

Structurally Embedded Electrical Systems Using Ultrasonic Consolidation (UC)

Erik J. Siggard^a, Anand S. Madhusoodanan^b, Brent Stucker^a, Brandon Eames^b
^aMechanical & Aerospace Engineering, ^bElectrical & Computer Engineering, Utah State University

Abstract

Current research has demonstrated the use of Ultrasonic Consolidation (UC) to embed several USB-based sensors into aluminum, and is working toward embedding suites of sensors, heaters and other devices, connected via USB hubs, which can be monitored and controlled using an embedded USB capable processor. Additionally, the research has shown that electronics can be embedded at room temperature, but with some inter-layer delamination between the ultrasonically bonded aluminum layers. Embedding sensors and electronics at 300°F to overcome the delamination issues resulted in optimal bonding, and the sensors used thus far have functioned normally. Future investigation will explore other UC parameter combinations to ascertain the quality of embedding at lower temperatures.

Keywords:

Ultrasonic Consolidation, structurally embedded, sensor, electronics

Abbreviations:

CAD	–	Computer Aided Design
CNC	–	Computer Numerically Controlled
COTS	–	Commercial Off-The-Shelf
CTE	–	Coefficient of thermal expansion
DW	–	Direct Write
FEA	–	Finite Element Analysis
SFF	–	Solid Freeform Fabrication
UC	–	Ultrasonic Consolidation
USB	–	Universal Serial Bus

Introduction

The mid-1980's represented the inception of a suite of technologies that would change the world, rapid prototyping, also known as solid freeform fabrication (SFF). Chua et al. (2003) consider SFF as the “third phase of the evolution of prototyping.”¹ This third phase provides a number of capabilities, as well as innovations, optimizations and freedoms, which are not readily available with conventional manufacturing (Cham et al. 1999, Chua et al. 2003, Ogando 2002). Some of the capabilities include the creation of heterogeneous structures with continuously varying material properties, formation of

¹ The three evolutionary phases of prototyping are: First Phase, Manual Prototyping, development of a physical model by a skilled artisan (Chua et al., 2003); Second Phase, Soft or Virtual Prototyping, development of a CAD based model for computer analysis of the characteristics of the model (i.e. stress, strain, etc.) generally performed using FEA (Chua et al., 2003); Third Phase, Rapid Prototyping, development of a physical model directly from CAD data, generally through the use of additive manufacturing methods (Malone, et al., 2004).

internal passageways and voids, and the embedding of mechanical and electrical components (Cham et al. 1999, Mosher et al. 2004, Weiss 1997). The final of these capabilities is considered “the least explored and most useful” (Cham et al. 1999).

The physical embedding or encapsulation of mechanical and electrical devices provides a means to produce “smart” parts² as well as provides a barrier to hostile environments (Li 2001). For example, wearable computers, small robotic limbs, structural panels, and injection molds (Cham 2002, Li, 2003, Mosher 2004, Varadan 2000). Li (1999) also explains that embedded electronics enable real-time monitoring at critical locations not accessible to ordinary sensors, which must be attached to the surface.

Most of the current SFF methods provide embedding capabilities to the designer, but many of the SFF methods are still limited to specific materials from which the part is fabricated, generally plastics (Cham et al. 2002, Li 2001, Prodan). Though there are SFF technologies that do provide metal parts, the parts created using most processes provide an inhospitable environment (usually high temperatures due to metal melting) for the embedding of delicate electronics and mechanical devices. Some methods have been developed to mitigate the effects of the high temperatures (Li 2001, Li et al. 2003, Weiss 1997), but require extensive preprocessing, elaborate procedures for embedding, and clean room environments. The designer is typically limited to either a device embedded in plastic (which with certain methods is still subject to high temperatures), or embedding the sensor in metal using specialized techniques and still running the risk of failure. One method provides a solution to this conundrum: Ultrasonic Consolidation (UC).

Ultrasonic Consolidation

The Solidica Ultrasonic Consolidation process is a relatively young SFF technology, which provides a nearly fully dense metal part fabricated at or near room temperature. UC, like most SFF technologies, builds a part from existing CAD data layer by layer, but according to Ogando (2002) “the similarities stop there.” Ultrasonic Consolidation is based on “solid state ultrasonic welding to additively manufacture components directly from metal foil feedstock (Mosher et al. 2004).” The ultrasonic welding provides a true metallurgical bond between each of the layers offering a dense metal part without solidification weld lines and extensive voids. The ultrasonic welding additive manufacturing process is supported by the subtractive manufacturing process of a three-axis CNC mill. The mating of additive and subtractive methods provides UC with the ability to create fully three dimensional metal parts with the following characteristics:

- Complex internal passageways
- Multiple materials
- Integrated wiring
- Encapsulated fiber optics
- Embedded mechanical and electrical systems

² Smart parts are considered parts which perform specific duties with minimal outside influence, such as health monitoring, stress and strain measurements, temperature measurements, etc. (Varadan 2000)

Currently, the Solidica UC SFF machine that is utilized at Utah State University uses aluminum feedstock foil 0.94” (23.9 mm) wide and 0.0061” (0.155 mm) thick. The first foil layer is ultrasonically welded to an aluminum semi-sacrificial base plate and is milled to create the layer’s cross-section. Additional milling operations are performed at the appropriate layer during build-up (Ogando 2002) to create the desired features within the part, such as pockets for embedding components.

The UC process can be performed at various temperatures ranging from room temperature (72°F/22°C) to 400°F (204°C), but builds are generally fabricated at 300°F (150°C) (Yang et al 2006). These build temperatures are relatively low compared to other metal SFF processes, and do not require extensive cladding (Li 2001, Li et al. 2003) to protect the embedded components. In addition, UC with the solid state bonding is able to avoid phase transformations (solid-liquid-solid) which generally result in residual stresses, dimensional changes, and possible metallurgical incompatibilities (Ogando 2002).

UC Embedding of Sensors

UC provides a process in which off the shelf components can be easily embedded into a metal substrate to create “smart” parts. Current research at Utah State University uses USB based electronics to enable a plug’n’play type system. This section illustrates the process of embedding COTS sensors into an aluminum substrate using Ultrasonic Consolidation, see Figure 1 below. Multiple sensors embedded into a UC structure would use the same technique as a single sensor.

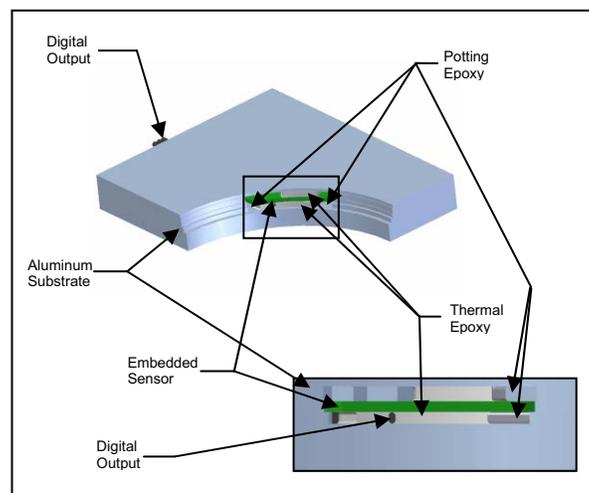


Figure 1: CAD representation of embedded sensor using UC process

Preprocessing

Preprocessing encompasses the effort and processes that need to be performed before the actual fabrication of the smart part can begin. The preprocessing needed for UC is similar to most Solid Freeform Fabrication (SFF) technologies in that an initial CAD

model is sliced into layers using supported software, then each layer is developed within the software with the given material, in this case, 0.0061” thick, 0.94” wide 3000 series aluminum tapes. Once these steps have been completed, CNC tool paths are created for the necessary near net shape tape depositions and the CNC milling shape trims, including any enclosed cavities as well as any additional geometric features.

Fabricating Substrate and Developing Overall Part Geometry

A substrate panel is created on the base plate using UC commensurate with the desired end application geometry. This substrate must have a sufficient thickness to accommodate the dimensions of the sensor/electronic being embedded, see Figure 2 and Figure 3 below. The developed substrate for the embedded sensor is generally formed from UC layered tapes and the base plate, and includes any desired geometric features, e.g. honeycomb pattern pockets, wire harness lines.

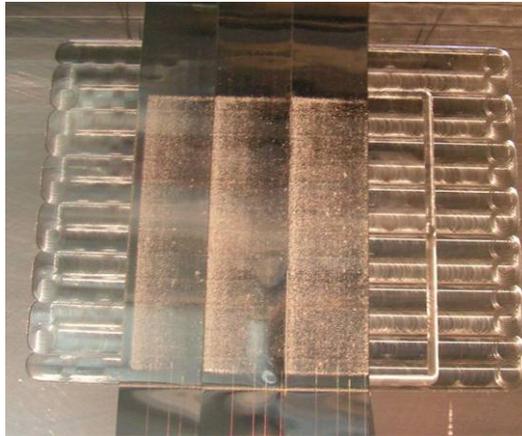


Figure 2: Initial Aluminum tapes being ultrasonically welded to the base plate.

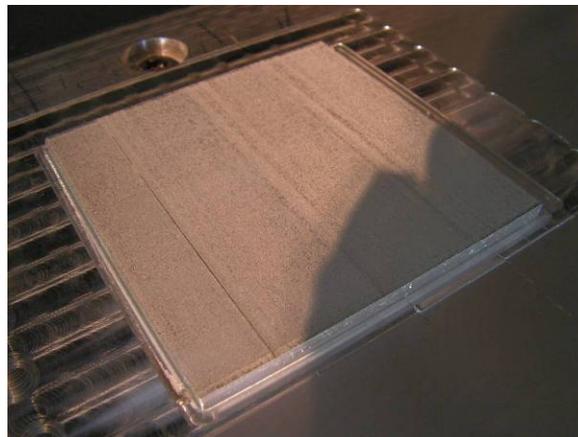


Figure 3 Substrate with sufficient thickness to support embedded components.

Milling Pocket

In order to embed a sensor, a pocket is milled into the substrate using a CNC mill attached to the UC machine, see Figure 4. The pocket is generally larger than the sensor

to enable the correct placement, but more explicitly to allow the potting material to flow around the sensor, and minimize the number of voids.

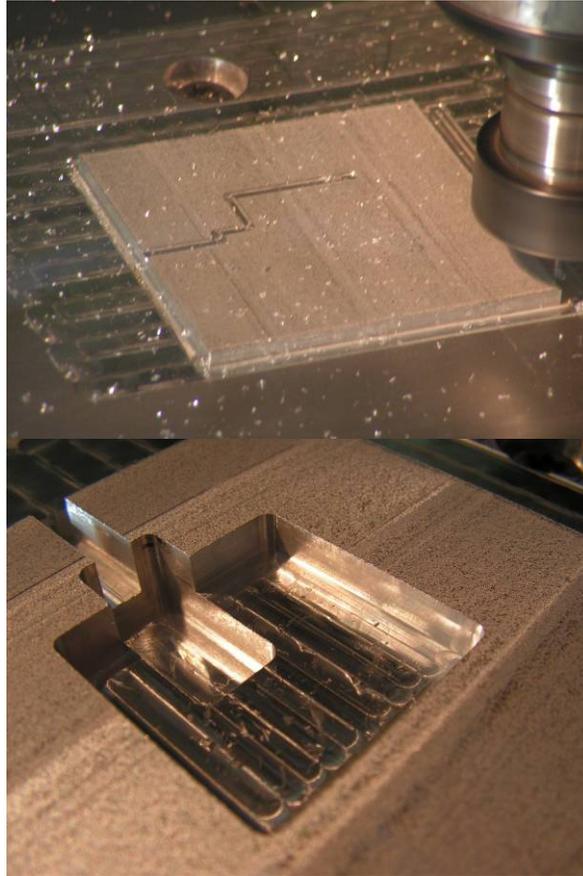


Figure 4: CNC milling of pocket, and finished pocket in substrate.

Embedding Sensor

The physical embedding of the sensor consists of three main actions: placement, bonding and potting.

Placement

To ensure the correct location, fit and orientation of the sensor, each sensor is dry fitted into the existing pocket. Upon certifying the correct placement, orientation marks are made to guarantee the final placement of the sensor.

Bonding

The bonding of the sensor to the substrate requires several steps:

1. The substrate and sensor is cleared of debris and contaminants using 99.9% pure Isopropyl alcohol.
2. The correct bonding agent is chosen commensurate with the purpose of the sensor, usually a quick curing, high temperature epoxy being highly thermally conductive and

electrically insulative (additional information on the type of bonding agent is evaluated in more detail later).

3. The bonding agent is applied directly to the sensor using a syringe to maximize the bonding area, and minimize overflow of the material.

4. The sensor with the bonding agent is vibrated to mitigate air encapsulation that may exist by allowing the air bubbles to rise to the surface and the bonding agent to flow into the crevices within the sensor.

5. The sensor is aligned with the orientation marks and bonded to the surface with slight pressure until the bonding agent begins to cure and the sensor is secured. A bonded sensor is shown in Figure 5.

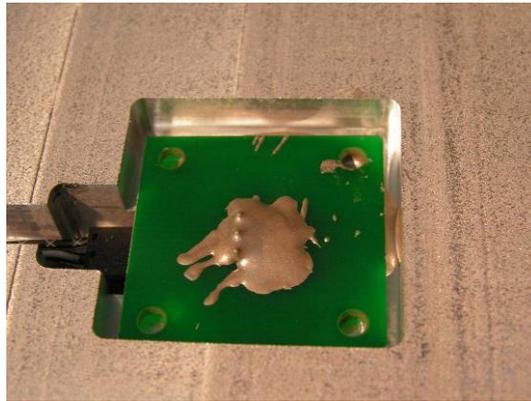


Figure 5: Fully bonded sensor using silver based conductive epoxy

Potting

With the sensor affixed, the sensor and pocket is then potted (filled) with an epoxy having similar characteristics to the previous bonding agent (usually the same) to provide a solid substrate for subsequent UC operations, shown in Figure 6. To allay the encapsulated air, the substrate is vibrated allowing the air bubbles to rise to the surface and the bonding agent to flow around the sensor and into the corners of the pocket.

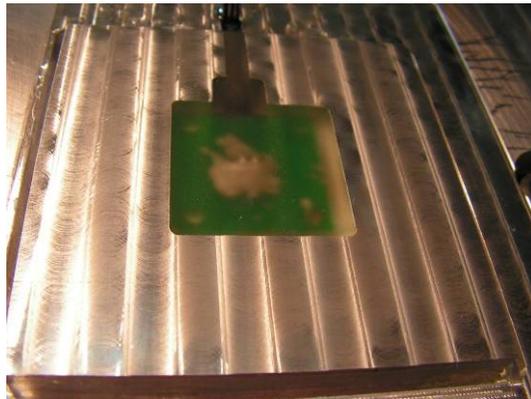


Figure 6: Potted sensor.

Continuing the Build

Once the potting material hardens, the top face is milled using the attached CNC milling apparatus to ensure a flat, uniform surface in preparation for the next UC layer. UC aluminum tape is then ultrasonically welded to the substrate to fully embed the electronic sensor. In Figure 7, one, four and 8 layers of subsequently bonded aluminum are shown. The build continues as before, ultrasonically welding one layer on top of another. When the final layer is complete, the part can be removed from the base plate.

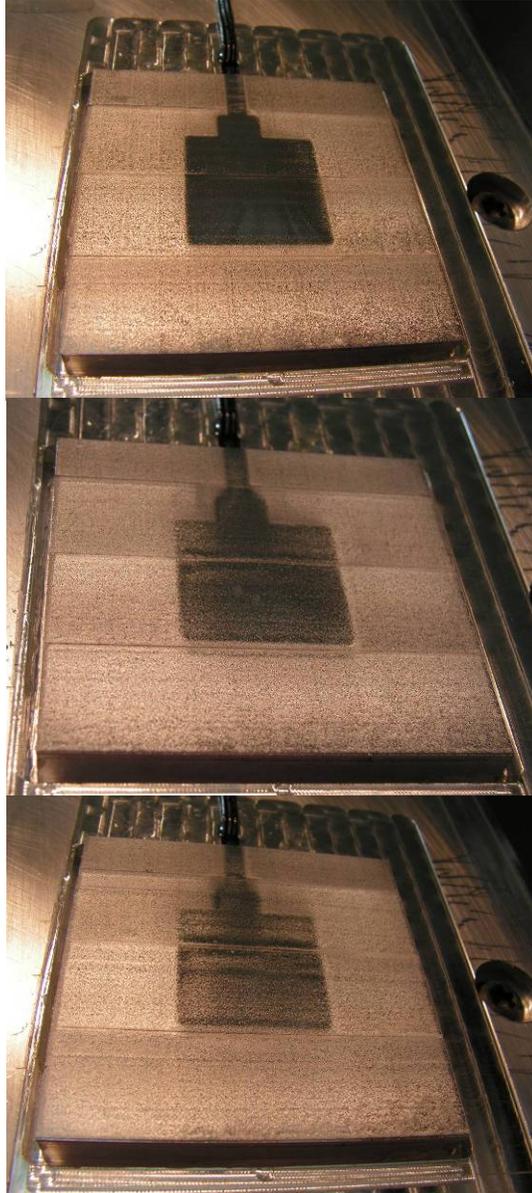


Figure 7: One, four, and eight layers of subsequently bonded aluminum foils on top of the sensor

Calibration and Testing

With the sensor fully embedded and removed from the base plate the sensor is ready for calibration and testing. The calibration and testing of embedded sensors is illustrated through the following example: First, two identical embedded thermal sensors are tested to ensure functionality post-embedding, see Figure 8. Using the linear characteristics of the given sensors, they are calibrated using the average value obtained from the sensor at a given temperature (as measured by an external thermocouple after sufficient time to ensure a steady state temperature reading). Several data points are obtained and plotted to obtain the linear equation associated with each sensor, see Figure 9. Heating the substrate in which each sensor is embedded shows the resulting temperature increase of the sensors in degrees Fahrenheit, see Figure 10. The sensors are ready to be used and tested within a given environment.

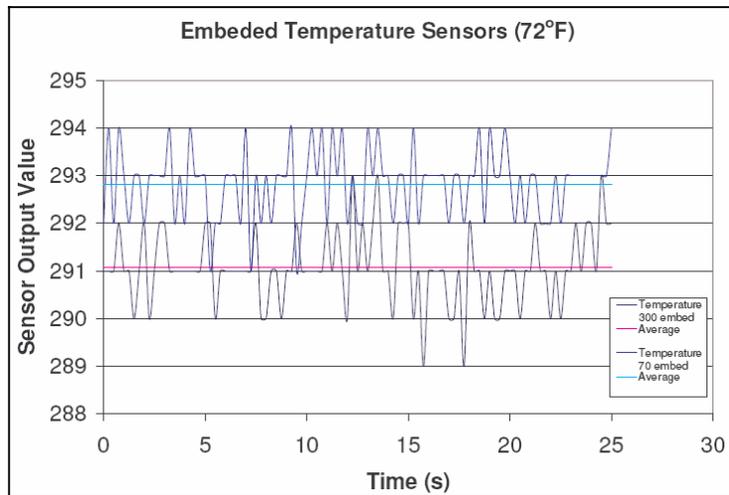


Figure 8: Sensor values post-embedding at 72°F

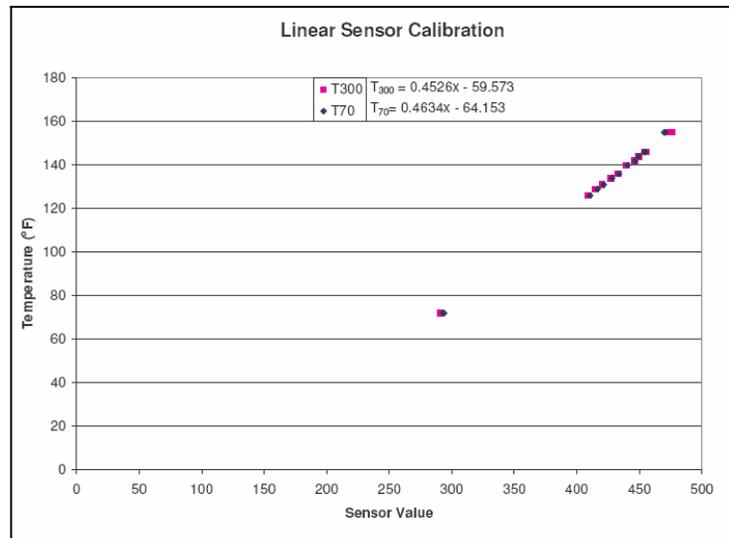


Figure 9: Calibration of linear embedded sensors from 72°F to 155°F

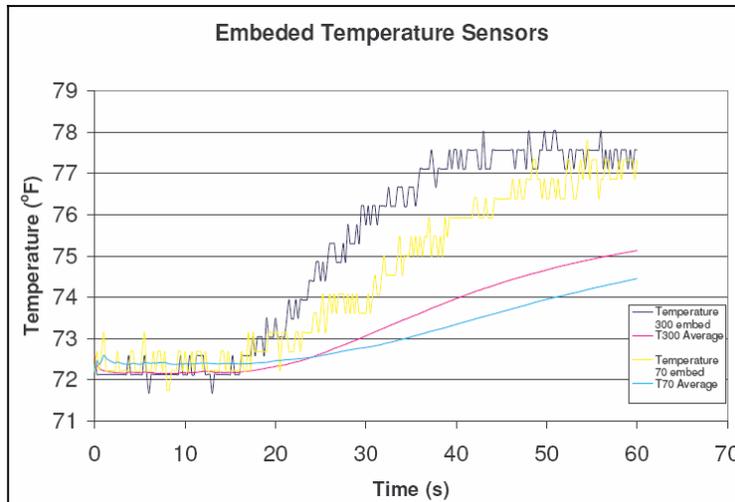


Figure 10: Heating of each substrate results in a subsequent temperature increase

Discussion

Through the use of extensive experimentation at USU, a number of design and manufacturing rules have been developed for embedded structures using UC. The following is a summary of some of these findings.

Build Temperature

As noted earlier the UC process is able to build effectively at or near room temperature, typically between 72°F – 300°F (20°C – 150°C). In order to test the effects of temperature and the stress of UC on embedded sensors, a set of experiments were carried out at room temperature (72°F/20°C) and at a more optimal UC bonding temperature (300°F /150°C). In the experiments the build geometry and sensor type as well as the other operational parameters (weld speed, normal force, and amplitude of vibration) were held constant at their normal parameters (28 ipm, 1750 N, 160 μs respectively.) As per the process denoted earlier, both sensors were tested before embedding to gain a baseline of the respective performance, and similarly tested post-embedding.

The first experiment was conducted at room temperature (72°F/20°C) to determine the general effects (i.e. free from the stresses induced by elevated temperatures, if any) of UC on embedded components. The embedded sensor worked flawlessly, and continued to collect temperature data at regular increments similarly to the pre-embedded state. The only problem associated with the room temperature build was associated to bond strength. Previous studies of the UC process noted degradation of the interlayer weld properties, and were evident during this build by the delamination of the upper layers and poor linear weld density (Janaki Ram et al 2006)

The second experiment conducted at the elevated temperature of 300°F (150°C) was executed to try to improve the inter-layer delamination problem that can occur at lower build temperatures, while also testing the robustness of the sensors. The elevated

temperature resolved the delamination, and resulted in a dense part, and the sensor continued to work flawlessly collecting data commensurate with heating or cooling of the substrate. As a result, all additional research and experimentation associated with embedding is being completed at this more optimal temperature to ensure proper weld density and bonding throughout the UC part.

Bonding and Potting Materials

The bonding of the sensor to the substrate is highly dependent upon the purpose of the sensor. For example, a temperature sensor requires the bonding material to be thermally conductive and electrically nonconductive. Therefore the sensor is placed within the pocket and secured in place using a thermally conductive/electrically nonconductive epoxy.

Initial tests were conducted using a silver based epoxy since the CTE as well as the thermal conductance was similar to the substrate material. The silver based epoxy provided ample thermal conductivity between the temperature sensor and the substrate, but further experimentation and research concluded that the silver epoxy could develop a capacitive charge and has a slight electrical conductivity, which could eventually damage the sensor. Subsequently, an insulating epoxy which included Al_2O_3 (alumina), which has a similar CTE to aluminum, a slightly lower thermal conductivity and provides an electrically insulating barrier was used. The potting epoxy has also changed from the initial experimentation, beginning with a liquid based two part epoxy usually used for potting specimens for polishing, to the alumina-filled epoxy used for bonding the sensors to the substrate.

Welding Recovery over Pockets

One main concern with the embedding of components using UC is creating an effective weld over the pocket (known as recovery). Currently, the first layer over the pocket does not bond to the pocket (since there is not a metal substrate to which the layer can weld). Ensuing layers slowly recover on a layer-by-layer basis and eventually develop proper weld strength, but this can hinder the build when only a thin skin layer is desired to cover the pocket. A few solutions are being explored, but the main process that can assist in the number of layers necessary for effective recovery is build geometry. If the pocket has a dimension less than one tape width, the build can be oriented in such a way that the pocket area is covered by a single tape. As a result the layer is bonded on each side of the pocket with the preceding layers, resulting in a stronger bond and reducing the number of layers needed for recovery. Another method used is “flat-passing” the build every few layers to trim off any excess or “bulging” material over the pocket, which also results in more rapid recovery. Additional methods are also being explored to produce more rapid recovery rates.

Benefits of Commercial Off-The-Shelf Electronics

The sensors used in this exploratory research were commercial off-the-shelf components, which can be connected and controlled through a compatible USB based A/D converter connected to a PC. Some of the advantages of this type of component include:

- Lower cost
- Ready availability – no need to try to “duplicate off-the-shelf items” (Cham et al. 1999)
- Short lead times
- Heritage/reliability/robustness
- Modularity (Multiple sensors with the same size, shape, etc.)
- Standard interfaces (both mechanically and electrically)

Fully functional systems developed from COTS components can be directly embedded into a part, as a result creating a system of plug’n’play reliable, available and affordable devices that can provide the necessary information in real-time. These COTS components do not need to be ruggedized for demanding applications (such as space applications or in other harsh environments) as they are protected by their embedment in aluminum.

Smart Panels Based on Structurally Embedded Electronics

The embedding of USB-based sensors in aluminum provides a foundation for the development of a new class of computer-based platforms. A “smart” panel can be developed based on this technology, which can be used as the basic structure of a modular satellite. The smart panel offers structurally integrated health monitoring sensors, as discussed above. Structural embedding also offers the ability to distribute power and data connections to various locations on the panel, allowing other COTS devices to be interfaced to the panel, or the linking of several “smart” panels to provide a complete system. Most importantly, the research group will embed a small, single-board computer platform directly in the panel, which is responsible for collecting health-monitoring data from the embedded sensors, as well as for facilitating software-based integration of third party devices.

The smart panel concept potentially offers a revolution in the manufacture of small satellites, or similar complex systems. By treating the on-board computer, bus and health monitoring functions as a single, integrated sub-system, much of the complexity of system integration is pushed into the software domain, where, with the support of lightweight middleware (Lyke, et. al 2005) and/or system configuration tools, subsystems can be dynamically “wired” via USB. Rapid integration of a system consisting of COTS components plugged into a smart panel thus becomes feasible.

Conclusion

Research at Utah State University has demonstrated the use of Ultrasonic Consolidation to embed USB based COTS devices in aluminum. The basic process for embedding is: preprocess, fabricate substrate, mill pocket, pot sensor, continue building,

and calibrate and test embedded sensor. The research has exhibited that electronics can be embedded at room temperature, but with some inter-layer delamination between the ultrasonically bonded aluminum layers. Embedding the sensors and electronics at 300°F to overcome the delamination issues resulted in more optimal bonding, and all the embedded sensors used thus far have functioned normally by maintaining linearity over the specified range of the devices. An alumina-filled epoxy is used because the epoxy maintains some thermal conductivity and a CTE similar to that of the aluminum while remaining electrically nonconductive. To ensure sufficient bonding quality over the pocket, proper geometries or recovery techniques must be used. The techniques employed for embedding electronic devices in aluminum set the ground work for “smart” systems development.

Future Work

As the research matures at USU additional techniques, materials and components will be used in the embedding process. Currently USU has embedded suites of sensors in a single build and is working toward embedding heaters and other devices, as well as an embedded USB capable processor which can monitor and control the respective devices lending to a true “smart” system. Additional research is investigating the integration of Direct Write³ (DW) techniques in conjunction with COTS devices to create more versatile and robust systems. Future investigations will also explore other UC parameter combinations to ascertain the quality of embedding at lower temperatures.

Acknowledgements

Support for this project was provided by the National Science Foundation by an STTR grant through MicroSat Systems, Inc. (OII 0512641) and by the State of Utah Centers of Excellence Program (Center for Advanced Satellite Manufacturing).

References

Chua, C. K., Leong, K. F., Lim, C. S., *Rapid Prototyping: Principles and Applications*, 2nd Edition, World Scientific Publishing Co. Pte. Ltd., Singapore, 2003

Cham, J. G., Bailey, S. A., Clark, J. E., Full, R. J., Cutkosky, M. R., *Fast and Robust: Hexapedal Robots via Shape Deposition Manufacturing*, The International Journal of Robotics Research, Vol. 21, No. 10–11, October–November 2002, pp. 869-882

Cham, J. G., Pruitt, B. L., Cutkosky, M. R., Binnard, M., Weiss, L. E., Neplotnik, G., *Layered Manufacturing with Embedded Components: Process Planning Considerations*, Proceedings of DETC99: 1999 ASME Design Engineering Technical Conference September 12-15, 1999, Las Vegas, NV

³ DW is capable of creating various sensors, resistive heating elements, batteries, antennas, custom wiring, and circuits which are key elements in the development of complete “smart” systems (Chen 2004, Mosher 2004, Sampath 2005.)

- Chen, Q., Tong, T., Longtin, J. P., Tankiewicz, S., Sampath, S., Gambino, R. J., *Novel Sensor Fabrication Using Direct-Write Thermal Spray and Precision Laser Micromachining*, Journal of Manufacturing Science and Engineering, Volume 126, November 2004, pp. 830-836
- Janaki Ram, G.D., Yang, Y., George, J., Robinson, C., Stucker, B.E., *Improving Linear Weld Density in Ultrasonically Consolidate Parts*, Solid Freeform Fabrication Symposium, August, 2006, Austin, TX.
- Li, Xiaochun, Prinz, F., *Metal Embedded Fiber Bragg Grating Sensors in Layered Manufacturing*, Journal of Manufacturing Science and Engineering, August 2003, Vol. 125, pp. 577-585
- Li, Xiaochun, *Embedded Sensors in Layered Manufacturing*, Doctoral Dissertation, Stanford University, June 2001
- Li, Xiaochun, *Embedded Fiber Bragg Grating Sensors in Polymer Structures fabricated by Layered Manufacturing*, Journal of Manufacturing Processes, 2003
- Lyke, J., Cannon, S., Fronterhouse, D., Lanza, D., Byers, T. *A Plug-and-play System for Spacecraft Components based on the USB Standard*, 19th Annual AAIA/USU Conference on Small Satellites, 2005
- Malone, E., Lipson, H., *Functional Freeform Fabrication for Physical Artificial Life*, 2004, Ninth Int. Conference on Artificial Life (ALIFE IX), Proceedings of the Ninth Int. Conference on Artificial Life (ALIFE IX), pp.100-105
- Mosher, T., Stucker, B., *Responsive Space Requires Responsive Manufacturing*, 2nd Responsive Space Conference, April 19–22, 2004, Los Angeles, CA
- Ogando, J., *Rapid Prototyping Rocks On*, Design News, 8 July 2002.
- Prodan, T., Amon, C. H., Finger, S., Weiss, L. E., *Shape Deposition Manufacturing for Embedding Electronics and Building Injection Molding Tools*, Student paper, Dept. of Mechanical Engineering and Institute of Complex Engineering Systems, Carnegie Mellon University, Pittsburgh, PA
- Sampath, S., *Novel Concepts in Direct Writing of Electronics and Sensors*, 2005, Center for Thermal Spray Research, State University of New York at Stony Brook, Stony Brook, NY
- Varadan, V. K., Varadan, V. V., *Microsensors, Micromechanical Systems (MEMS), and Electronics for Smart Structures and Systems*, Smart Material Structures, Vol. 9, 2000, pp. 953–972.

Weiss, L. E., *Shape Deposition Manufacturing of Heterogeneous Structures*, Journal of Manufacturing Systems, 1997

Yang, Y., Janaki Ram, G.D., Stucker, B.E., *Process Parameters Optimization for Ultrasonically Consolidated Fiber-Reinforced Metal Matrix Composites*, Solid Freeform Fabrication Symposium, August, 2006, Austin, TX.