# Multi-Material Ultrasonic Consolidation

G.D. Janaki Ram, C. Robinson, and B.E. Stucker
Department of Mechanical and Aerospace Engineering, Utah State University
Logan, UT 84322-4130, USA
Reviewed, accepted September 14, 2006

## Abstract

Ultrasonic consolidation (UC) is a recently developed direct metal solid freeform fabrication process. While the process has been well-demonstrated for part fabrication in Al alloy 3003 H18, including with intricate cooling channels, some of the potential strengths of the process have not been fully exploited. One of them is its flexibility with build materials and the other is its suitability for fabrication of multi-material and functionally graded material parts with enhanced functional or mechanical properties. Capitalizing on these capabilities is critical for broadening the application range and commercial utilization of the process. In the current work, UC was used to investigate ultrasonic bonding of a broad range of engineering materials, which included stainless steels, Ni-base alloys, brass, Al alloys, and Al alloy composites. UC multi-material part fabrication was examined using Al alloy 3003 as the bulk part material and the above mentioned materials as performance enhancement materials. Studies were focused on microstructural aspects to evaluate interface characteristics between dissimilar material layers. The results showed that most of these materials can be successfully bonded to Al alloy 3003 and vice versa using the ultrasonic consolidation process. Bond formation and interface characteristics between various material combinations are discussed based on oxide layer characteristics, material properties, and others.

## Introduction

Ultrasonic Consolidation (UC) is a novel application of ultrasonic welding for fabricating complex three-dimensional (3D) structures from metal foils. The process uses a high frequency ultrasonic energy source to induce combined static and oscillating shear forces within metal foils to produce solid-state bonds and build up a near-net shape part, which is then machined to its final dimensions using an integrated, 3-axis CNC milling machine [1]. UC combines the advantages of additive and subtractive fabrication approaches allowing complex 3D parts to be formed with high dimensional accuracy and surface finish, including objects with complex internal passageways, objects made up of multiple materials, and objects integrated with wiring, fiber optics, sensors, and instruments. Because the process does not involve melting, one need not worry about dimensional errors due to shrinkage, residual stresses and distortion in the finished parts. This will also help overcome the problems of brittle intermetallic formation and immiscibility while dealing with metallurgically incompatible dissimilar material combinations.

One unique aspect of UC is that highly localized plastic flow around embedded structures is possible, resulting in sound physical/mechanical bonding between the embedded material and matrix material, although the exact mechanism by which it is made possible is not yet fully understood [2,3]. This ability can be utilized in a number of ways, including manufacture of fiber-reinforced metal matrix composites with structural fibers for localized stiffening, optical fibers for communication and sensing, shape memory fibers for actuation, or wire meshes for planar or area stiffening. It is possible to simply insert pre-fabricated components (such as thermal management devices, sensors, computational devices, heat pipes, etc.) into machined cavities of the part under construction prior to encapsulation by subsequent material addition.

While, in principle, the UC process can be applied to the manufacture of functionally graded and multi-material compositions [1,4,5], the capabilities of the process are yet to be fully exploited. Practically no published information is available on multi-material UC, with most of the work being carried out on Al alloy 3003 [6]. Successful extension of the process to widely used engineering materials like Fe, Ni, and Cu, and to dissimilar combinations like Al/brass, Al/stainless steel, and Al/Ni, will significantly expand commercial opportunities for ultrasonic consolidation.

In view of the above, in the current work an attempt has been made to explore multi-material ultrasonic consolidation. A number of engineering materials have been tried in combination with Al alloy 3003, used as the bulk part material. This will help identify opportunities and limitations inherent in multi-material UC, and utilize the technology more effectively in high-end applications. Studies were focused on microstructural aspects to evaluate interface characteristics between similar and dissimilar material layers. Bond formation and interface characteristics between various dissimilar material combinations are discussed based on oxide layer characteristics, material properties, and others.

## 2. Experimental Work

### 2.1 Materials

Al-Mn alloy 3003 (nominal composition by wt.%: Al-1.2Mn-0.12Cu) foil (150 μm thick and 25 mm wide) obtained from Solidica, Inc., USA, was used as the bulk part material for all experiments. Deposition experiments were conducted on an Al 3003 base plate (dimensions: 355x355x12 mm) firmly bolted to the heat plate of the Solidica Form-ation UC machine. The materials used for multi-material UC experiments are listed in Table 1. These materials will be referred to as dissimilar or second materials hereafter. All these second materials were in the form of foil (except SiC (fiber) and stainless steel 304 (wire mesh)). Since the machine does not facilitate automatic feeding of multiple foil materials simultaneously, the second materials used in this study were not fed through the machine's foil feeding mechanism, but were manually placed, while the bulk part material Al alloy 3003 foil was automatically fed by the machine in the usual manner.

Table 1. Materials used for multi-material UC and their forms.

| Material | Nominal Composition (Wt.%)/Thickness |
|---|---|
| Al alloy 3003 (Al 3003) | Al-1.2Mn-0.12Cu, 150 μm thick foil |
| Al alloy 2024 (Al 2024) | Al-4.5Cu-1.5Mg, 225 μm thick foil |
| SiC fiber | 100 μm diameter |
| Metpreg | $Al_20_3$ short fiber reinforced Al matrix composite tape, 325 μm thick |
| Inconel 600 (IN 600) | Ni-15Cr-8Fe-0.15C, 200 μm thick foil |
| Brass | Cu-30Zn, 75 μm thick foil |
| Stainless steel AISI 347 (SS 347) | Fe-18Cr-11Ni-1Nb-0.08C, 150 μm thick foil |
| Stainless steel AISI 304 wire mess (SS mesh) | Fe-18Cr-8Ni-0.08C, 25 μm diameter wire |

**2.2 Deposition experiments**

Deposition experiments were conducted in such a way that they facilitate study of bonding between Al 3003 and a second material, and vice versa, following one or both of the following methods:

***Method 1 (direct welding):*** Method 1 deposition procedure consisted of depositing a few layers of Al alloy 3003 (on an Al alloy 3003 base plate) and then placing a layer of a given second material on the Al 3003 deposit, and running the ultrasonic head directly over the second material layer. This method was used to bond a single layer of second material or as many as three layers of second material, with each layer individually being welded to the previous layer.

***Method 2 (indirect welding):*** Method 2 deposition procedure consisted of depositing a few layers of Al alloy 3003 foil (on an Al alloy 3003 base plate) and then placing a given second material layer on top of the previously deposited layer, and then using the automatic tape feeder to lay Al 3003 over the second material while running the ultrasonic head over the layers, thus simultaneously bonding the top Al 3003 layer to the second material, as well as the second material layer to the Al 3003 substrate in one pass.

In the case of SiC fibers, the experimental procedure consisted of: i) depositing a layer of Al 3003 on top of an Al alloy 3003 base plate, ii) placing a SiC fiber on the top of the deposited Al 3003 layer and holding it in place using a custom-designed fixture, and iii) depositing a layer of Al alloy 3003 on the pre-placed fiber. More details on fiber embedment experiments are presented elsewhere in these proceedings by Yang et al. [7].

The process parameters used for all the deposition experiments are listed in Table 2. These parameters were found to ensure good bonding between Al alloy 3003 foils. However, no attempts were made in this study to optimize process parameters for maximizing bond quality between Al 3003 and any of the second materials.

**2.3 Metallography**

All the deposits were metallographically examined to assess the bond quality. Samples corresponding to longitudinal and transverse sections were extracted from each of the deposits and were prepared for microstructural study following standard metallographic practices. Microstructural observations were conducted on as-polished samples using optical and scanning electron microscopes.

Table 2. Process parameters used for multi-material UC experiments.

| **Material** | **Amplitude (μm)** | **Speed (mm/s)** | **Force (N)** | **Temperature (°F)** |
|---|---|---|---|---|
| All material combinations except Al 3003-SiC fiber | 16 | 28 | 1750 | 300 |
| SiC fiber | 20 | 34 | 1550 | 150 |
| | Fiber was oriented at 90° to the welding direction. | | | |

## 3. Results and Discussion

Fig.1 shows the microstructure of an ultrasonically consolidated Al alloy 3003 deposit consisting of four layers. The dark regions seen along the layer interfaces are the unbonded regions. During ultrasonic welding, the mating surfaces come in contact with each other at surface asperities under the influence of an applied normal force. As noted earlier, the combination of normal and oscillating shear forces results in generation of dynamic interfacial stresses between the two mating surfaces. The stresses produce elastic-plastic deformation of surface contact points, which breaks up the oxide film, producing relatively clean metal surfaces under intimate contact, establishing a metallurgical bond. However, this process leaves some unbonded regions along the interface. These unbonded areas arise due to: (i) lack of complete contact between mating surfaces due to surface roughness and/or entrapped air, (ii) persistence of surface oxide layers preventing intimate nascent metal contact, and (iii) accumulation of removed surface oxides at localized regions along the interface. For these reasons, 100% bonding is difficult to achieve in ultrasonic welding. Preliminary microstructural results pertaining to each of the dissimilar combinations examined in the present work are discussed below under separate headings.

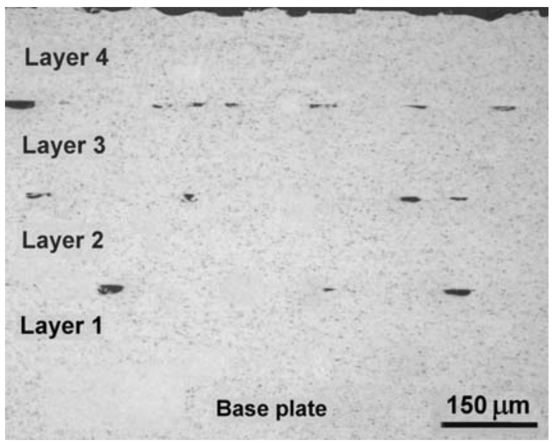
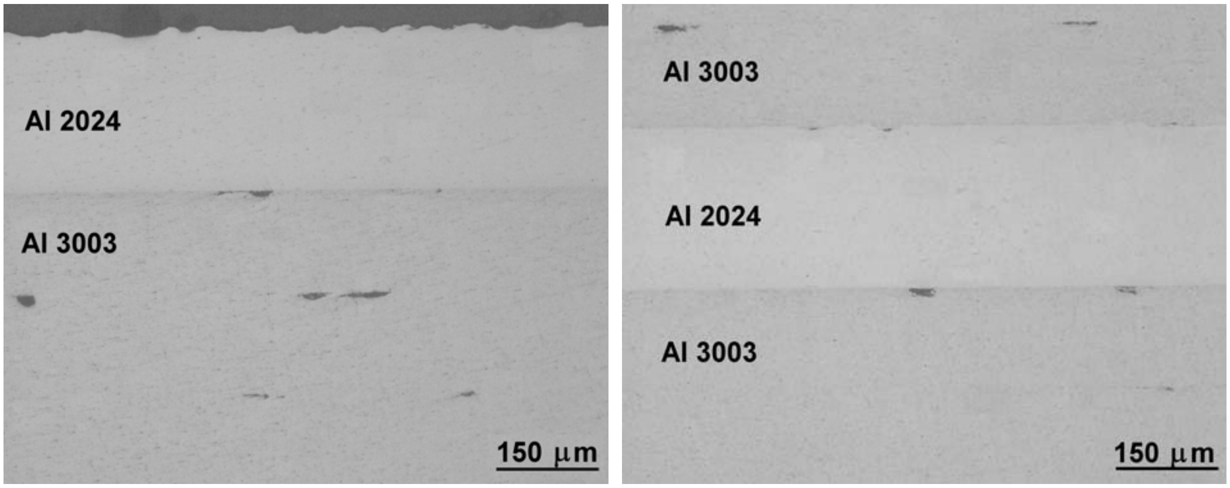



Fig.1. Optical microstructure of Al alloy 3003 UC deposit (as-polished, longitudinal section).

### 3.1 Al 3003/Al 2024

Al 3003/Al 2024 deposits were made using both the direct and the indirect welding methods detailed in Section 2.2. Fig.2 shows the optical microstructures of these deposits. These pictures show that Al 3003 can be very well bonded to Al 2024 and vice versa. It is interesting to note that Al 2024 was very well bonded to Al 3003, even when it is not directly welded (Fig.2b). Further, Al 3003/Al 2024 bonding appeared to be as good as that of Al 3003/Al 3003. Thus the current work shows that multi-material parts can be successfully fabricated out of Al-Mn and Al-Cu alloys employing the UC process, allowing one to take advantage of the superior strength characteristics of Al-Cu alloys and the superior corrosion resistance characteristics of Al-Mn alloys.

Al 2024 to Al 2024 bonding was not examined in the current work. In an earlier study Kong et al. reported inferior weld quality in ultrasonically consolidated Al-Mg alloy 6061 [8], which was attributed to difficulties in oxide layer removal due to the presence of MgO in the oxide layer of alloy 6061. Alloy 2024 also contains a considerable amount of Mg (1.5 wt.%). Therefore, Mg might present similar difficulties during ultrasonic welding of alloy 2024 to itself. The presence of Mg, however, did not result in any problems during ultrasonic welding of alloy 2024 to alloy 3003, which contained very little Mg (0.05 wt.% max.).




(a) (b)

Fig.2. Optical microstructures of Al 3003/Al 2024 deposits: (a) Al 2024 layer directly welded to Al 3003, (b) Al 2024 layer sand witched between Al 3003 layers (indirectly welded).

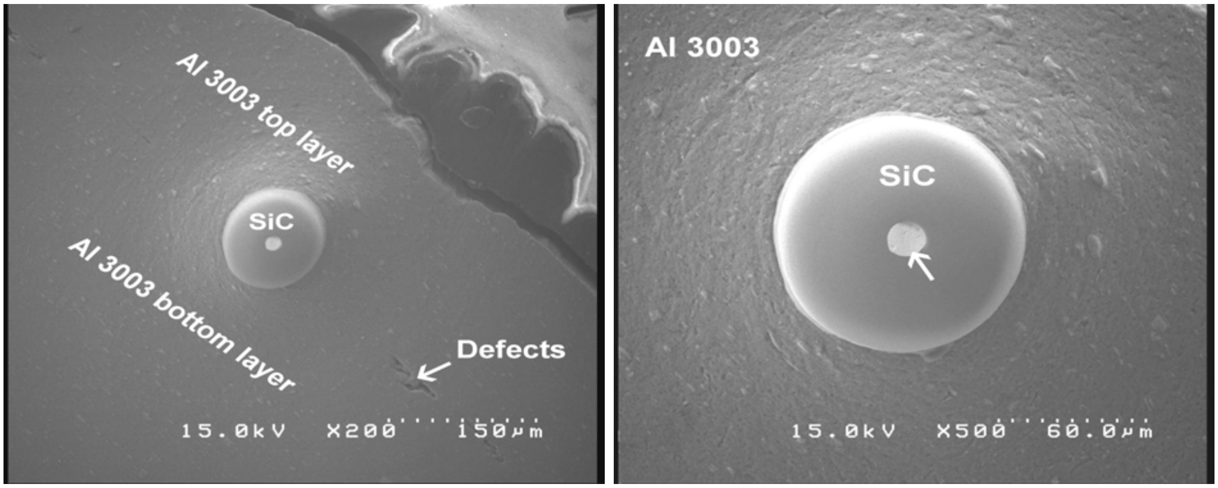
**3.2 Al 3003/SiC**

Fig.3 shows the SEM microstructures of Al 3003/SiC deposits. The SiC fiber used in this study has a tungsten core (about 10 μm dia). For successful embedment of fibers, there must be adequate plastic flow of the matrix material to close the gaps that were created by placing the fiber between the layers. As can be seen in Fig.3, there is extensive plastic flow around the fiber, evidenced by flow lines in a circular pattern around the fiber (Fig.3b), resulting in excellent fiber embedment. Similar success was reported earlier by Kong et al. with shape memory alloy fibers in Al 3003 matrix [4]. The authors, through detailed elemental mapping studies, concluded that the matrix and the embedded fiber were not chemically or metallurgically bonded. Similarly in the present case, bonding between SiC fiber and Al 3003 matrix is expected to be physical/mechanical, rather than chemical/metallurgical.

Studies thus show that SiC fibers can be successfully embedded in an Al 3003 matrix, making UC a viable process for fabrication of intricate parts out of continuous fiber reinforced metal matrix composites [7].

**3.3 Al 3003/Metpreg**

Fig.4 shows the SEM microstructures of directly welded Metpreg to Al 3003. As mentioned earlier, Metpreg is a commercially available $Al_2O_3$ short fiber reinforced aluminum matrix composite. As can be seen, the Metpreg layer was very well bonded to the Al 3003 substrate with a featureless interface. On the other hand, when the Metpreg layer was indirectly welded, the Al 3003 top layer was bonded very well with the Metpreg layer, but the Metpreg layer was not well bonded to the Al 3003 bottom layer. These observations are illustrated in Fig.5.

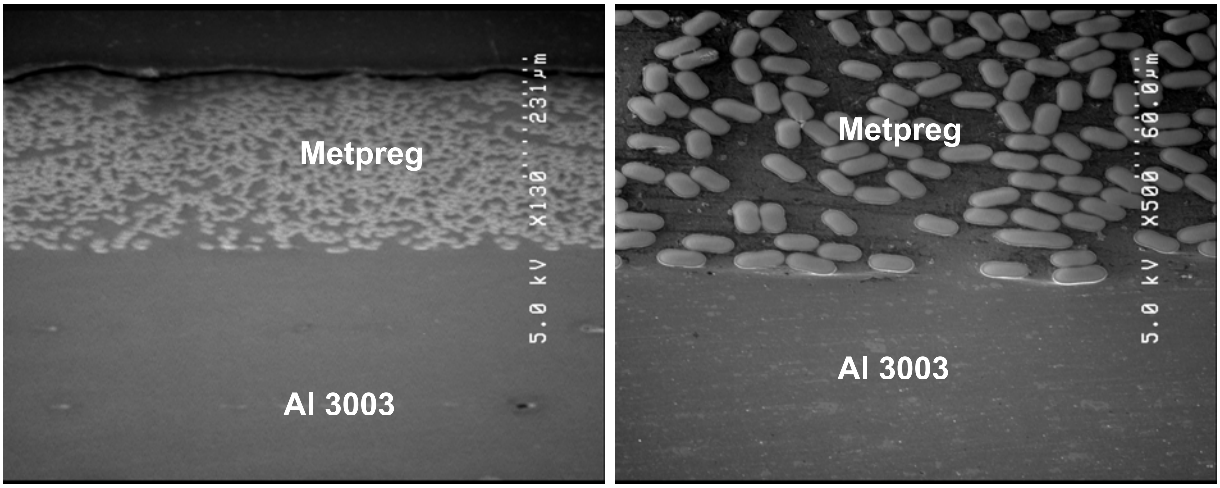



(a) (b)

Fig.3. SEM microstructures of Al 3003/SiC: (a) SiC fiber embedded between Al 3003 layers, (b) SiC fiber at a higher magnification showing metal flow lines in a circular pattern. Arrow shows tungsten core.

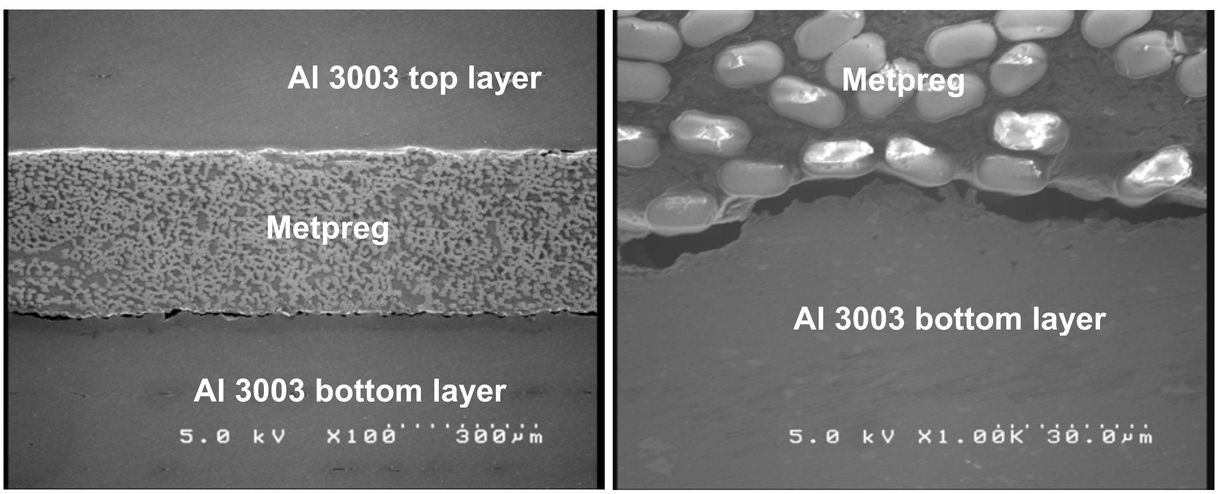
The discrepancy can be explained as follows. When the ultrasonic sonotrode is passed on the Al 3003 top layer, much of the available ultrasonic energy acts at the Al 3003 top layer/Metpreg interface (therefore producing good bonding), as it is located directly beneath the sonotrode. Compared to this, the amount of ultrasonic energy that reaches or acts at the Metpreg/Al 3003 bottom layer interface would be much less. This makes oxide layer removal and/or plastic deformation difficult at the Metpreg/Al 3003 bottom layer interface, leading to poor bonding. In this context, one might argue that the same should be the case with indirectly welded Al 3003/Al 2024. However, indirect welding did not result in poor bonding at the Al 2024/Al 3003 bottom layer interface (Fig.2b). This is understandable when we consider that: i) Al 2024 foil (225 µm) is considerably thinner than the Metpreg foil (325 µm), and ii) Metpreg is significantly stronger and stiffer than Al 2024.

The present work thus shows that it is possible to ultrasonically consolidate Al metal matrix composite layers and Al 3003 layers in various combinations with excellent interface characteristics adopting the direct welding methodology. This capability can be utilized in many ways. For example, lighter, stronger, and stiffer Al parts can be produced by embedding metal matrix composite laminates. Further, fabrication of functionally graded Al metal matrix composite parts is a possibility. Fabrication of composite parts using metal matrix composite tapes is yet another possibility. Although bonding between Metpreg/Metpreg was not examined in the current work, it is expected that this material combination can be ultrasonically welded, at least up to a certain volume fraction of the reinforcing phase. Plastic deformation due to ultrasonic excitation of the softer Al matrix of the mating composite surfaces is expected to result in necessary readjustments at the interface, producing sound matrix/matrix metallurgical bonding.




(a) (b)

Fig.4. SEM microstructures of directly welded Al 3003/Metpreg: (a) Metpreg layer very well bonded to Al 3003 layer, (b) Al 3003/Metpreg interface at a higher magnification.




(a) (b)

Fig.5. SEM microstructures of indirectly welded Al 3003/Metpreg: (a) Metpreg layer sandwiched between Al 3003, (b) Al 3003 bottom layer/Metpreg interface at a higher magnification.

### 3.4 Al 3003/IN 600

The interface microstructure of the directly welded Al 3003/IN 600 is shown in Fig.6. As can be seen, IN 600 was well bonded to Al 3003. The interface is free of physical discontinuities. The indirect welding method also produced good bonding between an Al 3003 top layer/IN 600 (Fig.7a). The interface microstructure is quite similar to that shown in Fig.6. However, numerous unbonded regions were observed at the IN 600/Al 3003 bottom layer interface (Fig.7b). As explained in section 3.3, insufficient ultrasonic energy is likely the reason for this, rather than intrinsic difficulties in bond formation.

While IN 600 appears to be well bonded to Al 3003, it is necessary to examine the interface in greater detail since Ni and Al can form intermetallic compounds, which can affect the bond quality. Nevertheless, the current work shows that IN 600 can be ultrasonically bonded to Al 3003 and vice versa, proving the combination viable for multi-material part fabrication using ultrasonic consolidation.

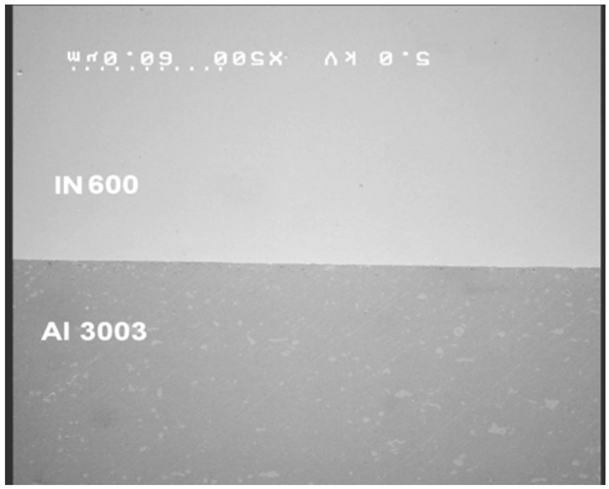
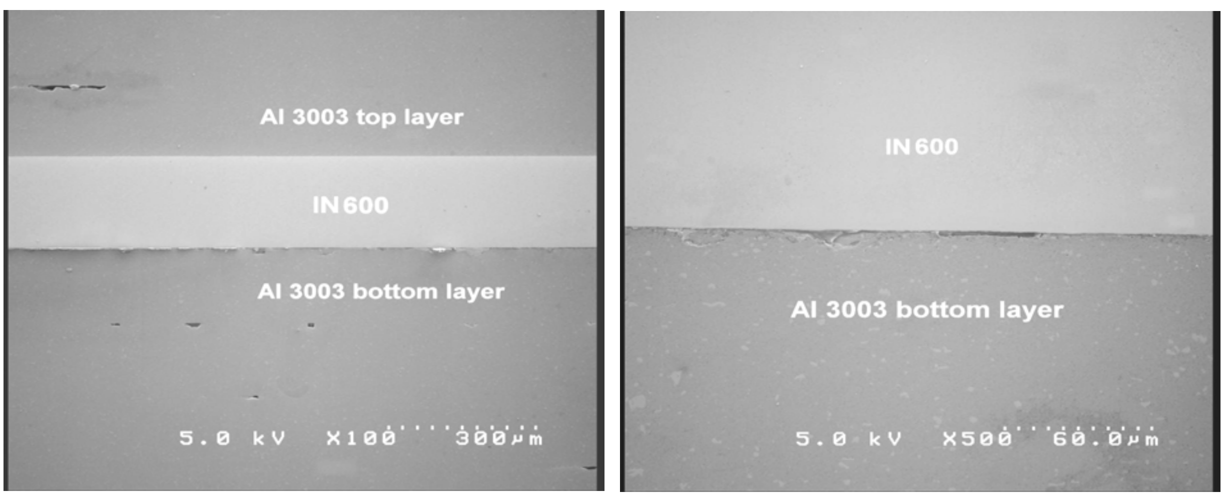



Fig.6. SEM microstructure of directly welded Al 3003/IN 600.




(a) (b)

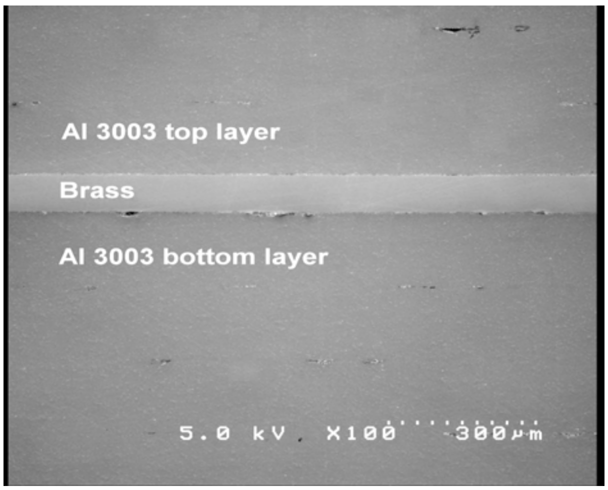
Fig.7. SEM microstructures of indirectly welded Al 3003/IN 600: (a) IN 600 layer sandwiched between Al 3003 layers, (b) Al 3003 bottom layer/IN 600 interface at a higher magnification showing the interfacial defects.

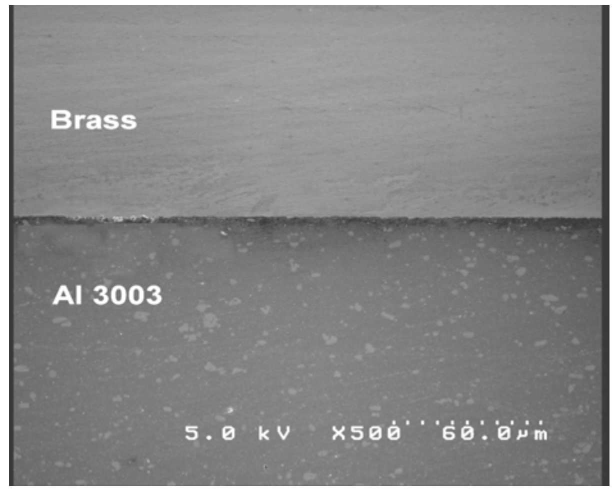
**3.5 Al 3003/Brass**

Experiments with Al 3003/brass combinations were conducted in two ways. In one method, the standard indirect method was used. The interface microstructures of this deposit are shown in Fig.8. As can be seen, the brass layer was not well bonded to the Al 3003 layers. The

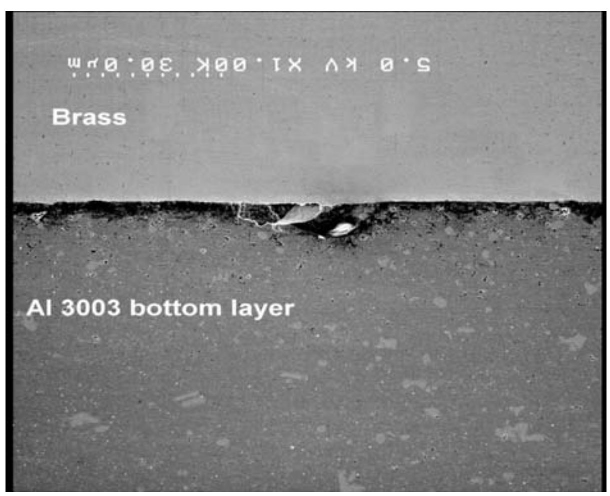
Al 3003 top layer/brass interface (Fig.8b) looked better compared to the brass/Al 3003 bottom layer interface (Fig.8c), although both interfaces were not tight and contained numerous interfacial defects.

In another method, three layers of brass were deposited one by one using the direct method of bonding. The microstructures of this deposit are shown in Fig.9. Again, the brass layer was not well-bonded to the Al 3003 substrate (Fig.9b). However, there was reasonable bonding between the brass layers (Fig.9a and 9b).



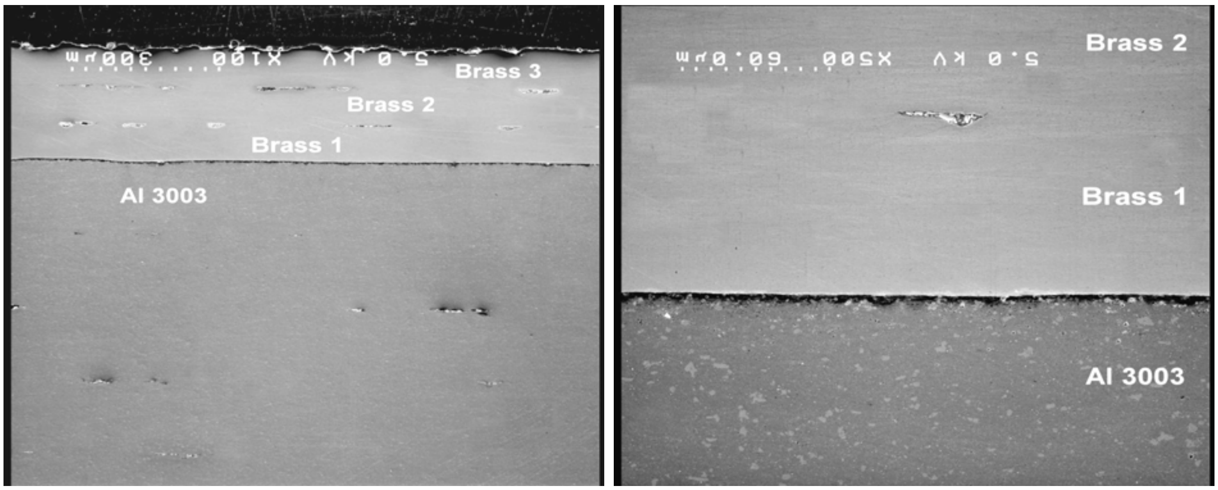

(a) (b)




(c)

Fig.8. SEM microstructures of Al 3003/brass: (a) Brass layer sandwiched (indirectly welded) between Al 3003 layers, (b) Al 3003 top layer/brass interfaces at a higher magnification, (c) Al 3003 bottom layer/brass interfaces at a higher magnification.

The reason for the lack of bonding between Al 3003 and brass layers was not clear. It may be noted that both Cu and Zn, the main constituent elements in brass, can be ultrasonically welded to Al, as shown by earlier investigators [9,10]. Therefore, brass can be expected to be ultrasonically weldable to alloy 3003. Although the bonding between brass and alloy 3003 requires further characterization, the current work shows that brass layers can be ultrasonically welded to themselves, adding to the list of materials for part fabrication with ultrasonic consolidation.




(a) (b)

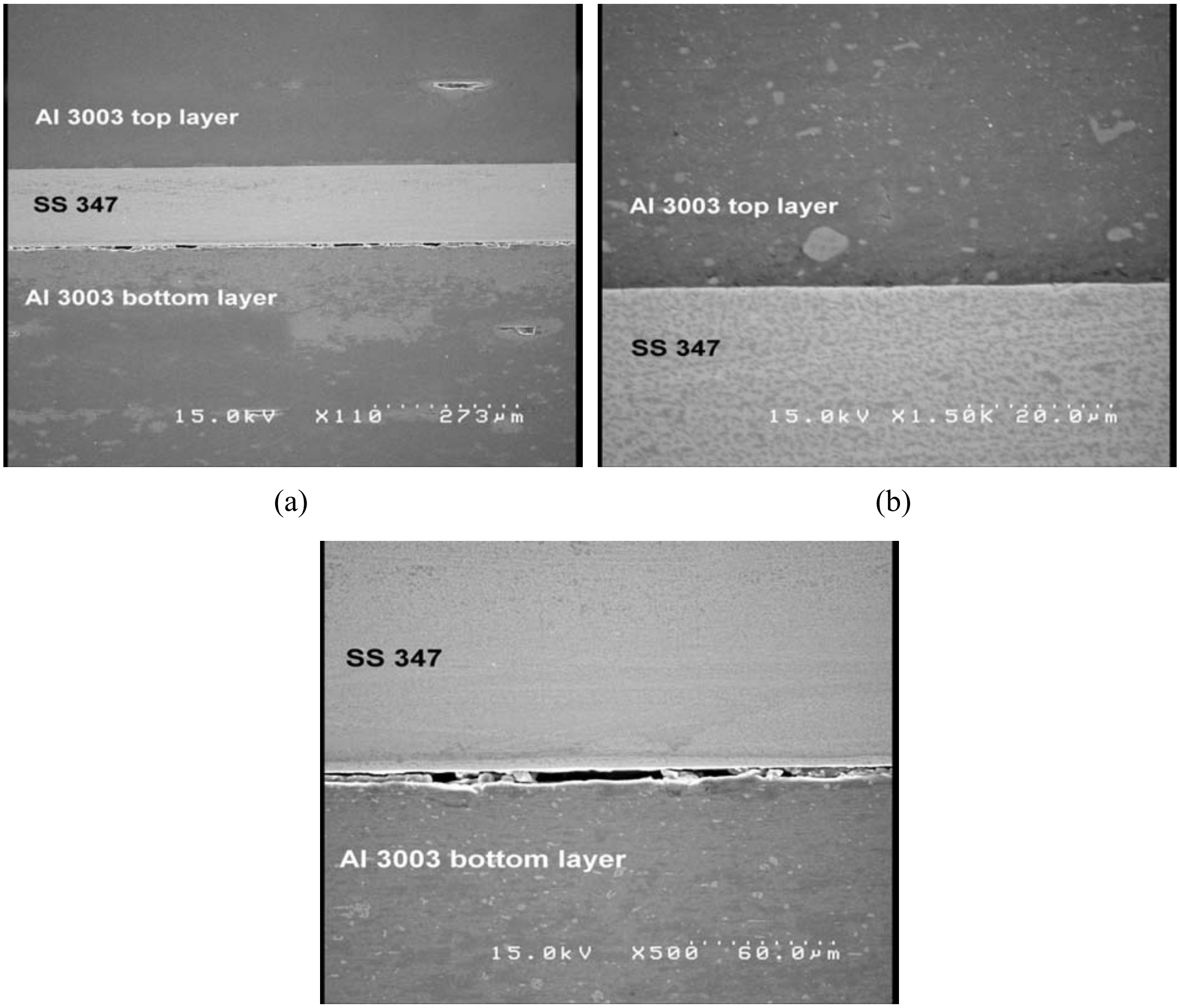
Fig.9. SEM microstructures of directly welded Al 3003/brass: (a) Three layers of brass over Al 3003, (b) Al 3003/brass interface at a higher magnification.

**3.6 Al 3003/SS 347**

Experiments with the Al 3003/SS 347 combination were conducted in two ways. In one method, the standard indirect method was used. The interface microstructures of this deposit are shown in Fig.10. The Al 3003 top layer/SS 347 interface (Fig.10b) looked tight without any large physical discontinuities. Further microstructural studies are required to confirm whether the SS 347 layer is truly metallurgically bonded to the Al 3003 top layer. In contrast, the SS 347/Al 3003 bottom layer interface (Fig.10c) showed wide gaps and a total absence of bonding, which is attributable again to a lack of sufficient ultrasonic energy at the interface.

In another method, three layers of SS 347 were individually bonded on the top of an Al 3003 deposit using the direct deposition method. The first layer stuck well to the Al 3003 substrate. The microstructure at the interface of Al 3003/SS 347 is shown in Fig.11. As can be seen, the interface is flat and even, but the method did not result in satisfactory metallurgical bonding between SS 347 and Al 3003. Also, the method did not result in any bonding between SS 347 layers, resulting in the top two SS 347 layers completely coming off the deposit.

Based on the experiments conducted in this study, it was not clear whether SS 347 can be ultrasonically welded to itself and to Al 3003. Nevertheless, considering the reasonably good characteristics of the Al 3003 top layer/SS 347 interface (Fig.10b), it appears that SS 347 is potentially weldable to Al 3003.




(a) (b)

(c)

Fig.10. SEM microstructures of indirectly welded Al 3003/SS 347: (a) SS 347 layer sandwiched between Al 3003 layers, (b) Al 3003 top layer/SS 347 interface at a higher magnification, and (c) SS 347/Al 3003 bottom layer interface at a higher magnification.

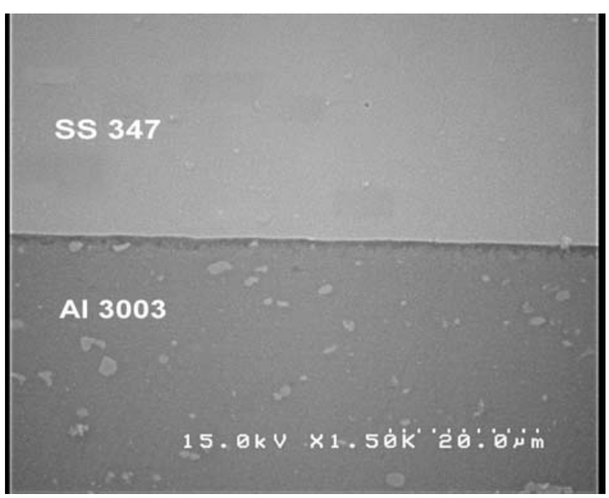
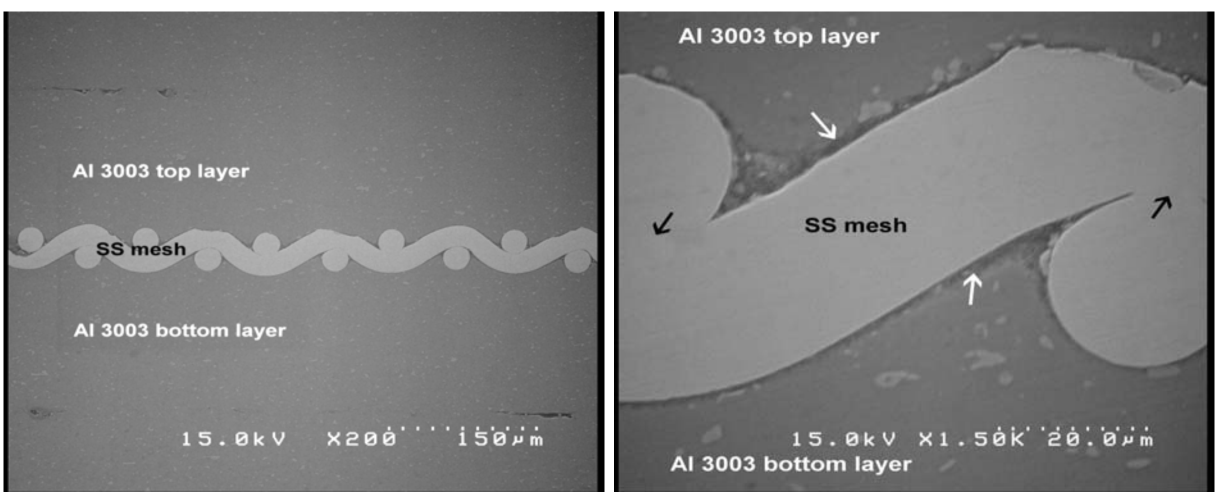



Fig.11. SEM microstructure at the interface of directly welded Al 3003/SS 347.

### 3.7 Al 3003/SS Mesh

Experiments involving Al 3003/SS mesh consisted of using the direct method by depositing the mesh and running the ultrasonic head over it and then applying another layer of Al 3003 on top of the mesh and directly welding the Al 3003. The SEM microstructures of the deposit thus made are shown in Fig.12. As in the case for fiber embedment, plastic flow of the matrix material is critical for successful embedment of the mesh. Microstructural observation revealed excellent metal flow into the gaps of the SS mesh between the Al 3003 layers, resulting in good physical/mechanical bonding between the Al 3003 matrix and SS mesh. Also, passage of the ultrasonic head using the standard, normal pressure over the mesh did not damage the original wire weaving arrangement of the mesh (Fig.12a). Further, it was observed that the wire elements of the mesh were metallurgically bonded to their neighbors. This can be seen in Fig.12b (black arrows), where the circular wire cross-sections present a featureless interface with the sine wave-like horizontal wire. This indicates that SS 304 can be ultrasonically bonded to itself and, therefore, it can be used for part fabrication with ultrasonic consolidation. However, the SS 304 mesh was not metallurgically bonded to the Al 3003 matrix, as evidenced by a clearly discernible narrow physical gap that existed between Al 3003 and SS mesh (shown by white arrows in Fig.12b).

The current work thus shows stainless steel wire meshes can be successfully embedded in Al 3003 parts for area stiffening and other purposes. Such a task would be quite difficult, if not impossible, with conventional manufacturing methods. Although metallurgical bonding was not demonstrated between SS 304 mesh and Al 3003, the embedding capability of the process results in a physically intimate bond, where the well-embedded wire mesh can serve its intended function very well, even in the absence of true metallurgical bonding.




(a) (b)

Fig.12. SEM microstructures of Al 3003/SS mesh: (a) SS mesh embedded between Al 3003 layers, (b) Al 3003/SS mesh interface at a higher magnification. The featureless interface between SS 304 wire elements is shown by black arrows, and the interfacial defects between Al 3003/SS mesh are shown by white arrows.

### 3.8 Multi-Material Ultrasonic Consolidation

Of the material combinations studied in the current work, only two combinations, Al 3003/brass and Al 3003/SS, appeared to be problematic. The lack of bonding in these cases is not entirely understood, but may be due to the fact that these alloys are noted for their corrosion resistance and the mechanisms responsible for inhibiting corrosion may also inhibit metallurgical bonding. It is likely, however, that bonding could be improved through more effective deposition techniques. Further, more detailed microstructural and microchemical characterization of the interfaces is necessary for comprehensively assessing the bond quality. It should be noted, however, that the current deposition and characterization procedures were sufficient for a preliminary assessment of the process potential for multi-materials part fabrication and served the purpose of qualifying certain materials of interest for small satellite fabrication, as was the primary purpose of the experiments in the first place.

Another important aspect that is missing in this study is process parameter optimization. In the current work, process parameters were not fine-tuned to maximize bonding between Al 3003 and the second materials. Each material combination requires a unique set of process parameters for achieving optimal bonding because of the varying physical, chemical and mechanical characteristics of the materials. Determination of such process parameter combinations necessitates rigorous experimentation with parameters, which is a very time-consuming task. When a right combination of process parameters is chosen for each material combination, it may be possible to achieve better results than the ones presented in this work.

Finally, the current work amply demonstrates that multi-material parts can be successfully fabricated using the ultrasonic consolidation process. It shows that materials with widely differing physical, chemical and mechanical properties can be ultrasonically welded with excellent interfacial characteristics. The ultrasonic consolidation process, therefore, is not limited to Al 3003 for part fabrication, but can build parts in a wide range of engineering materials. This flexibility in terms of part material in combination with the multi-material capabilities opens up tremendous opportunities for the ultrasonic consolidation process.

## 4. Summary

Fabrication of multi-material parts presents a significant challenge. In this context, the ultrasonic consolidation process, by virtue of its inherent process characteristics, is quite promising. The current work examines the capacities of the process for fabrication of multi-material parts. A number of engineering materials have been tried in combination with Al alloy 3003, used as the bulk part material. Studies show that Al-Cu alloys, Al matrix composites, and Inconel 600 can be ultrasonically welded to Al alloy 3003 and vice versa with excellent interfacial characteristics. Successful embedment of SiC fibers and AISI 304 wire meshes into an Al alloy 3003 matrix was also demonstrated. AISI 347 stainless steel and brass could not be welded well to Al alloy 3003 using the parameters chosen for this study. However, there are indications that better results can be achieved in these cases with the right process parameters. Overall, the current work shows that multi-material part fabrication out of materials with widely differing physical, chemical and mechanical characteristics is more than a mere possibility with ultrasonic consolidation, and that the process is not limited to Al 3003 for part fabrication and can successfully build parts in a wide range of engineering materials.

**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**

1. D.R. White, Ultrasonic consolidation of aluminium tooling, *Advanced Materials and Processes*, Vol. 161, 2003, 64-65.
2. C. Doumanidis and Y. Gao, Mechanical modeling of ultrasonic welding, *Welding Journal*, Vol. 83(4), 2004, 140s-146s.
3. C.Y. Kong, R.C. Soar, and P.M. Dickens, Ultrasonic consolidation for embedding SMA fibres within aluminium matrices, *Composite Structures*, Vol. 66, 2005, 421-427.
4. T. Wohlers, *Wohlers Report 2003*: Rapid Prototyping and Tooling State of the Industry Annual Worldwide Progress Report, Fort Collins, CO, Wohlers Associates, Inc.
5. Y. Hu, G.M. Fadel, V.Y. Blouin, and D.R. White, Optimal design for additive manufacturing of heterogeneous objects using ultrasonic consolidation, *Virtual and Physical Prototyping*, Vol.1(1), 2006, 53-62.
6. C.Y. Kong, R.C. Soar, and P.M. Dickens, Optimum process parameters for ultrasonic consolidation of 3003 aluminium." *Journal of Materials Processing Technology*, Vol. 146, 2004, 181-187.
7. Y. Yang, G.D. Janaki Ram, and B. Stucker, Process parameters optimization for ultrasonically consolidated fiber-reinforced metal matrix composites, Solid Freeform Fabrication Symposium, Austin, TX, 2006.
8. C.Y. Kong, R.C. Soar, and P.M. Dickens, Characterization of aluminium alloy 6061 for the ultrasonic consolidation process, *Materials Science and Engineering A*, Vol. A363, 2003, 99-106.
9. H.P.C. Daniels, Ultrasonic welding, *Ultrasonics*, 1965, 190-196.
10. R.L. O'Brien, Welding Processes, in *Welding Handbook*, Vol.2, 8th ed., 1991, American Welding Society, Miami.