Rapid Manufacturing of Reconfigurable Satellite Panels with Embedded Electronics, Embedded Thermal Devices, and Novel Structural Features

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ABSTRACT: The Center for Advanced Satellite Manufacturing (CASM) at Utah State University has been investigating the use of new, advanced manufacturing technologies for the rapid manufacture of highly capable satellite panels. Using Ultrasonic Consolidation it is now possible to additively manufacture (a.k.a. rapid prototype) aluminum structures with embedded electronics, thermal devices, internal structural features, and fibers. CASM has built and tested embedded USB networks, electronic devices, thermal sensors, heat pipes, optical fibers, and other features within aluminum structures to create intelligent, self-monitoring panels for space applications. This work and its potential for providing rapid reconfigurability and rapid manufacturability for Responsive Space purposes will be presented.

INTRODUCTION

New, advanced manufacturing technologies are being investigated by the Center for Advanced Satellite Manufacturing (CASM) at Utah State University. A number of technology demonstrations have been completed showing the potential for use in satellite applications. This paper summarizes these technology demonstrations and potential applications for the aerospace industry.

CENTER FOR ADVANCED SATELITE MANUFACTURING

The Center for Advanced Manufacturing (CASM) at Utah State University is a State of Utah Center of Excellence, funded by the Governor’s Office of Economic Development. CASM’s primary objective is to transition satellite technology innovations developed at Utah State University and its Space Dynamics Laboratory into the marketplace. CASM is focused on two sets of technology innovations, applying platform architecture design concepts to satellites and applying advanced manufacturing methodology to satellite fabrication.

ULTRASONIC CONSOLIDATION

With the exception of ultrasonic consolidation (UC) no current rapid prototyping (RP) process is capable of forming metal structures at or near room temperature. This feature alone opens the door to a number of new manufacturing techniques for specialized or multi-functional structures. Embedding components within a structure has become possible using this technology. The elevated temperatures inherent in current metal-based RP processes that utilize molten metal during processing would damage or destroy most components of interest for embedding within the metal structure – such as circuitry, sensors or actuators. With recent advances in ultrasonic consolidation, fully functional metal structures can be formed at ambient temperatures under highly localized plastic flow, thus making possible the embedding and encapsulation of components without worrying about elevated-temperature effects on those components.

The SOLIDICA Formation ultrasonic consolidation technology, which has been purchased by USU, is a novel application of ultrasonic welding aimed at forming complex 3-dimensional structures from metal
foils. The UC machine is a fully integrated machine tool which incorporates an ultrasonic consolidation head, a 3-axis milling machine, and software to automatically generate tool paths for material deposition and machining. The machine is shown in Figure 1.

Figure 1: USU's SOLIDICA Formation ultrasonic consolidation machine

Figure 2 illustrates the basic mechanism by which UC joins materials. An excitation source is utilized to create interfacial vibration at a boundary between two materials. Friction at the interface causes local plastic deformation and breaks up surface oxides, resulting in atomic diffusion and a true metallurgical bond. The affected material is approximately 20 μm thick, and the rise in bulk material temperature is on the order of a few degrees Celsius.

Figure 2: The ultrasonic consolidation process

UC technology enables built-in internal channels, internal supporting structures, multi-material structures, and embedded wiring and components. For satellite applications these capabilities could enable built-in cooling channels, heat pipes, honeycomb sandwich panels and internal ribs. With embedded components there is a wide range of multi-functional structures that can be conceived that have application to small satellites.

Another clear advantage to UC technology is the ability to build structures, whether multi-functional or not, directly from Computer-Aided Design (CAD) models. This ability could significantly reduce the amount of touch labor required for satellite construction, thereby significantly reducing costs and human-factor risks.

Mechanical Properties

UC bonding in aluminum is dominated by plastic deformation at the interface, and mechanical properties are highly dependent upon the quality of the bond between deposited layers. As stated previously, differential motion breaks up surface oxides and plastically deforms the interface, enabling clean metallic materials to come into contact, forming a metallurgical bond. By carefully controlling the parameters during ultrasonic consolidation, we have been able to consistently exceed 98% linear weld density (LWD) with bonding. LWD is a measure of bonding quality, which is a ratio of defect-free bond length divided by total length when viewed under the microscope. Figure 3 shows the typical defect types which may be present between bonded layers.

Figure 3: Typical defects in ultrasonic consolidation: D1: Line like, D2: parabola-like, D3: point-like.

We have developed an ANSYS model of bonding physics which is tracking well with our experimental
results. Based on what we have learned from our modeling and experimental efforts, we have been able to identify optimum parameter combinations which result in LWD consistently in excess of 98%, as shown in Figure 4.

Figure 4: Linear weld density in excess of 98%

A series of tensile tests were performed on specimens created with a LWD between 80% and 90%. It was found that the tensile strength of ultrasonically consolidated parts is similar to that of the wrought material alloy, but the ductility was quite low, as can be seen in Figure 5. Table 1 lists the results of these tensile tests. Follow-up tensile test are being planned on specimens which exceed 98% LWD, and an improvement in mechanical properties is expected.

Table 1: Tensile test results for Aluminum

<table>
<thead>
<tr>
<th>Tensile Test Item</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Strength</td>
<td>83% of wrought, perpendicular to tape</td>
</tr>
<tr>
<td></td>
<td>105% of wrought, parallel to tape</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>Comparable to wrought</td>
</tr>
</tbody>
</table>

ADVANCED STRUCTURES

Honeycomb Panels

Using UC it is possible to create sandwich panel geometry, such as a honeycomb structure with aluminum face sheets that is essentially a single structure rather than three components bonded together using an epoxy. Figure 6 shows one such panel that was created as a payload deck plate for USU’s entry in the University Nanosat competition. One benefit of such a panel is that it can be created directly from a CAD file, in a matter of a couple of days, and is reconfigurable digitally to design changes. For instance, the bolt pattern shown could be modified and the part re-made in a couple of days if the payload were to change. In addition, the current deck plate has wiring channels internal to the deck plate for wire to be fed from the outside of the deck plate to the appropriate location for connection to the payload. These wiring channels can also be reconfigured digitally and re-made rapidly in response to design changes.

Figure 6: Finished prototype deck panel

Multi-Material Structures

In addition to the basic Al 3003 alloy typically used in ultrasonic consolidation, we have successfully bonded a number of materials to Al 3003 at USU. These materials include:

1. Stainless Steel (316 & 347 foils and wire meshes)
2. Copper (OFHC)
3. Brass (90/10)
4. Nickel (201 & 600)
5. Al 2024 T3
6. Metpreg® (pure Al with aluminum oxide fibers)
Figure 7 illustrates some examples of multi-material bonding performed at USU.

![Figure 7: Examples of multi-material bonding](image1)

**Embedded Fibers**

One unique aspect of UC is that highly localized plastic flow around embedded structures is possible. This is due to the fact that ultrasonic excitation has the same effect on enhancing plasticity that elevated temperatures have. Figure 8 illustrates the ability of aluminum to flow around a SiC fiber, which is possible even when the fiber diameter exceeds the thickness of an individual aluminum layer. The ability to embed fibers within an aluminum matrix can be utilized in a number of ways, including the embedding of structural fibers for localized stiffening, optical fibers for communication and sensing, shape memory fibers for actuation, or wire meshes for planar or area stiffening and ballistic impact resistance. Figure 9 shows a stainless steel mesh embedded in aluminum.

![Figure 8: SiC fiber embedded in Al.](image2)

**Figure 8: SiC fiber embedded in Al.**

![Figure 9: Stainless Steel mesh embedded in Al.](image3)

**Figure 9: Stainless Steel mesh embedded in Al.**

**EMBEDDED ELECTRONICS**

Another enabling technology for advanced satellite structures is the ability to embed electronics within the structure. With UC, temperatures remain low enough during the manufacturing process to allow UC welding with electronics embedded within the aluminum or similar material. This technology would allow multifunctional structures with the potential for reducing mass and increasing the robustness of the structure at the same time. With a repeatable manufacturing process, the risk of damage or defects from “touch labor” is greatly reduced.

To further enhance the capabilities of embedded electronics manufacturing, direct write (DW) technologies have been developed. DW allows traces of conductors and insulators to be “written” freeform directly onto the surface of the part. Complex circuitry can be written onto internal layers during the construction process, encasing the circuitry in a robust metal structure.
Panels with embedded electronics have been manufactured to demonstrate these capabilities. This paper discusses two such panels to illustrate the capability. The first is an encapsulated USB device. The second is a switchable LED circuit embedded in a panel with DW traces.

**Encapsulated USB device**

Simple or complex electronics can be embedded within a structure. USB accelerometers, temperature sensors, and strain gages have been successfully demonstrated at USU. For these demonstrations, a pocket is machined in the structure, the unit is inserted, potted with thermal glue and epoxy in place, and then enclosed using UC. This process is illustrated in Figure 10 through Figure 12.

**LED Panel**

The LED Panel demonstration was more complex, including a connector, switch, DW circuitry, and the LED itself. A CAD model of this demonstration panel is shown in Figure 13. The panel as built-up with UC, machined, and ready for circuitry is shown in Figure 14, and the final panel with the embedded circuitry and a face sheet is shown in Figure 15.

Figure 10: USB device inserted in pocket within structure, held in place using thermal glue

Figure 11: USB device encased in epoxy

Figure 12: USB device covered with aluminum

Figure 13: CAD model of LED panel with embedded space connector and DW traces.
Figure 14: LED panel structure after deposition and machining operations

Figure 15: The Finished LED panel is an embedded system that works to transmit power.

The ability to embed electronics and connectors within an aluminum structure is an enabling technology for many potential advancements. In addition to offering a simple suite of sensors for health monitoring, embedded electronics and connectors makes possible the physical infrastructure for making truly plug and play systems, where patterns of connectors allow various payloads, instruments or other devices to be connected anywhere on the panel. In addition, embedded intelligent electronics can provide real-time health monitoring, power-on health checks, and other useful functions.

EMBEDDED THERMAL CONTROL

UC technology can also be used in a number of ways to provide advanced methods of thermal control. Multi-material structures, with high or low thermal conductivity layers or sections can be used to channel heat. Embedded fluid channels, heat pipes, heaters, and temperature sensors are other ways to improve thermal control. Each of these applications of UC has been demonstrated.

High conductivity materials

High thermal conductivity layers of copper have been successfully applied between layers of aluminum, as shown in Figure 16. Excellent metallurgical bonding was achieved.

Figure 16: Aluminum/copper/aluminum bonded layers

A second thermal demonstration panel included embedded fluid lines as well as a layer of copper for heat spreading. This unit is shown in a partially completed form in Figure 17.

Figure 17: Demonstration of embedded fluid channels and copper layer

Embedded sensors and heaters

With the ability to encapsulate electronic components, an obvious application for thermal management is the encapsulation of temperature sensors and heaters. Embedded sensors and heaters offer a number of
advantages, including a tighter thermal coupling with the structure, reduced footprint and placement constraints, an extraordinarily robust mechanical attachment, and the ability to optimize these components within a complex, multi-functional system. USU has completed a demonstration of an embedded temperature sensor very similar to the USB device shown in Figure 10.

**Embedded heat pipes**

Perhaps the greatest thermal management performance tool demonstrated was the embedded heat pipe. Heat pipes have traditionally been used only in areas where high heat transfer or very low thermal gradients are required. With the ability to embed this technology within the structure, the cost, mass, and time required to implement a heat pipe within a spacecraft panel can be optimized. A demonstration unit, built up using UC is shown in Figure 18. Test results comparing a “dry” heat pipe and a “wet” heat pipe are shown in Figure 19 through Figure 22.

![Figure 18: Conductivity test setup](image)

**Figure 18: Conductivity test setup**

![Figure 19: Thermal imaging of a "dry" heat pipe, showing the thermal profile when transferring 22.2 watts of heat through conductive heat transfer only](image)

**Figure 19: Thermal imaging of a "dry" heat pipe, showing the thermal profile when transferring 22.2 watts of heat through conductive heat transfer only**

![Figure 20: Corresponding temperature graph for the “dry” heat pipe with 22.2 watts heat input](image)

**Figure 20: Corresponding temperature graph for the “dry” heat pipe with 22.2 watts heat input**

![Figure 21: Thermal imaging of a "wet" heat pipe, showing the thermal profile when transferring 22.2 watts of heat through a two-phase heat pipe flow with 2.5 mL of acetone](image)

**Figure 21: Thermal imaging of a "wet" heat pipe, showing the thermal profile when transferring 22.2 watts of heat through a two-phase heat pipe flow with 2.5 mL of acetone**

![Figure 22: Corresponding temperature graph for the “wet” heat pipe with 22.2 watts heat input](image)

**Figure 22: Corresponding temperature graph for the “wet” heat pipe with 22.2 watts heat input**
Flexible Thermal Links

The final thermal management demonstration unit was a UC flexible thermal link, shown in Figure 23. Using UC to form a metallurgical bond eliminates the thermal contact resistance associated with soldered thermal links. UC technology has the added advantage of allowing the thermal link to be an integral part of the larger structure, further reducing thermal resistance.

Figure 23: Demonstration UC flexible thermal link

CONCLUSIONS

Research into ultrasonic consolidation at Utah State University’s Center for Advanced Manufacturing has been shown to effectively create advanced structures applicable to satellites. Complex structures, multi-material structures, embedded fibers, embedded components, and embedded thermal management devices have all been demonstrated. These advanced manufacturing processes and technologies have opened a new door full of possibilities for the small satellite community.

ACKNOWLEDGEMENTS

The authors would like to thank those organizations that provided funding for the research presented herein, including the National Science Foundation (NSF Grants DMI-0522908 & OII-0512641), the State of Utah Centers of Excellence Program, MicroSat Systems, the Air Force Research Laboratory, Sandia National Laboratories, and the Space Dynamics Laboratory. We would like to thank the research Co-PIs: Dr’s Leijun Li, Wenbin Yu, Charles Swenson, Patric Patterson, Randy Jost, Ryan Wicker, and Jeremy Palmer as well as post-doctoral researcher Dr. G.D. Janaki Ram, Ph. D. student Yanzhe (James) Yang, Masters students Joshua George, Christopher Robinson, Jared Clements, Erik Siggard & Denton Johnson, and undergraduate student Justin Gastrich.