Rapid Manufacturing of Satellite Structures and Heat Pipes using Ultrasonic Consolidation

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Ultrasonic consolidation of aluminum alloys is evaluated for use in the manufacture of multifunctional satellite structures. This paper details the work completed in the design and manufacturing of heat pipes and structural panels. The effects of rib design, build temperature, amplitude of oscillation, and feed rate on bond strength and part quality have been evaluated. Manufacturing obstacles such as bond porosity have been overcome. Proof of concept hardware has been manufactured.

I. Introduction

DUE to the inherent complexity and stringent requirements involved in fabricating satellites, cost remains extremely high and production times very long. Traditional methods of machining and assembly make every satellite produced "one of a kind." This craftsmanship approach has been useful in the fabrication of many satellites over the past few decades but as the desire for a responsive space initiative increases, methodologies in satellite fabrication must also evolve. Advanced additive manufacturing techniques provide this desired shift in methodology where satellites are built in an automated and very repeatable process. In addition, unitizing construction processes allows a satellite to be manufactured very rapidly and with significantly decreased cost (Mosher, 2004).

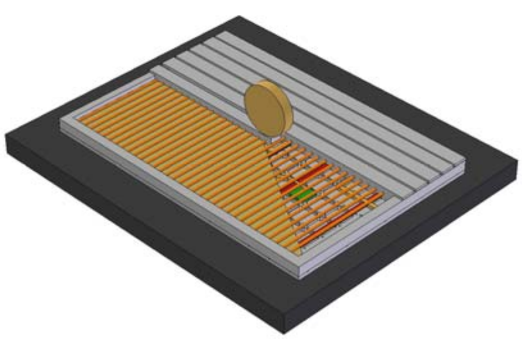

Figure 1. Manufacture of a multipurpose structural panel using ultrasonic consolidation.

One additive manufacturing technique that has tremendous potential in the aerospace industry is a process developed by the rapid prototyping industry called ultrasonic consolidation. This technology uses a sonotrode (see Figure 1) to apply pressure to two mating surfaces while ultrasonically vibrating one of the surfaces. In the case of aluminum, this vibration breaks up and displaces surface contaminants and oxides. Without the presence of the contaminants, and with modest pressure on the two surfaces, the atomically clean surfaces join to create a true metallurgical bond without melting (White, 2002). By repeating the process over and over again with aluminum tape about 0.006 inches thick, it is possible to build a satellite component from the bottom up.

A company by the name of Solidica has integrated the ultrasonic consolidation process into a machine that also acts as a computer numerically controlled milling machine (CNC). Because features may be machined into the deposited tapes and subsequently covered with more layers, it is possible to create parts with internal features. This is very desirable since sensors, electronics, thermal regulators, and simple voids can be integrated to create a multifunctional satellite. In theory, it is possible, as the Center for Advanced Satellite Manufacturing at Utah State University is pursuing, to create a "printed" satellite which offers reproducibility and functionality never before seen in the satellite industry.

Using ultrasonic consolidation to manufacture small satellites guarantees two key advantages over standard manufacturing methods: speed, and the ability to embed sensors, harnessing, thermal control hardware, etc. Students at Utah State University have been evaluating how well UC lives up to this guarantee. Currently there are several students focusing on structural designs, heat pipes, embedding sensors and electronics, and using direct-write technology for antennas and embedded harnessing. This paper will discuss the development of structures and heat pipes using the ultrasonic consolidation process.

II. Structures

Because of its ability to create aluminum objects in an additive fashion, and at near-room temperatures, ultrasonic consolidation (UC) offers a powerful solution to the problems found in creating satellite structures. To achieve the high stiffness and low weight requirements typically found in aerospace structures, internal features such as honeycomb core, or composite materials are commonly used. Both methods require tremendous expertise in assembly and present problems related to the adhesives used in the materials. Additive manufacturing techniques allow internal features to be implemented during a build without the use of adhesives; however, all of the techniques except UC present limiting factors. Some of these factors include operation at elevated temperatures, feature resolution caused by the feedstock media, and extremely high cost.

A. Satellite Structures Overview

Over the past 40 years, many designs have arisen to solve the problem of creating structural panels for spacecrafts. In order to generate a customized solution, it is important to understand the reasoning behind different panel designs.

The most common solution for deck fabrication is a honeycomb sandwich panel. This type of panel provides a large surface area and has a high ratio of stiffness to weight. A simple form of the sandwich construction consists of two thin, stiff, strong sheets of dense material separated by a less stiff and strong central layer (Allen, 1969). Generally, the central layer is much thicker to prevent shear deformation in the panel. Honeycomb is widely used in the aerospace industry. Satellites requiring large surface areas for solar cells almost always use some form of honeycomb sandwich construction. There are also drawbacks to using this type of sandwich construction. Traditional methods require precision in assembly since the process is extremely sensitive to any type of variation. In addition, any bolted or riveted joints can cause high stress concentrations and special potted inserts are required to prevent local failures of bolts (Shirgur, 2000). This customization of design discourages modularity and increases both time and cost with any slight modification in the panel.

Another common solution for structural panels is the use of a milled isogrid or orthogrid pattern in aluminum plate metal. The USUSat design originally used the isogrid pattern due to its isotropic and lightweight properties (Ashby, 2001). This configuration of equilateral triangles proved easy to analyze and desirable for the mission design at that time. The current USUSat design uses an orthogrid pattern (Quincieu, 2003). Though the isogrid was more structurally sound, it became cumbersome when moving components. Hence, a design change came as a result of a push for modularity.

The third most common type of structural panel is a composite panel. Composites are a very appealing solution due to their incredible light weight and stiffness. They do, however, present many difficulties due to their required expertise, molds, and special equipment for manufacturing. SpaceWorks, Inc. has investigated the applications of multifunctional structures to small spacecraft (DiPalma, 2004). They created a composite panel with embedded wire harnessing as well as another structure with embedded thermal control inserts, foils for spot shielding, and structural inserts.

All of the solutions mentioned above posses both good and bad attributes. The design of an ultrasonically consolidated panel endeavors to implement the good features from each solution while avoiding the negative aspects. First, the deck panel adopts the sandwich honeycomb configuration of having a thick core composed of thin webs along with rigid face sheets. This ensures a rigid and stiff structure. Because the Solidica machine is used, the fabrication process does not require the tremendous amount of expertise and precision required for honeycomb. Second, the deck panel adopts the modular USUSat bolt pattern from the orthogrid configuration. This helps avoid the expensive process used in potting inserts in honeycomb. Third, the deck panel integrates the multifunctional capability of composite panels. This is possible since features can be embedded during the build on the Solidica machine.

B. Optimization

Due to the nature of how the ultrasonic consolidation is implemented, there are limitations on build configurations. One of the most important considerations is the mechanical vibration, or "scrubbing" action, which generates the metallurgic bond. It is absolutely imperative that the scrubbing action of the sonotrode be performed on a stationary platform to which the aluminum tape can be

Figure 2. Testing the ultrasonic bond through a peel test of a tape bonded to a rib structure.

consolidated. As the z height of the part increases, a cantilevered effect allows the part to vibrate. This impedes the scrubbing action necessary to break up oxides on the surface of the tape and can create a very poor bond between aluminum layers. Parts that accommodate a large surface area and have a small z height are stiff and therefore the problem doesn't exist. For conventional sandwich panels, however, thin webs are the key to a lightweight structure, which presents problems in the fabrication process. One way to mitigate the vibration effect is to orient the ribs such that the mechanical oscillation of the sonotrode doesn't affect the rib. Ribs perpendicular to the traversing direction of the sonotrode would be ideal except for the fact that the sonotrode would dip into the pockets due to the applied force. A 45 degree angle on the ribs relative to the transverse direction, however, would give the sonotrode enough cross section to avoid dipping and would still provide stability against vibration. The theory was tested by using a test fixture which followed the Standard Test Method for Floating Roller Peel Resistance of Adhesives (ASTM D3167-03a). Tapes were consolidated to a plate containing ribs at 0 and 45 degree angles. The tapes were then removed in the tensile test apparatus (see Figure 2) to give the effective peel strength (see Figure 3). It was difficult to test 90 degree ribs because, as mentioned earlier, they allowed the sonotrode to dip into the voided region. On honeycomb tests, however, the 90 degree ribs were reinforced with angled ribs which supported the sonotrode. In many cases, peeling the tapes consolidated over a hexagon core tore the

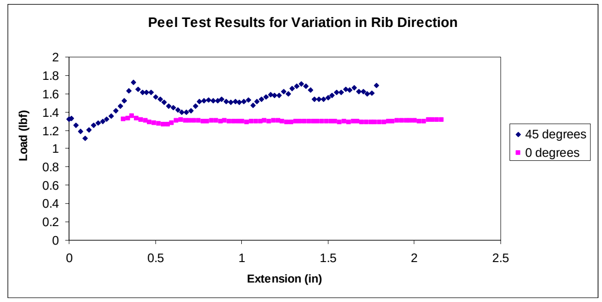

Figure 3. Effective peel strength from a typical peel test.

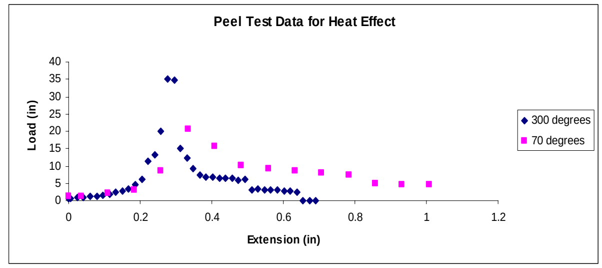

Figure 4. Peel strength data when tape tears while peeling.

material before peeling could occur which revealed a very good bond. This validated the assumption that the ribs vibrate easier when placed in the same direction that the sonotrode traverses. In addition, the results lead to the conclusion that either triangles or hexagons were most suitable for the process.

The Solidica machine is equipped with a heater plate because it is understood that elevated temperatures enhance the ultrasonic consolidation to give a better bond. To understand the significance of heating the plate, the peel test was used to remove a tape that had been consolidated at 70 degrees F and a tape that had been consolidated at 300 degrees F. The results from the peel test are shown in Figure 4. The 300 degree specimen shows a spike at about 0.3 inches of extension. The spike is a valid data point and exists because the bond was so strong that the peel test pulled until the material failed. This is why the load quickly returned to zero. The 70 degree specimens had more of a consistent peel resistance but at a significantly lower value.

Finally, optimization of the build parameters was of concern. This included the weld pressure, weld speed, and amplitude of oscillation from the sonotrode. Though Kong (2003) has conducted a series of tests that would explore the mechanical and physical properties of the welds produced for any given combination of process variables, and current research on the process parameters is ongoing at Utah State University, it was important to explore optimized parameters for tall ribs connected in a hexagonal pattern. The network of interlocking beams behaved vastly different than normal build conditions specified by Solidica. It was observed that the bond strength was significantly better when the amplitude was increase from 16 kHz to about 19 kHz. A slower weld speed has also been shown to contribute to better bond formation for placing skins on core sections.

C. Case Study: TOROID

The most significant structural build using UC has been for the small satellite, TOROID, at Utah State University. Their entry into the 4th University Nanosatellite competition is the Tomographic Remote Observer of Ionospheric Disturbances (TOROID). The scientific mission of TOROID is to observe scintillations in the low latitude ionosphere with increased fidelity. This data will provide the scientific and military communities with a greater understanding of the morphology and equatorial phenomena which currently impede accurate space based geolocation. Another focus of TOROID is to implement rapid manufacturing techniques into the satellite. Such integration will enable technology development and investigation of the usefulness of advanced manufacturing techniques for small satellites. Over the past few years, Utah State University has created a robust modular platform which lends itself very well to integration of ultrasonically consolidated panels.

It was decided to use ultrasonic consolidation on a deck which would be added to the current TOROID structure. There were several reasons a deck was needed in the structural design of the bus. First of all, the Utah State University satellite (USUSat) design emphasized the importance of modularity by using panels. Components for the various subsystems were attached to the panels which were, in turn, assembled into a boxlike structure. This also allowed each panel to be tested individually for vibration and thermal effects. There was very little space for mounting a new payload such as the TOROID science instrument. The problem is that the science instrument required a large area and cantilevered support (see Figure 5). While the inside of the panels of the boxlike structure was covered with components and harnessing, the majority of the interior volume of the satellite was empty. This empty space, however, was the perfect place to install a horizontal deck panel, upon which the science instrument could be mounted.

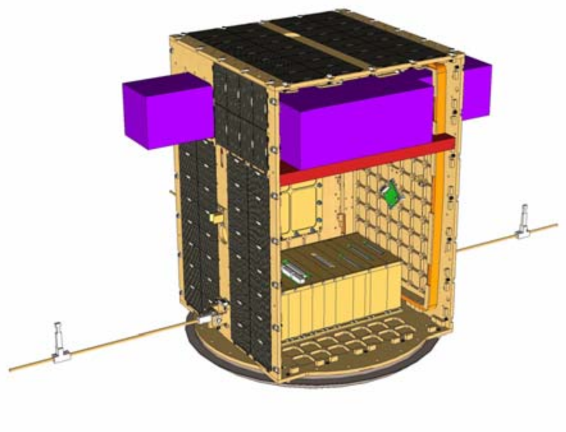

Figure 5. Artist's concept of the TOROID satellite illustrating science instrument and deck.

A 10.75 x 10.75 inch panel was designed for fabrication in the Solidica machine. The design consisted of a honeycomb core with attached face sheets on both sides. A small notch was milled half way during the rib build to ultimately create pathways for wiring and sensors. The rib height was 0.258 inches and the face sheets were .024 inches thick. Reinforced solid sections ran along the perimeter of the deck to allow excellent bonding along the edges. There was also an integrated bolt pattern with fastening points about every 2 inches. The fastening points consisted of reinforced honeycomb sections with tapped holes. Finally, attachment points for mounting brackets were added.

The actual build of the deck panels was done in many segments. First, a solid plate of aluminum was fixed in the Solidica machine. The solid plate provided a rigid support during UC as well as became part of the finished deck panel. Next, aluminum tapes were ultrasonically consolidated to the plate to create an 11 x 11 x ¼ inch cladding on the solid plate. During the application of the tapes, a channel was milled for wiring (see Figure 6). It was subsequently covered with tapes and thus embedded within the structure. The CNC mill was used to mill the hexagonal pattern into the cladding and into the solid plate. The skin was attached by ultrasonically bonding four layers of tapes to the milled substrate.

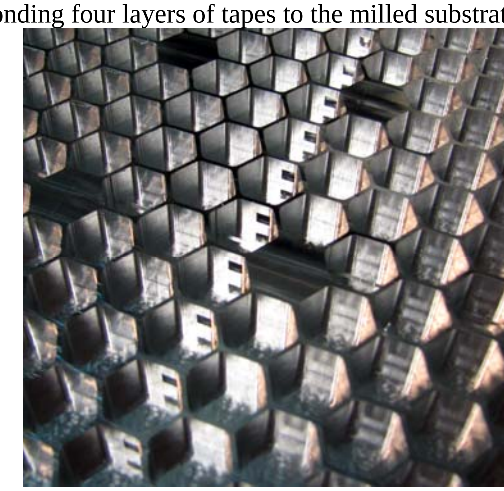

Figure 6. Detailed view of sandwich panel core illustrating wiring channel through ribs.

Figure 7. Finished deck panel for TOROID satellite.

After the part had been built up and machined in the Solidica machine, the unusable portions of the solid plate were removed and the plate was deburred. Finally, the holes were tapped and nonlocking helicoils were installed.

The resulting deck panel (see Figure 7) is a very stiff and lightweight structure. The face sheets are bonded very well to the honeycomb core. The pathway cut for wiring and sensors has shown to be very effective. Testing of the finished deck panel is currently underway and a second iteration of the deck is being pursued. As the design becomes more robust, other subsystems such as thermal control can be embedded to create a multifunctional panel.

III. Heat Pipes

Heat pipes are a two phase passive heat transport device. They are usually divided into three sections: an evaporator, an adiabatic section and a condenser. All three sections are traversed by the vapor space and wick. Heat is absorbed at the evaporator by the vaporization of the working fluid. The constant production of vapor produces a pressure gradient that drives the vapor from the evaporator, down the adiabatic section to the condenser. The condenser is thermally coupled to a heat sink, cooling and condensing the vapor. The condensing fluid is absorbed into the wick and returns, through the adiabatic section, to the evaporator. Surface tension and the adhesion of the liquid to the heat pipe wall form the meniscus at the liquid/vapor/wall interface in the evaporator. The meniscus provides the force necessary to draw the liquid through the wick to the evaporator.

Many different wick geometries have been employed in heat pipe design including grooved wicks, screen wicks, and sintered wicks. The most commonly used in aerospace applications is the axially grooved wick. Capillary grooves are formed in the heat pipe wall, usually by the extrusion of aluminum. Grooved wicks can also be produced by threading the inside of the heat pipe, although this is a more time consuming and costly method of production. A variant on the groove design, the monogroove heat pipe, transports the working fluid axially in one large diameter groove while circumferential transport is obtained by threading the inside of the vapor space. Grooved wicks are simple, but are limited in the amount of capillary head that can be produced.

Screen wicks have also been extensively used in heat pipes though less commonly today than in past years. To produce the basic screen wick stainless steel mesh is wound three to four times on a mandrel and inserted into the heat pipe. When the mandrel is removed the released mesh produces a sufficient spring force to hold the wick against the wall. Ceramic fabrics, metal felts, and metal foams have also been used for screen wicks because they offer a much smaller pore size. Despite the advantages smaller pore sizes offer these materials have been used less commonly in aerospace because they lack a self-springing action and their design and assembly require more complexity. Standard screens have been augmented by arteries (larger diameter liquid flow paths) for lower viscous pressure drop and thus higher capillary pumping capacity through the wick. Again, the complexity in manufacturing the arteries limits their utility.

Sintered wicks are produced using either powdered ceramic or metal. The powdered metal is sintered around a mandrel inside the heat pipe wall. The voids left by the sintering process act as capillaries. The small pore sizes produced by this method produce high capillary forces at the evaporator and correspondingly high viscous pressure loss throughout the length of the wick.

A. Heat pipe design for ultrasonic consolidation

The manufacturing of heat pipes using ultrasonic consolidation presents some challenging limitations. UC requires a strong and stiff structure in order to produce differential vibration and scrubbing at the tape/substrate interface. Overhanging features lack the required stiffness and cannot be produced. A second limitation includes the inability of the UC process to produce circular structures. To design for the ultrasonic consolidation process the usual circular cross section of a heat pipe must be modified to a rectangular cross section. There are also limitations on the width of a heat pipe. The topside of the heat pipe is completely unsupported. The width of the heat pipe must be less than the width of a single tape so that a single tape can bridge the gap and seal the structure. The bond between layers has also presented a challenge. It is inherently porous and a sealant must be used to fill in pores and provide a contained system for the working fluid. The thermosetting sealants currently in use are driven in with a vacuum,

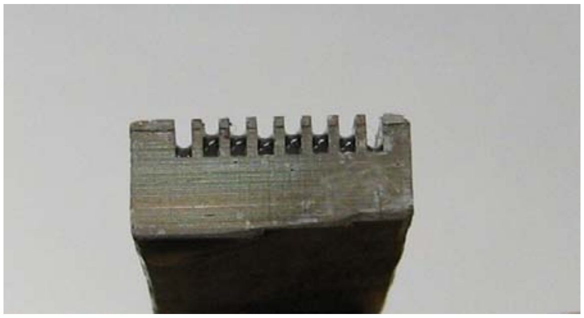

Figure 8. Multiple menisci formed with isopropanol in sealed aluminum grooves.

flushed from the heat pipe with solvent and then heat cured. Any pores in the wick that cannot be cleared by flushing will be sealed off as well, eliminating the possibility of using wicks with small pore sizes such as sintered wicks and ceramic screens.

Another concern introduced with the sealant is the possible loss of adhesion and wetting between the working fluid and the wall material after sealing. To address this concern a grooved sample was prepared and sealed and isopropanol, the desired working fluid for these experiments, was introduced into the grooves. Figure 8 shows the meniscus formed during evaporation. This experiment shows good wetting between isopropanol and the sealed aluminum sample.

With the limitations imposed by the manufacturing process of ultrasonic consolidation also come new abilities. It has been shown that stainless steel meshes can with ease be embedded in aluminum using ultrasonic consolidation. A combination wick of mesh and grooves will therefore be the most likely wick to perform well within the limitations given.

B. Heat Pipe Manufacturing: Proof of Concept

A proof of concept heat pipe has been manufactured as the first step in evaluating the feasibility of manufacturing embedded heat pipes using ultrasonic consolidation. An axially grooved wick design has been adapted for this proof of concept build. The wick grooves are located solely in the base of the heat pipe instead of around the entire circumference. This does reduce the wicking capacity but the remaining capacity is expected to be sufficient to validate the design.

Figure 9 illustrates the cross section of the completed heat pipe. The actual build width is significantly larger than the final dimensions of the heat pipe. This is necessary as experiments have shown that ultrasonic consolidation cannot build higher than a one to one aspect ratio. This limitation is overcome in this instance by building a low aspect ratio part and then trimming it to the desired width.

To produce the build, tapes are bonded layer upon layer on an aluminum substrate until the thickness is equal to the sum of the bottom wall thickness and the groove depth. The capillary grooves are then machined and more tapes are bonded on top of the grooves until the desired vapor space height is reached. The vapor space is then machined and the top wall is bonded layer by layer onto the surface to complete the heat pipe. After the heat pipe is complete it is trimmed from the substrate and the excess build volume is removed. Fill holes are drilled in either end and tapped. Brass valves and fittings are installed and the heat pipe is filled with sealant and placed in a vacuum chamber for 4 hours. After 4 hours it is removed and flushed with alcohol. Following the alcohol flush it is placed in boiling water for crosslinking. Filling is performed by volume and a sufficient amount of isopropanol is introduced to reach 110% of the volume needed to fill the grooves. This allows for condensation on the walls and lessens the chance of evaporator dry-out. A photo of a completed heat pipe is shown in FIGURE.

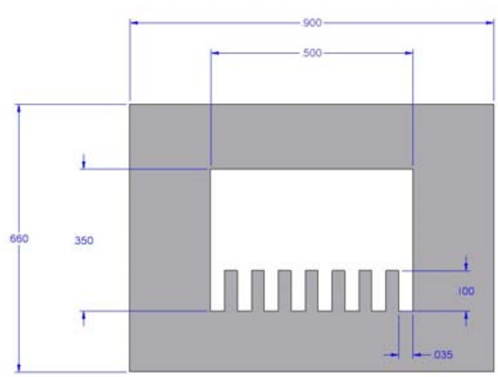

Figure 9. Cross section of proof of concept heat pipe.

Figure 10. Completed proof of concept heat pipe with fill valves.

IV. Future Development

Utah State University students working in the Center for Advanced Satellite Manufacturing will continue to research the performance of the ultrasonic consolidation in satellite manufacturing. Bending and vibration tests will be performed on the TOROID deck panel. Design changes to improve the performance of the panel will be completed. A more thorough characterization of bond strength verses build parameters will be performed. Thermal conductivity tests will be performed on the proof of concept heat pipe. Further study will also be completed on the inclusion of screen wicks to maximize wicking performance. Integration of heat pipes with a structural panel will also be undertaken. It is the hope of current researchers to have construction and testing of heat pipes and structural panels completed and ready for presentation at the Small Satellite conference in August 2006.

V. Conclusion

Additive manufacturing and especially ultrasonic consolidation promise to significantly enhance the functionality of satellite structures. Preliminary research has been completed into the feasibility of manufacturing satellites with ultrasonic consolidation. Proof of concept hardware has been manufactured. Obstacles have been identified and solutions found. Aspect ratio limitations can be overcome with the correct order of operations. The inherent porosity in the ultrasonic bond can be overcome with thermosetting sealants. Wetting of isopropanol on sealed aluminum has been shown to be satisfactory.

Testing on the current hardware is expected to reveal areas that can be improved. Future work will focus on improvements in the performance of both the manufacturing process and the components that are built using it.

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