integration of these lightweight components into wind turbine systems will increase electrical energy generation efficiencies. Table 4 shows the estimated volumes of composite material in 2015 and 2030 in each industry and the potential energy savings produced by the introduction of this technology. The development of this process is aimed at the providing the needed energy efficiency and affordability as the application of large volumes of composite materials moves sharply upward in the next couple of decades. Finally, these thermoplastic materials provide potential for full component recyclability for reduced landfill issues and improved utilization of the initial energy used to create the material in the first place.

Table 3. Comparison of the energy required to manufacture one ton of composite using the various standard competing processes from each of the participating industrial segments

Data Type, Units, Processing Step	Autoclave (Aerospace)	Compression Mold (Automotive)	Heated Tool (Wind Energy)	Induction (estimated) Laminated / Ceramic		
Energy (mmBTU/Ton)	29.51[2]	8.7[1]	1.38[3]	7.1[5]	3.3[6]	0.8[7]
Carbon Footprint (grams C02 per ton of product)	2686.5[4]	793.8[4]	125.6[4]	646.4[4,5]	300.4[4,6]	72.8 [4,7]

[1] Includes press, heated tool, IR heater, & automation
[2] measured data from production of thermosetting composite parts via autoclave processing
[3] measured data from production of thermosetting composite parts via heated tool processing
[4] data calculated using EPA 2005 data: national average output rate, 1.37 pounds of CO2 per kilowatt-hour generated (Ref. 3)
[5] the induction molding energy value when working with the higher temperature thermoplastic resins associated with the aerospace industry and includes ancillary equipment
[6] the induction molding energy value when working with the lower temperature thermoplastic resins associated with the automotive industry and includes ancillary equipment
[7] a cast ceramic tool induction consolidation tool with a 45 minute cycle time is anticipated and fits with the Vestas production scenarios and cost constraints

Table 4. Comparison of the energy required for both the induction molding process and the standard processes in order to meet the anticipated materials volumes for each industrial segment in the year 2030

Million of Pounds used in 2015/2030	Autoclave B-BTU's	Compress Mold B-BTU's	Heated Tool B-BTU's	Induction B-BTU's	Potential Energy Savings B-BTU's
15 *Aero (2015)* 45 *Aero(2030)*	221.3 664.0			53.3 159.6	168 504.2
614 *Auto (2015)* 1200 *Auto (2030)*		2670.9 4410.9		1013.1 1673.1	1657.8 2737.8
800 *Wind Energy (2015)* 2400 *Wind Energy(2030)*			552 1656	320 960	232 696
		2015 Potential/Probable (0.5%) Total Savings =			2.06/.01 T- BTU's
		2030 Potential/Probable (78%) Total Savings =			3.94/3.07 T- BTU's

3.4.1 Aerospace

The main processing system utilized in the aerospace industry for fabrication of composites is the resistively or gas heated autoclave (see figure 87). This system has a characteristically long processing cycle and utilizes large amounts of energy to process the composite components. This is due to the fact that the entire inner volume, including the large tools, of the autoclave is heated to the processing temperature needed for the composites to consolidate and cure in the case of thermoset materials. Therefore, this system typically has large thermal masses and long cycle times associated with enabling the temperature to reach equilibrium. Therefore, significant energy savings of over 75% are estimated when using induction consolidation of thermoplastic composites over autoclave consolidation of thermosetting composites. These savings include the fact that higher consolidation temperatures are needed for thermoplastic composite materials over thermosetting materials.

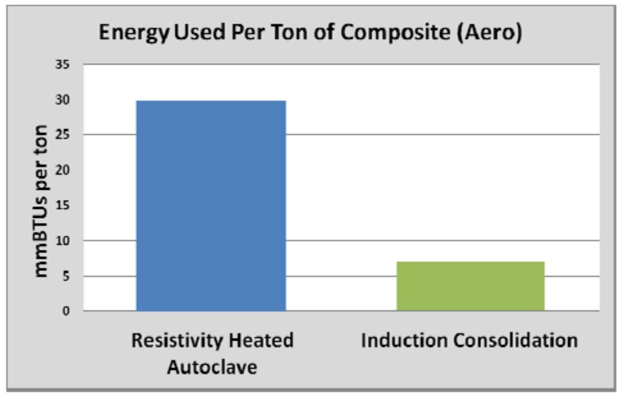


Figure 87. Comparison on the energy use by the standard aerospace composite processing system (resistively heated autoclave) and the induction consolidation process

3.4.2 Wind Energy

The main processing system utilized in the wind energy industry for fabrication of composites is the self heated tool (see figure 88). Heated air is circulated within the box that surrounds the tooling surfaces to heat the entire inner volume of the tooling box. Typically vacuum pressure is used to perform the consolidation of the thermoset resin composites. This system has a characteristically long processing cycle the composite components. Wind energy would most likely utilize a reinforced ceramic tool with the induction heating coil imbedded within the cast ceramic. This would provide additional energy savings and reduce the cost of the tooling.

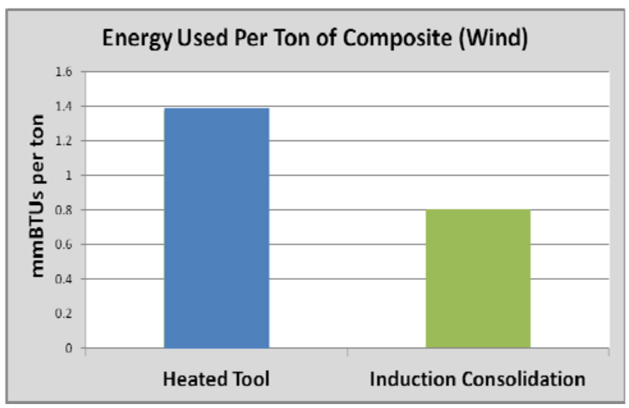


Figure 88. Comparison on the energy use by the standard wind energy composite processing system (convectively heated tool) and the induction consolidation process

3.4.3 Automotive

The main processing system utilized in the automotive industry for fabrication of thermoplastic composites is the resistively heated compression molding press (see figure 89). This system utilizes heated tooling and preheated preform charge of material. Figure 90 shows the standard compression molding cell with the associated equipment. The opportunity for energy savings in this system is the utilization of induction heating to rapidly heat the preform, reduce the energy needed to heat and hold the large steel tools at the molding temperature, and finally the reduced amount of energy needed to power the press due to the fact that a 5X reduction in molding pressure is required for the induction molding system.

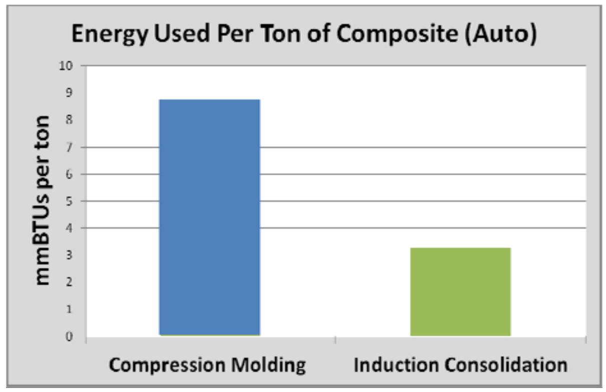


Figure 89. Comparison on the energy use by the standard automotive composite processing system (resistively heated compression molding press) and the induction consolidation process

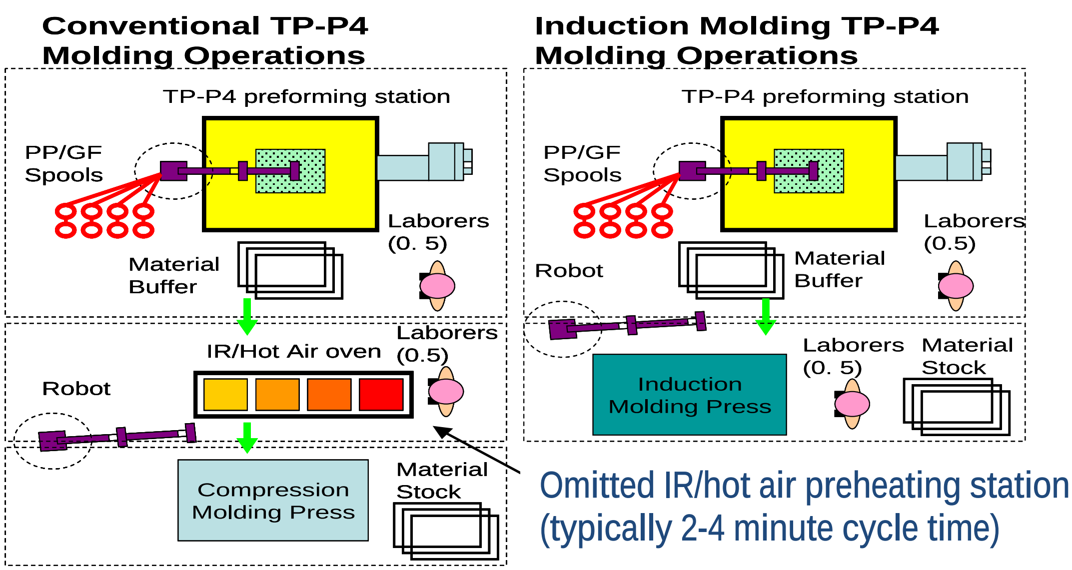


Figure 90. Diagram of manufacturing cell for the standard compression molding process for automotive applications as compared to an induction molding cell

3.4.4 Laboratory Data and Estimates

Monitoring of the energy associated with the induction molding trials during the course of the project was accomplished. Figure 91 shows the various energy use categories associated with the induction molding system and the typical energy used during processing. A learning curve for each of the 3 industrial segments is shown with the associated technology improvements envisioned in figures 92, 93, and 94 for aerospace, wind energy and automotive, respectively. The aerospace energy comparison shows that a significant energy savings has already been established even with the current laboratory set-up. Additional improvements associated with more efficient coils, less reliance on the compressed air quench, and improved smart susceptor alloys will be available as development continues. More efficient coils will be available as large scale component processing is developed. These larger coils typically have much lower percentage losses associated at the ends of the coil because these ends make up a much lower percentage of the coil than the smaller coils. In addition, as near net shape smart susceptor manufacturing development continues, this will not only lower the cost of the smart susceptors but also allow for the development of optimized smart susceptor alloys that can be incorporated into these net shaping processes (i.e. the cold spray process). In the case of wind energy, the current laboratory system needs further improvements to reach the goal of the project (see figure 93). Once again, improvements can be made in more efficient coils as the scale of the components are increased and improved smart susceptor chemistries will be available, as the near net shape smart susceptor manufacturing development is conducted. Furthermore, in the case of wind energy cast ceramic tools seem to be a good solution to help lower the cost of the tools but also to improve the energy efficiency. Since the wind energy industry is more sensitive to tool cost than ultra fast processing rates, cast ceramic tools are a viable alternative. The automotive energy use is shown in figure 94. In the case of automotive application, the current laboratory system needs further improvements to reach the goal of the project. Here again, the preheating of both the tool and the preform discussed earlier in the report along with the water quenching (see figure 94) would benefit not only the cycle time but the energy use as well.

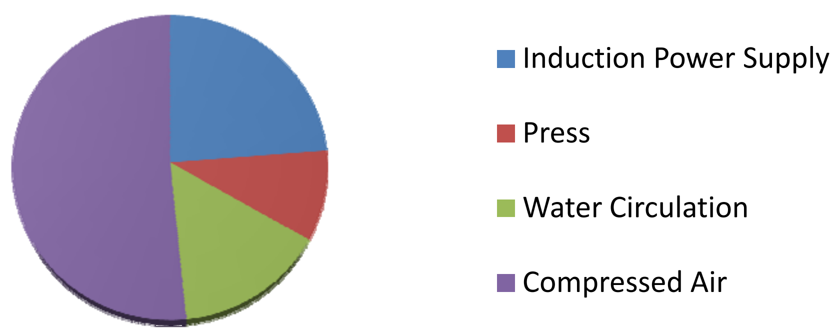


Figure 91. A pie chart showing the contributions of each of the 4 main systems that comprise the induction processing facility

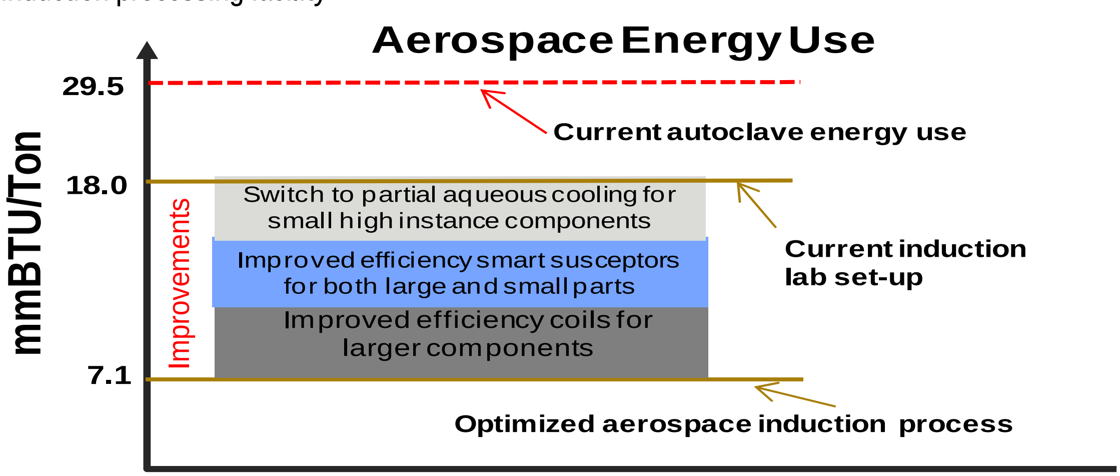


Figure 92. Comparison of the energy used for by the current aerospace autoclave system and the current induction laboratory system and the potential energy efficiency of an optimized induction processing system

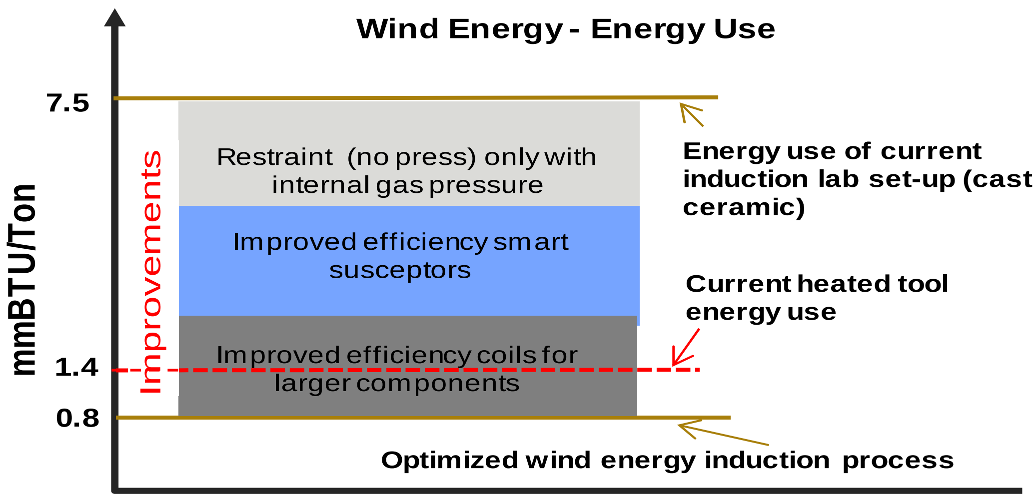


Figure 93. Comparison of the energy used for by the current wind energy self heated tooling system and the current induction laboratory system and the potential energy efficiency of an optimized induction processing system

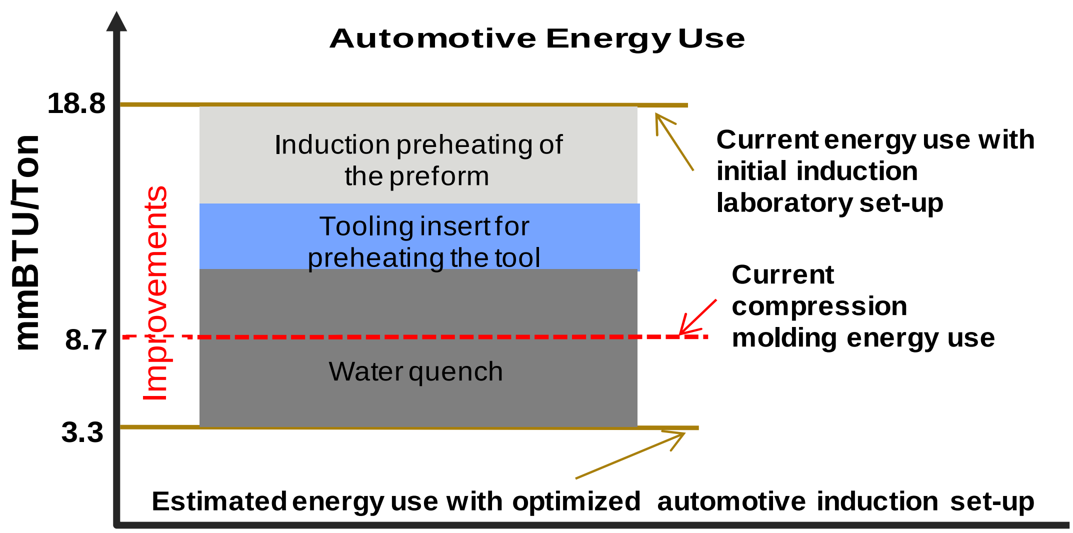


Figure 94. Comparison of the energy used for by the current automotive resistively heated compression system and the current induction laboratory system and the potential energy efficiency of an optimized induction processing system

3.4.5 Recycling Plan

Currently, although some polymeric products are recycled, the majority is still put in a landfill, incinerated or otherwise disposed of (1). Economic advantages can be achieved through reduction in energy consumption by reusing materials that can be re-melted, such as steel, aluminum, thermoplastic polymers and thermoplastic composites. Thermoplastics are materials that can be re-melted and formed several times without significant degradation, as opposed to thermosets such as polyesters, epoxies, sheet molding compounds, etc. Due to cross-linking of thermoset materials, they are typically not readily recycled. Thermoset composite materials require more rigorous processing such as hydrolysis and glycolysis to separate the reinforcement fibers from the matrix material, to be able to reuse the fibers [2]. Thermoplastic composite materials only require mechanical shredding at minimum, which is currently considered both feasible and economically viable. Indeed, energy consumption and carbon footprint can be significantly reduced through the use of more efficient manufacturing processes along with recycling. Recycling not only within an industry, but finding new uses outside of one industry expands the possibilities of the recycled material usage. In this sense, several process streams can occur, which are explained below and can be seen in the various schematics shown.

3.4.5.1 Aerospace Recycling Plan

The specified material for making the aircraft seat back is with the BMS 8-399 qualified material, APC (PEKK FC)/AS4D unidirectional tape (unitape). Figure 95 shows the entire life cycle for this composite part along with the recycle stream to recover both the monetary and process energy values inherent in the high performance material used to make the aircraft seat back. The cumulative process energy estimated for this material was in the 175 – 238 mmBTU/ton range with the major process energy component coming from the carbon fiber used [3, 4]. Carbon fiber is also what gives the material its high strength and stiffness properties that result in being able to design and fabricate a lighter weight part relative to the incumbent aluminum parts. The weight savings for this part over the life of the aircraft would easily compensate for the small difference in process energy between making the part from aluminum (168.5 – 221 mmBTU/ton) versus carbon fiber reinforced PEKK tape. Inserting recycle streams in the front and back end of the life cycle flow only further improves the sustainability of using this material and induction molding process for making these parts.

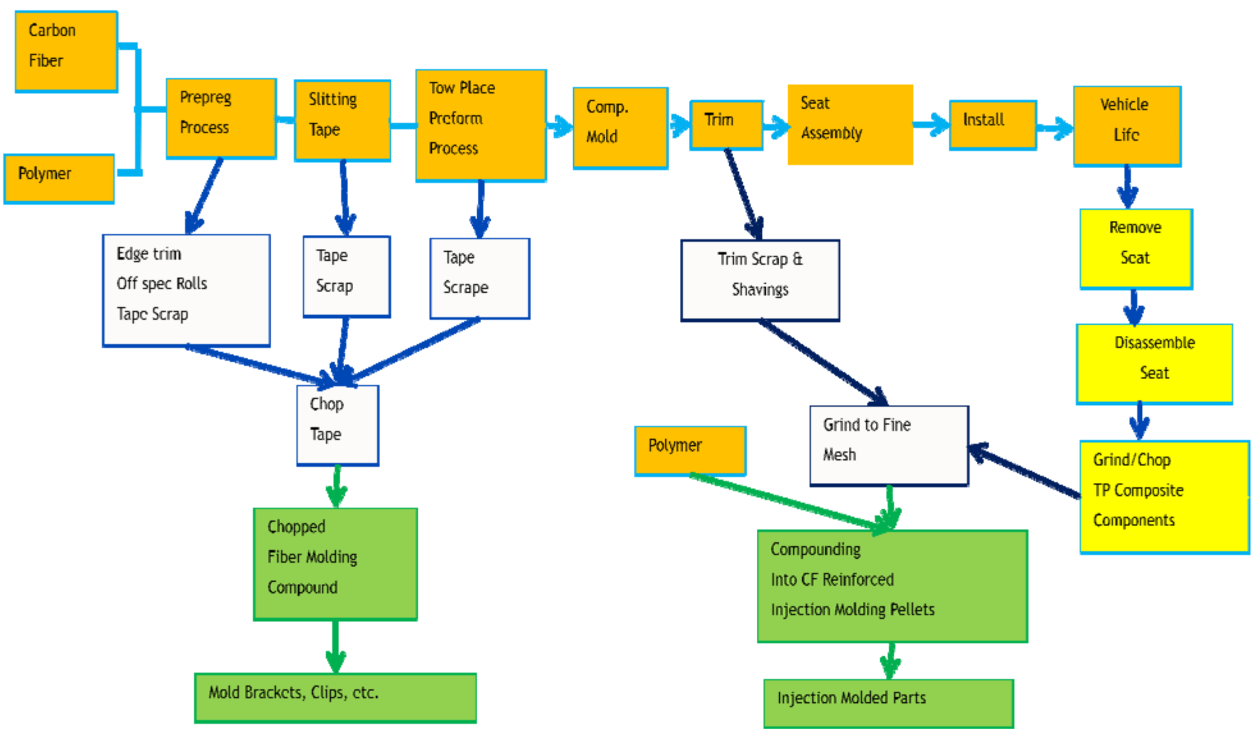


Figure 95. Aircraft Seat Back Life Cycle Flow Diagram with Recycle Streams

3.4.5.2 Wind Energy Recycling Plan

Nylon was chosen as the initial resin for application in the wind energy components. Further testing and evaluation will be needed to ensure this resin is the best choice. The generalized life cycle flow in figure 96 will apply regardless of what thermoplastic or product form is selected. Recycle streams will utilize existing thermoplastic recovery operations for bulk engineering thermoplastics. It will also leverage some of the techniques being used for the automotive industry as illustrated by the recovery plan for the Ford automotive seat back. As in the case of the aircraft seat back, the key in this recycle stream flow is the shredding and "chipping" of the molded articles which will also have a much higher fiber content (65 – 80 wt%) than what is being used today in the industrial market. De-bulking the molded article by heating back to the melt to more easily chip the molded articles may be needed if the molded article is found to be too tough to chip into a desirable size for re-processing the material.

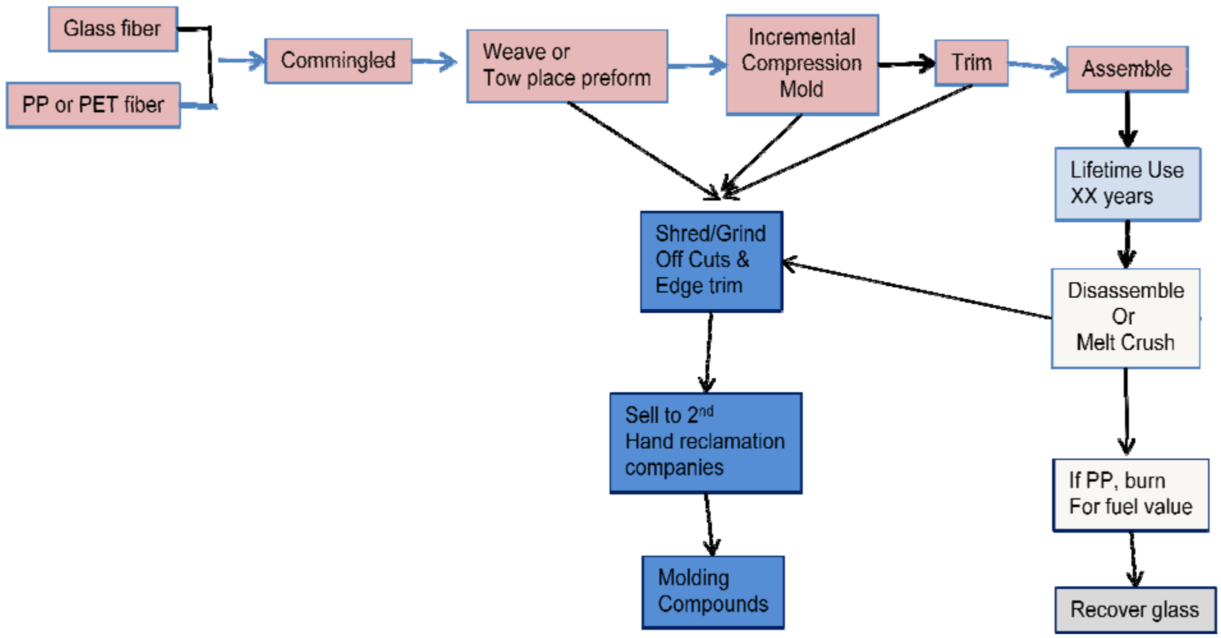


Figure 96. Wind Energy Material Life Flow Diagram with Recycle Streams

3.4.5.3 Automotive Recycling Plan

Today, automobiles are one of the most recycled products, with more than 95 percent of all vehicles in the United States going through a market-driven recycling infrastructure. More than 84 percent, by weight, of each end-of-life vehicle (ELV) is recycled [5].

Polypropylene is an excellent polymer to recycle within the automotive industry due to its abundance. Also, the fiberglass in reinforced versions is typically discontinuous and in a random orientation, likely decreasing the amount of energy to shred the materials. For our project, fiberglass reinforced polypropylene is the specified material for manufacture of the automotive seat pan. In this case, Twintex® commingled glass and polypropylene fiber (60 wt%) in the roving form. Currently glass fiber reinforced polypropylene makes up a significant portion of the automotive industry's structural thermoplastic components. These are typically under hood (front end bolsters, mounting brackets, etc.) or under car components (shields, wells, etc.) that contain carbon black for pigment. The cost (primary factor in automotive industry) of polypropylene and standard fiberglass fibers is relatively low compared to nylons and other engineering polymers and reinforcement fibers.

There are two main possible recycle streams for the automotive industry; the first involves introduction of recycled material into the manufacturing process directly, whether used in a part or as a fuel. The direct path for recycled material introduction for the automotive seat composite part recovers both the monetary and process energy values inherent in material used to make the automotive seat pan (see figure 97). The second possible stream involves introduction into a separate processing stream via a compounder, other industry, or used as fuel (see figure 98). As an example, figure 99 shows chipped polypropylene material that has been used in conjunction with the preform fabrication system via induction molding to fabricate a seat pan component. This demonstrates the ability to perform industry recycling of these materials.

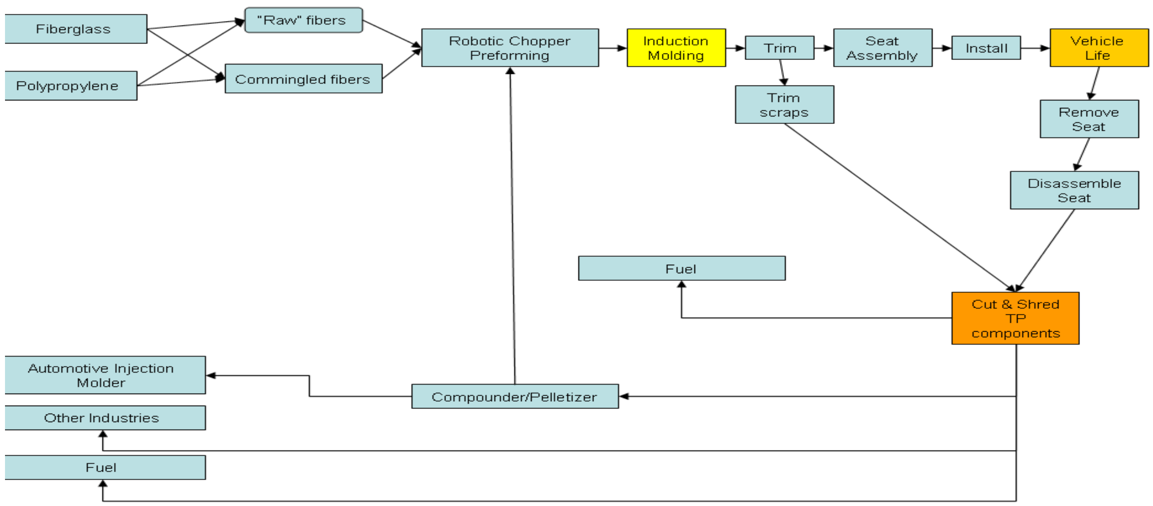


Figure 97. Direct (in automotive) recycling stream within automotive production boundary

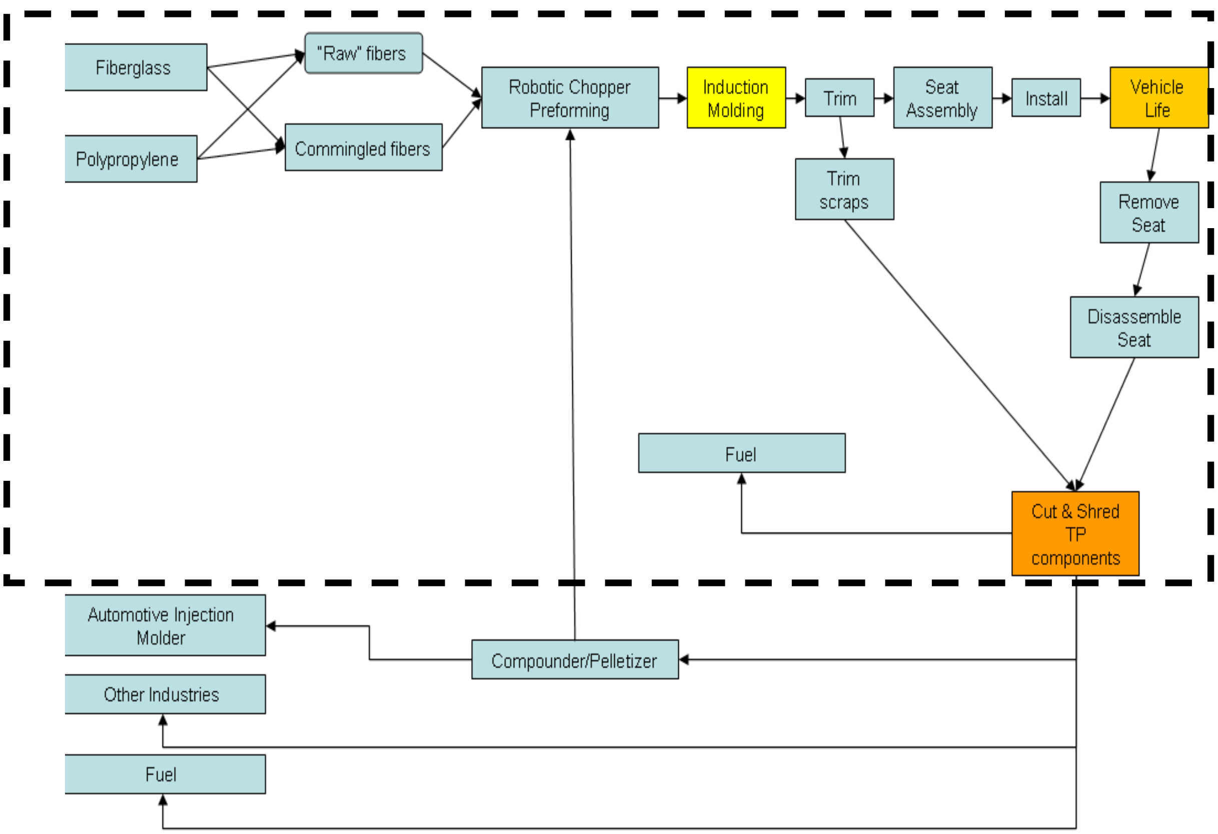


Figure 98. Indirect recycling stream outside automotive production boundary

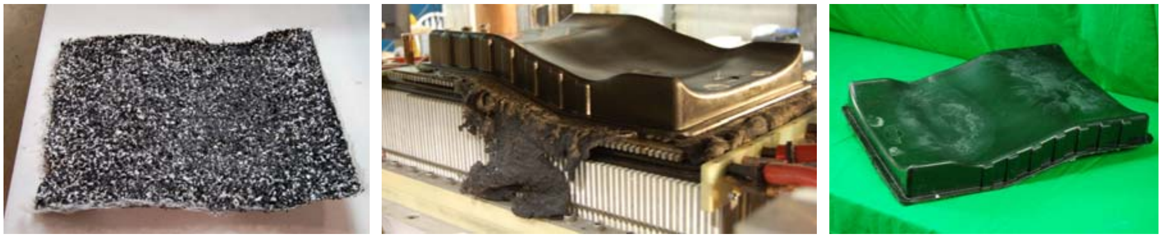


Figure 99. Incorporation of shredded fiberglass reinforce polypropylene material into the processing of an induction molded component

3.5 Cost Baseline and Economic Benefits

Induction consolidation/molding of thermoplastic composites using smart susceptors will significantly reduce the cycle time and energy use for manufacturing and increase the performance of the resulting components. The characteristic rapid process cycle of induction consolidation of thermoplastic composites not only saves energy, but also significantly improves component affordability. In addition, integrating these lightweight components into aerospace and automotive industry will reduce fuel consumption and therefore carbon emissions and integration of these lightweight components into wind turbines will increase electrical energy generation efficiencies. Finally, the thermoplastic material provides potential for full component recyclability. Overall, the cost of the tooling and equipment will be a push, but the advantages in cycle time, the improved efficiency, the improved quality, and improvement in product performance will be the driving forces for implementation.

3.5.1 Aerospace Cost Baseline and Economic Benefits

During the course of the fabrication of the seatback the tooling costs were collected and an estimate of the current cost per square foot of this type of tooling is shown in figure 100. The current costs are above the current costs of autoclave tooling. However, significant tooling cost reductions are anticipated due to a standard learning curve, the introduction of near net shape smart susceptor shell fabrication, and for larger parts the use of pneumatic pressure instead of press pressure. In essence, the tooling costs are considered roughly equivalent to the existing cost of today's autoclave and press forming tools, respectively. The real advantage of induction processing with smart susceptors is the ability to more efficiently meet higher rate production with composite materials (see figure 101). It is this attribute that has real economic benefit. Coupling this with the ability to rapidly, effectively, and reliably join thermoplastic composite structures provides a compelling economic incentive to use and further develop this technology.

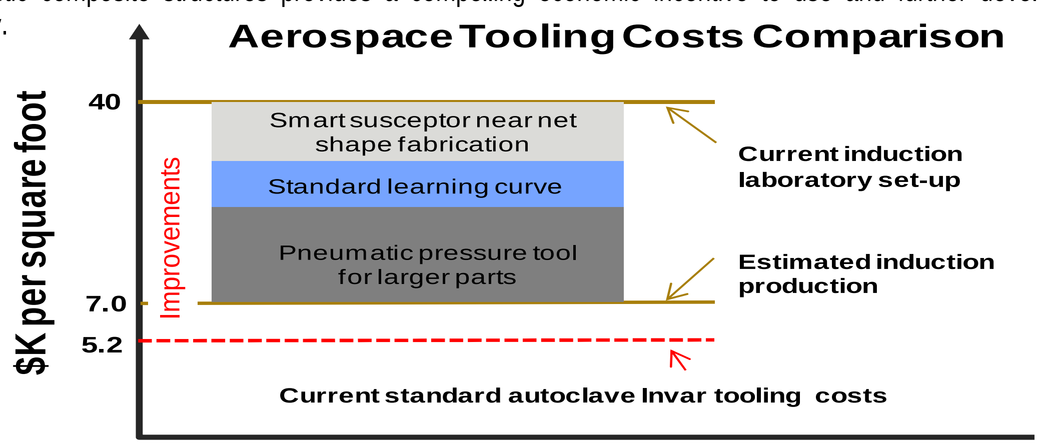


Figure 100. Chart depicting the current cost of the induction consolidation tooling to the existing autoclave tooling cost plus the estimated tool cost for the optimized induction process

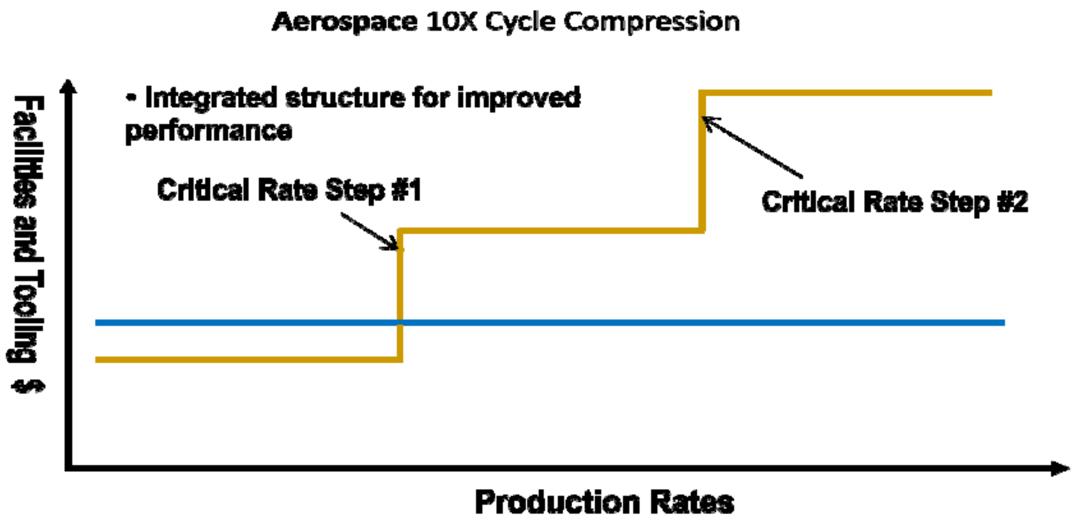


Figure 101. Chart depicting the effect of the more rapid thermal cycle on the ability to lower production costs as airplane production rates rise

3.5.2 Wind Energy Cost Baseline and Economic Benefits

During the course of the fabrication of the Vestas flat panel, the tooling costs were collected and an estimate of the current cost per square foot of this type of tooling is shown in figure 102. The current costs are above the current costs of heated tools currently used. However, significant tooling cost reductions are anticipated due to a standard learning curve, the introduction of near net shape smart susceptor shell fabrication, and particularly the use of cast ceramic tools. The cast ceramic tools are made from inexpensive fused silica castable material and provide significant reduction in tooling costs. A significant economic advantage of using induction processing with smart susceptors in the wind energy segment is the ability to more efficiently meet higher rate production with composite materials (see figure 103). Coupling this with the ability to rapidly, effectively, and reliably join thermoplastic composite structures provides a compelling economic incentive to use this technology.

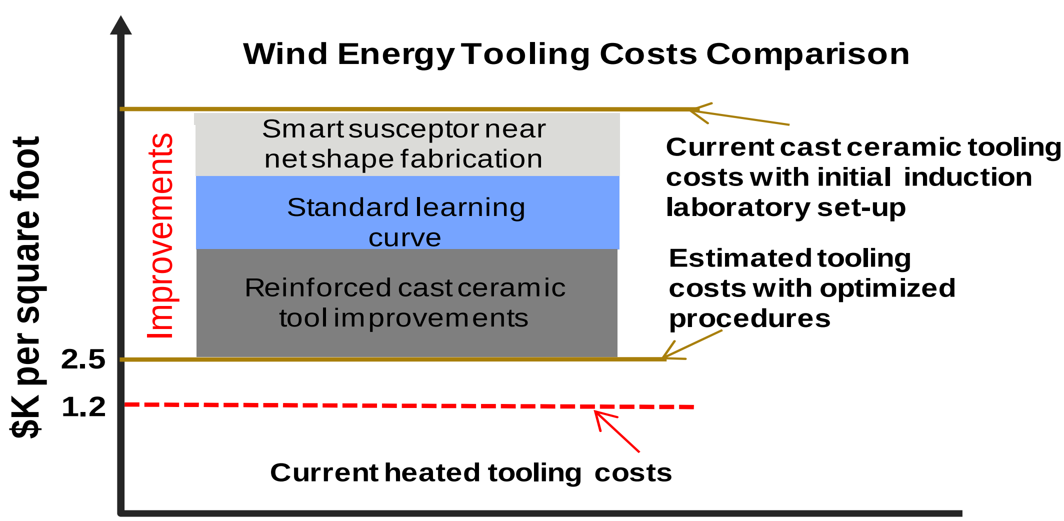


Figure 102. Chart depicting the current cost of the induction consolidation tooling to the existing self heated tooling cost plus the estimated tool cost savings aviable for the optimized induction process

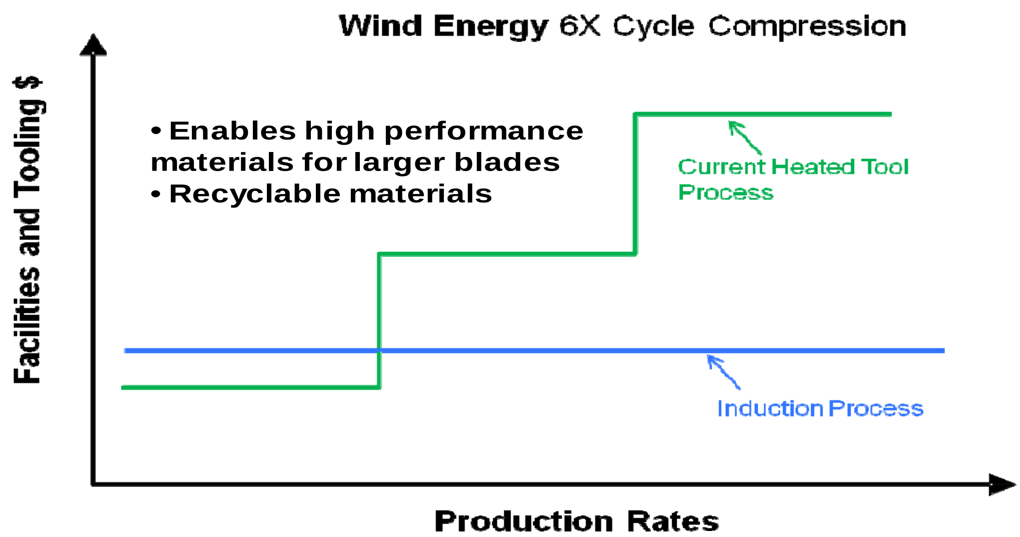


Figure 103. Chart depicting the effect of the more rapid thermal cycle on the ability to lower production costs as wind turbine production rates rise

3.5.3 Automotive Cost Baseline and Economic Benefits

During the course of the fabrication of the Ford seat pan outer, the tooling costs were collected and an estimate of the current cost per square foot of this type of tooling is shown in figure 104. The current costs are above the current costs of heated tools currently used. However, significant tooling cost reductions are anticipated due to a standard learning curve and particularly the introduction of near net shape smart susceptor shell fabrication. Significant expense of the current tooling was attributed to the machining of this complex smart susceptor shell made of alloy DK 510. The utilization of preheating for both the preform and the tools will dramatically decrease to the time to induction mold a part (see figure 105). The additional development effort to establish this rapid rate capability is needed to provide the economic incentive to utilize this technology.

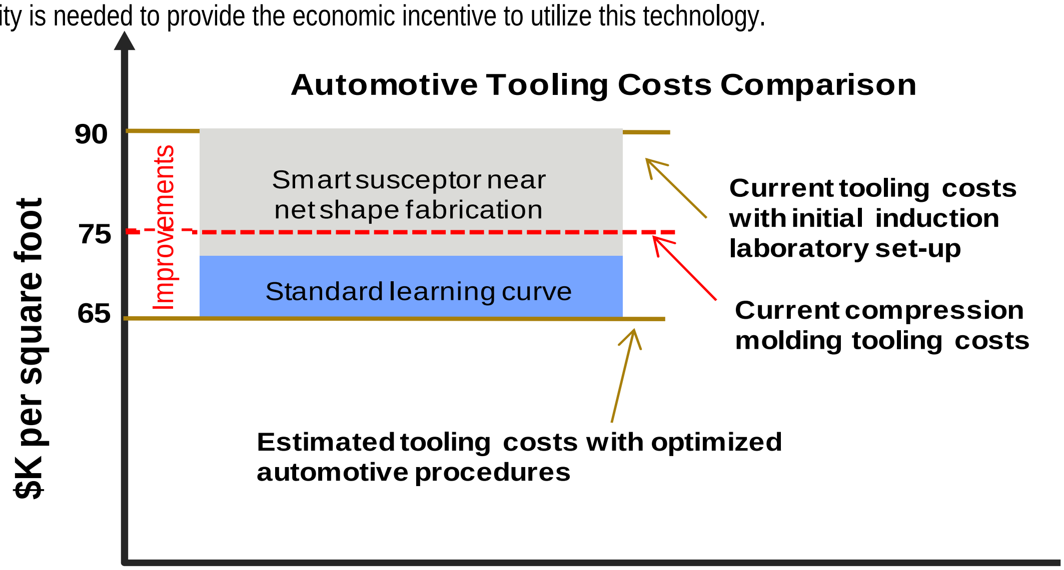


Figure 104. Chart depicting the current cost of the induction consolidation tooling to the existing compression molding tooling cost plus the estimated tool cost for the optimized induction process

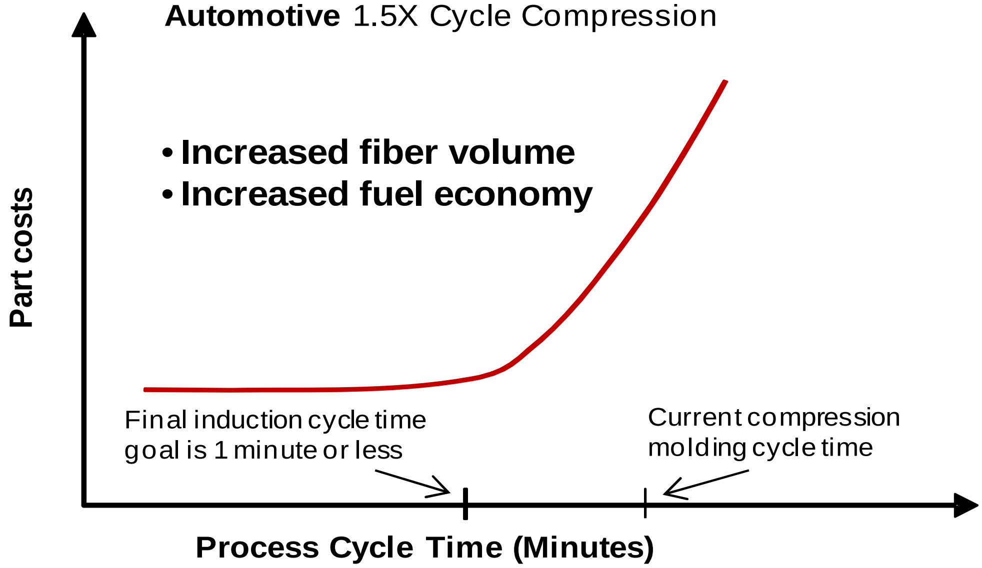


Figure 105. Depiction of the effect of a one minute induction processing cycle goal to the automotive part costs

3.6 Scope of Application

The following list describes the advantages of the use of induction consolidation and welding of thermoplastic composite structures for applications. It is these advantages that form the basis for the applications to each of the business segments. The sum of the applications as shown in the next 3 sections (3.6.1, 3.6.2, 3.6.3) that make up the estimate for the volume of material in table 4 that describes total energy saved.

- Thermoplastic composites provide improved inter-laminar strength, toughness and hot/wet mechanical properties in addition to improved flammability, smoke, and toxicity ratings
    - *Weight savings*
- Automated tow placement using light consolidation (thermal tacking) for part pre-form fabrication enables the rapid application of materials to meet production rates affordably.
    - *Higher application rates can be achieved*
- Induction consolidation provides controlled cooling rates that optimize the physical properties of the thermoplastic resins
    - *Optimized properties*
- Induction consolidation provides rapid fabrication of net-shaped components for greater affordability of high instance components.
    - *Mitigation of rate tooling and additional facilities*
- Induction consolidation enables fabrication of large structure made in a lean and efficient manner (i.e. short controlled thermal cycles for rapid non-batch processing for reduced WIP)
    - *Mitigation of rate tooling and additional facilities*

- Induction welding provides an avenue for integrated structures that not only improve the performance of the composite structures but also reduce the cost by minimizing labor of assembly.
    - *Weight savings and reduced labor*
- Less mass is being heated enabling faster processing cycles and enhanced energy savings
    - *Higher fabrication rates and energy savings*
- Recyclable materials leads to energy savings and reduction of land fill issues
    - *Reduced energy usage and environmental benefits*

3.6.1 Aerospace Applications

The following list shows some of the various applications that would be part of the application set for the induction consolidation and welding of thermoplastic composites for aerospace. The items in blue are within the ability for the process at its current state for consideration of implementation. The remaining items require scale-up and/or welding development.

- Interior components (seat structure, sidewall panels, brackets)
- Frames
- Floor beams
- Wing skins
- Upper fuselage section
- Nose section of fuselage
- Engine lips
- Leading and tailing edges

3.6.2 Wind Energy Applications

The following list shows some of the various applications that would be part of the application set for the induction consolidation and welding of thermoplastic composites for wind energy and the rationale. All of these items require scale-up and/or welding development.

- Nacelle panels
- Blade skins
- Spar fabrication
- Blade assembly
- Leading and tailing edges
- Blade section joining at the field site

3.6.3 Automotive Applications

The following list shows some of the various applications that would be part of the application set for the induction consolidation and welding of thermoplastic composites for automotive. All of these items require scale-up and/or welding development.

- Closures
- Body panels

- Cross members
- Seat frames
- Instrument panel structures
- Spare wheel wells
- Shields

3.7 Development - Next Steps

This initial set of components fabricated under this GO-18135 contract shows the basic feasibility of the process for each of the industrial segments. However, risk still exists in the establishment of very rapid thermal cycle needed by automotive and the scale-up of demonstration components with much larger part dimensions and integrated structural characteristics to meet the requirements for aerospace and wind energy. The following tasks outline the next steps for development.

Demonstrations needed:

- The thermal cycle for induction consolidation of thermoplastic composite components for automotive applications needs to be 1 minute or less
    - o Automotive - demonstration of rapid part and tool pre-heat along with the rapid consolidation and water quench of the tool/part on seat pan type component
- The ability to consolidate large thermoplastic skins is needed for both aerospace and wind energy to be competitive.
    - o Wind Energy - consolidation of large thermoplastic skins approximately 7 feet by 11 feet
    - o Aerospace - consolidation of large thermoplastic skins approximately 5 feet by 15 feet skins
- The ability to weld stiffeners onto large skins to create integrated structures and to join structural segments together is needed for both aerospace and wind energy to be competitive.
    - o Wind Energy - welding stiffeners onto 7 feet by 11 feet skins
    - o Aerospace - welding stiffeners onto 5 feet by 15 feet skins

Risk will need to be reduced via completion of these demonstrations before implementation on the order necessary to realize 3T BTU's in energy savings is possible. The basic foundational technical information needed for embarking on these demonstration efforts have been established under this GO -18135 contract as shown in sections *3.1.3 Process Scalability* and *Utilization of Smart Susceptors for Joining.*

3.8 Commercialization Plan/Strategy

The implementation strategy consists of starting with the most easily implemented components and then progressing to more critical/challenging structure. The proposed implementation plans would rely on the completion of the additional risk reduction activities mentioned above. At the completion of these efforts the technology licensing and production plans would begin. In regard to implementation in the automotive business sector, the initial implementation articles would start with shields, cross members and seat frames then proceed to instrument panels and spare wheel wells, then finally on to closures and body panels. Implementation would begin in approximately 2018 and then proceed through 2023. At that point, given that the process meets all its processing goals, induction consolidation for automotive would be a standard process in automotive production. Automotive implementation is driven by efficient manufacturing attributes aimed at meeting higher fuel economy and recycling targets. The quick thermal cycle and improved molding characteristics of the induction processing system would enable efficient production and significantly reduced equipment costs. In regard to implementation in the aerospace business sector, initial interior part fabrication using this process could begin as soon as 2015 with additional scale-up applications such as floor beams and frames following in 2019 with the large fuselage, empennage, and wing structure following in 2024. Induction processing of integrated structures for aerospace applications would be a standard aerospace process at this point. Aerospace implementation is driven by efficient fabrication of lightweight structures aimed at meeting longer range and higher fuel economy targets. The quicker thermal cycle, improved durability of the thermoplastic polymer, and integrated structure fabrication enabled by the induction processing of thermoplastic composite system address these aerospace requirements. From a business perspective, this process represents a potential for large productivity gains when dealing with high production rates for composite airplane designs. In regard to implementation in the wind energy business sector, initial implementation of nacelle panels is planned for 2015. Small blade/spar fabrication and assembly would follow in 2018 and large blade/spar fabrication and assembly be implemented in 2022. Wind energy implementation is driven by efficient/affordable fabrication and assembly of very large integrated structures aimed at meeting greater energy generation efficiencies along with improved durability and recycling targets. The quicker thermal cycle, improved durability of the thermoplastic polymer, and integrated structure fabrication enabled by the induction processing of thermoplastic composite system along with the improved recyclability of the thermoplastic material would drive this implementation effort. This implementation plan when executed would provide the completed commercialization of this process in the 3 business segments addressed. However, there would be additional industrial segments with potential for implementation of this process such as rail, trucking, and others yet to be determined.

4 Products Developed and Technology Transfer Activities

The following sections will provide the details of the patent applications submitted to the United States Patent Office and the conference related papers and presentations.

4.1 Patent Applications

The 5 US patent applications developed under this contract and submitted to the US Patent Office are listed as follows:

1. The first is entitled “INDUCTION FORMING OF METAL COMPONENTS WITH SLOTTED SUSCEPTORS” was filed on July 13th, 2010.

2. The second is “COMPOSITE INDUCTION CONSOLIDATION APPARATUS AND METHOD” was filed on April 8th, 2011.

3. The third patent is entitled “THERMOPLASTIC WELDING APPARATUS AND METHOD” filed on May 17th, 2011.

4. The fourth patent is entitled “INDUCTION HEATING USING INDUCTION COILS IN SERIES-PARALLEL CIRCUITS” was filed September 29th, 2011.

5. The fifth patent is entitled SYSTEM AND METHOD OF ADJUSTING EQUILLIBRIUM TEMPERATURE OF AN INDUCTIVELY- HEATED SUSCEPTOR was filed November 28th, 2011.

4.2 Publications

Please see the list below for the conference presentations associated with the technology developed under this development contract. The SAMPE presentations also have companion technical papers that are part of the proceedings of the conferences.

1. *Induction Molding of Thermoplastic Composites Using Smart Susceptors for Manufacture of Automotive Structural Composites*: Glen Smith, Ford Motor Company, May 18th; 2010 SAMPE 2010 Seattle, WA

2. *Induction Consolidation/Molding of Thermoplastic Composites Using Smart Susceptors:* W. P. Geren, M. R. Matsen, M. A. Negley, Boeing Research and Technology; W C. Dykstra, Temper, Inc.; 2010 SAMPE 2010 Seattle, WA

3. *Induction Consolidation/Molding of Thermoplastic Composite Structural Components Using Smart Susceptors* www.sae.org/amaf SAE 2010 Aerospace Manufacturing and Automated Fastening Conference & Exhibition (AMAF) Technology for the Next Generation Aircraft; September 28-30, 2010 • Century II Convention Center • Wichita, Kansas, USA

4. *Induction Molding of Structural Thermoplastic Composite Components* Marc R. Matsen1, William P. Geren1, Mark A Negley1, William C. Dykstra2 1The Boeing Company 9725 E. Marginal Way South Seattle, A 981082 Temper Inc., PO Box 755, Rockford, MI 49341 SAMPE 2011 Long Beach, CA

5. *Induction Molding Thermoplastic Composites*: Marc R. Matsen1, William C. Dykstra2, Glen Smith3 1The Boeing Company, 9725 E. Marginal Way South, Seattle, WA 98108, 2Temper Inc., PO Box 755, Rockford, MI 49341. 3Ford Motor Company: SAMPE 2012 Baltimore, MD

References

[1] "Prediction of Energy Intensity of Carbon Fiber Reinforced Plastics for Mass Produced Passenger Cars", T. Suzuki and J. Takahashi; 9th Japan International SAMPE Symposium, Nov. 29 – Dec. 2, 2005 pp. 14 - 19

[2] "Development and Application of GREET 2.7 – The Transportation Vehicle – Cycle Mode", Argonne National Lab ANL/ESD/06-5, A. Burnham, M. Wang, and Y. Wu (Work supported by U.S. Dept. of Energy FreedomCAR and Vehicle Technologies Program

[3] "Life Cycle Energy Analysis of Fiber Reinforced Composites" Y.S. Song, J.R. Youn, and T.S. Gutowski; Composites: Part A (2009) doi. 10.1016

[4] "Energy Use and Energy Intensity of the US Chemical Industry", E. Worrell, D. Phylipsen, D. Einstein, and N. Martin; LBNL-44314, April 2000

[5] "Energy and Environmental Profile of the US Chemical Industry", Energetics Inc. for U.S. Department of Energy, May 2000

[6] "2007 Cradle to Gate Life Cycle Inventory of Nine Plastic Resins and Two Polyurethane Pre-cursors" Franklin Associates for the Plastics Division of the American Chemistry Council

[7] "Energy Implications of Bottled Water", P.H. Gleick and H S Cooley, Environ. Res. Lett 4 (2009) 014009 pp 1 -6