Further Exploration of Multi-Material Fabrication Capabilities of Ultrasonic Consolidation Technique

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Abstract

The increasing interest in engineering designs involving parts with multiple materials, and function specific members has placed more demand for technologies to fabricate such parts. This work discusses results of further exploration of multi-material freeform fabrication using ultrasonic consolidation. Various combinations of materials, including Titanium, Silver, Tantalum, Aluminum, Molybdenum, stainless steel, Nickel, Copper, and MetPreg have been studied. Some were found to be effective as a suitable intermediate layer between difficult to join materials. Elemental Boron particles were added *in situ* between selected materials to modify the bonding characteristics. Microstructures of deposits were studied to evaluate bond qualities. Results show evidence of good bonds between various combinations of materials, thus illustrating increasing potential for multi-material freeform fabrication using ultrasonic consolidation.

1. Introduction

Ultrasonic consolidation is a solid-state fabrication process that combines ultrasonic metal welding and layered manufacturing techniques to produce three-dimensional freeform objects. The process uses the power of high frequency ultrasonic vibration at low amplitudes to bond thin foils of materials to form solid objects. It combines normal and oscillating shear forces on mating foils and the resulting friction forces between the materials to fracture and displace surface oxides from the materials. The exposed atomically clean surfaces are then brought into direct contact under modest pressure and temperatures that are less than half of the melting points of the materials. The materials are thus metallurgically bonded [1]. Fractured oxides and surface impurities in the materials are distributed in the bond zone. The process combines the layer-by-layer addition of foils with contour milling using the integrated 3-axis CNC machining facilities to produce desired component geometry. It is therefore both an additive and subtractive process. Fabrication involves the generic freeform fabrication additive process chain in which a solid CAD model is numerically sliced and the thin layers sequentially sent to the fabricating machine to build the part from bottom up. Apart from removing the substrate upon which the deposition is made after fabrication is completed, no further machining of the part is required, making it a near-net shape fabrication. If the substrate is part of the final component, it is net shape fabrication.

Some notable advantages of the solid state UC process are as follows [1].

- No high-temperature process-associated safety hazards.
- No atmospheric control is required.
- As low temperature is involved and the volume of material affected is small, less energy is needed.
- Embrittlement, residual stress, distortion and dimensional changes are greatly reduced with the low temperature processing.

The UC machine consists of a welding horn, also known as a sonotrode, that exerts a normal force and the oscillatory high-frequency vibration on the materials to be welded. Welding takes plate on a substrate fixed on a heated plate. The UC machine is designed for automatic foil material feeding, but materials can also be fed manually. Figure 1 shows the schematic view of the ultrasonic consolidation process. The primary process parameters are vibration amplitude, temperature, welding speed, and normal force [2]. Other parameters that can affect weld qualities include sonotrode roughness, material surface finish [3], and side-by-side foil positioning accuracy with respect to the automated material feed system [4].

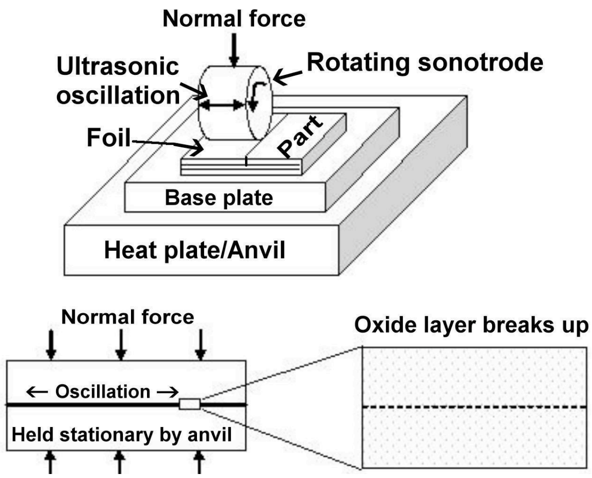


Figure 1: Schematic of UC process

Ultrasonic consolidation is applicable for rapid tooling for injection molding, extrusion, vacuum forming tools and others. It is also been used for fabricating tools with conformal cooling channels [1]. Previous work have demonstrated other potential applications of UC, which include honeycomb structures [5], embedding shape memory alloy (SMA) fibers and silicon carbide fibers in aluminum matrices [6-9], and embedded electronics [10]. While the process has been widely used for single material fabrication with aluminum alloys, only a few researchers have demonstrated its capabilities for multiple material fabrications. The multi-materials capabilities of UC was demonstrated by Janaki Ram *et al.* [11] in their work in which copper, brass, nickel, inconel 600, AISI 347 stainless steel, stainless steel AISI 304 wire mesh, MetPreg, and aluminum alloy 2024 were individually welded to aluminum 3003 H18 materials. Domack *et al.*, also in their work [12], demonstrated the capability of UC for graded materials composition fabrications using titanium and nickel alloys. In this present work, the capabilities of UC to fabricate multi-material structures are further explored. Suitable combinations of Molybdenum, Tantalum, Nickel, Stainless Steel 316L, Silver, MetPreg, Copper, Aluminum 1100-O, Aluminum 3003 H18, and Aluminum 6061-O, were bonded using aluminum alloy 3003-H14 and Aluminum alloy 6061-T6 substrates. Boron powder was added *in situ* for some of the material combinations.

Engineers and designers desire to harness the benefits of combining a variety of function-specific materials where they are needed, and the geometrical complexities offered by the UC process to fabricate these structures. The applications of multi-material functional structures are diverse, including surface protection with corrosion or wear resistant materials, radiation shielding, and combining electrical insulators with highly conductive materials for use in aerospace, automobile, ship building, nuclear, electronics, industrial machineries and other industries.

2. Experimental Work

A Solidica Formation™ machine was used for the experimental work. Although the machine has capability for automatic foil feeding, all foils used were manually fed except aluminum 3003 foils. Materials of 40x20mm size of variable height, depending on the number of foils and their thicknesses, were deposited on the Al 3003 and Al 6061 substrate materials. The two substrates were of 355 x 355 x 12 mm size. For each deposit, several layers of materials were welded to demonstrate their weldability within the current limits of the primary welding parameters of the UC machine. Different arrangements of foil stacking for the materials used were experimented with. In each material combination, the welding parameters used for each layer was dependent on the material to be welded at any instant, so for each material, the most suitable welding parameters were used. The compositions and crystal structures of the materials used, valid at UC operating temperatures, are shown in Table 1.

Table 1: Materials used and their nominal compositions and crystal structures

Material	Composition	Crystal Structure at UC Temperature	Thickness (μm)
Al alloy 1100	Al-0.12Cu	FCC	50
Al alloy 3003 H18	Al-1.2Mn-0.12Cu	FCC	150
Al alloy 6061-O		FCC	150
MetPreg	Al2O3 Short fiber Al matrix reinforced tape	-	200
Molybdenum	99.5%Mo	BCC	127
Tantalum	99.5%Ta	BCC	127
Titanium	Ti-0.59Fe-0.38Mn	HCP	70
Nickel	99.5%Ni	FCC	100
Silver	99.5%Ag	FCC	127
Copper	99.5%Cu	FCC	127
Stainless Steel 316L	Fe-18Cr-14Ni-0.08C	FCC	100
Elemental Boron	B-1Mg	Rhombohedral	< 5 μm diameter

Table 2: Process parameters used for each of the materials

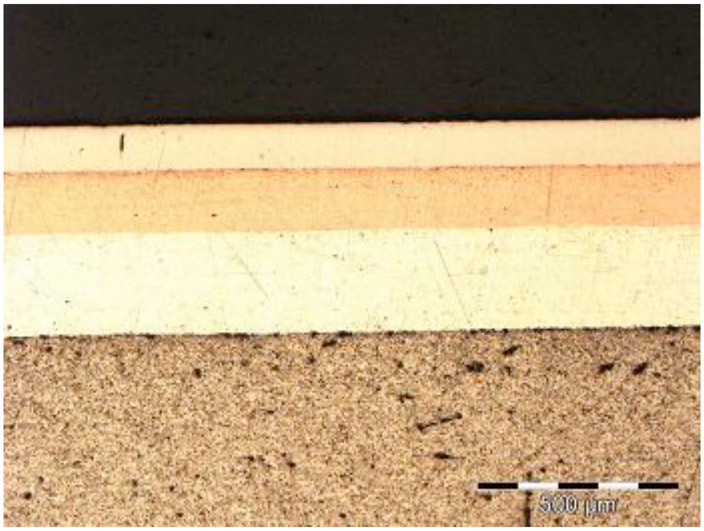
Material	Amplitude (μm)	Speed (mm/s)	Normal Force (N)	Temperature (^{o}F)
Al 3003	16	23.70	1750	300
Al 6061	18	19.05	1750	300
Cu	28	15.24	1750	150
Ag	24	15.24	1750	150
Ni	28	12.70	2000	300
Ta	28	10.58	2000	300
Ti	28	10.58	2000	300
Mo	28	10.58	2000	300
MetPreg	28	12.70	1750	300
SS 316L	28	10.58	2000	300

All materials except Al 1100-O and boron powder were welded directly using the appropriate parameters shown in Table 2. The optimum process parameters for Aluminum alloy 3003 were obtained in previous work by Kong et al and Janaki Ram et al [2-3]. While work is still ongoing to determine the optimum parameters for most of the other materials in different combinations, the parameters used in the present work were found to work well for the respective materials in Table 2. Aluminum alloy 1100 was generally used as an interlayer material between difficult to weld materials. The interlayer was manually placed between the difficult to join materials and the sonotrode run on the topmost material to weld them together. The Al 1100-O interlayer material was found to bond well with most of the materials used in this study. In cases where boron powder was added at the interface of two materials, the powder was thoroughly mixed in water and a brush was used to apply the mixture onto the surface of the substrate or already welded foil. After moisture evaporation, the foil to be welded on it is manually placed for welding. Mixing the boron powder in water was found to make it adhere more effectively to the substrate before welding than applying loose, dry powder.

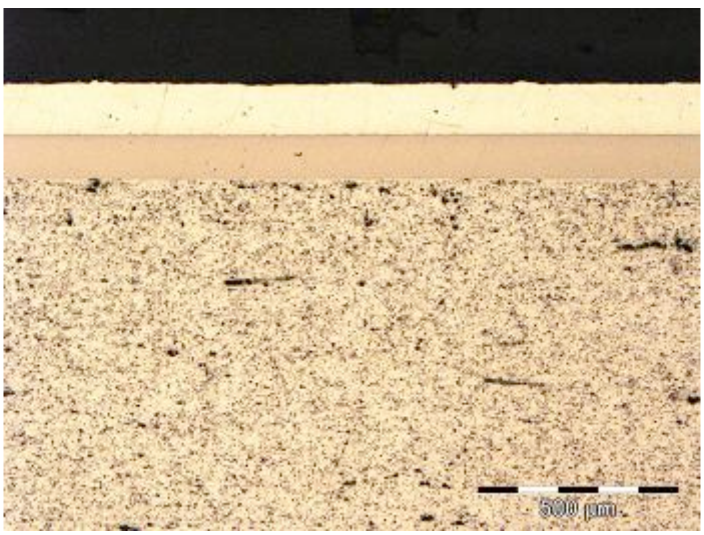
Small samples of the deposited materials were mounted and polished according to standard metallographic procedures and observed under an optical microscope. The bond qualities between the foils of different materials were qualitatively evaluated.

3. Results

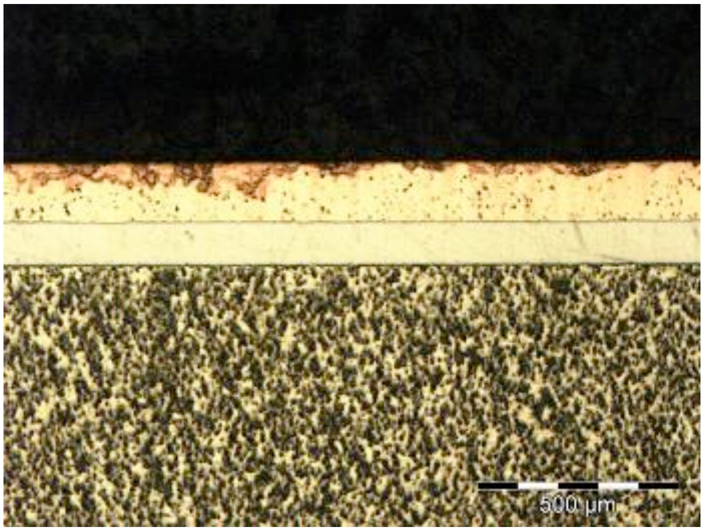
Micrographs of bonded materials are shown in Figures 2 to 8. The description of the welded foils in each figure is such that, the material that is welded directly on the substrate is the first, followed by the next material, and continuing to the topmost foil material. As an example, Figure 2a shows the macrographs of two Silver foils welded to an Al 3003-H14 substrate, followed by Copper and Nickel foils consolidated on each other with a Nickel foil at the top.



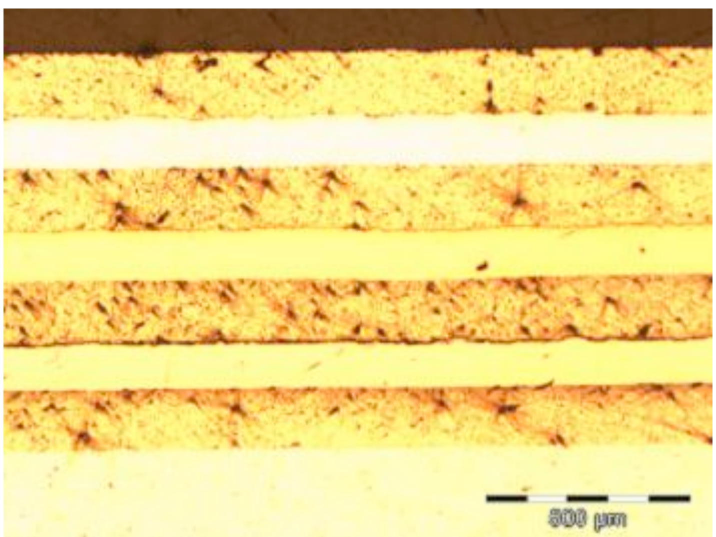
a: 2Ag/Cu/Ni on Al 3003-H14 substrate



b: Ni/Ag foils on Al 3003-H14 substrate

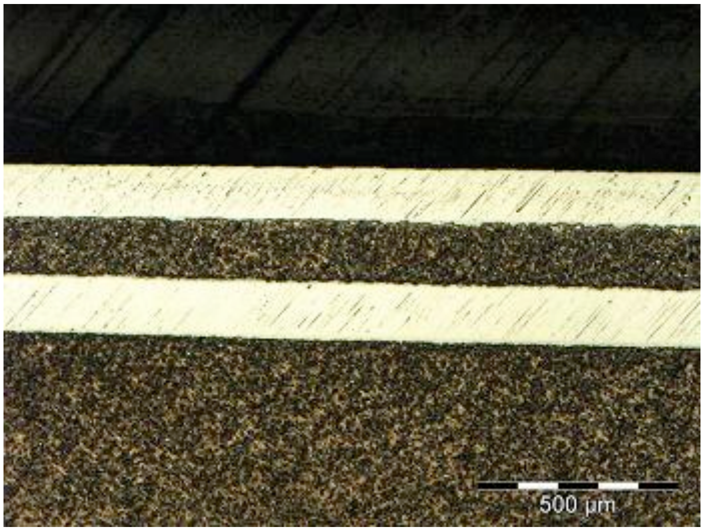


c: Ni/Cu foils welded on Al 3003-H14 substrate

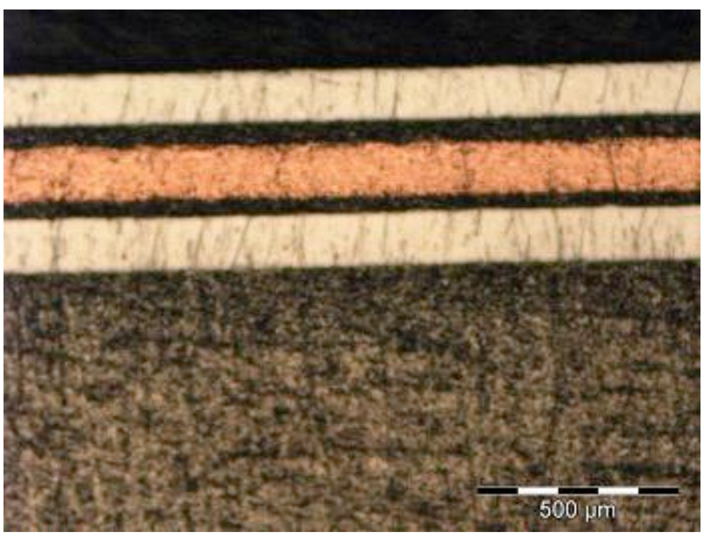


d: Al 6061/Ni/Al 6061/Cu/Al 6061/Ag/Al 6061 on Al 6061-T6 substrate

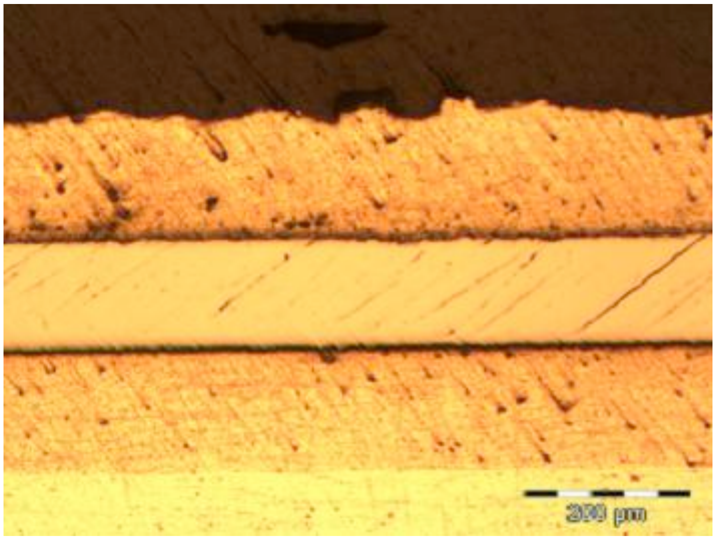
Figure 2: Micrographs showing the bond qualities of UC welded Nickel, Copper, Silver and Aluminum alloy 6061-O foils.



a: Mo/Al 3003-H18/Mo on Al 3003-H14 substrate

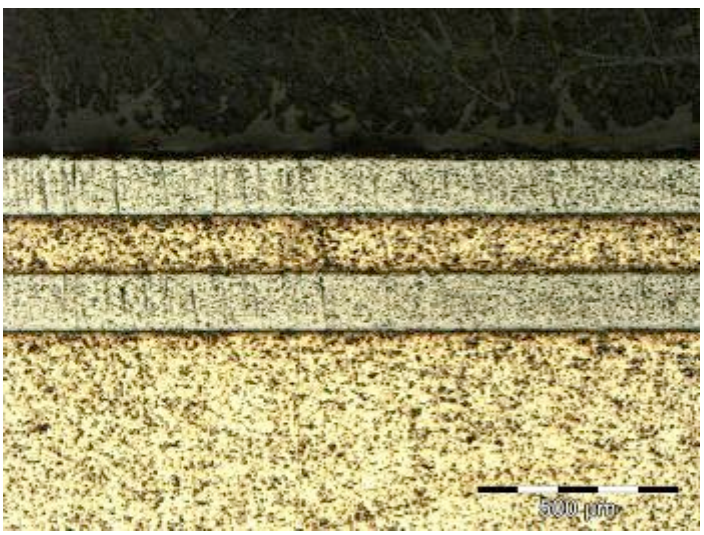


b:Mo/Al 1100/Cu/Al 1100/Mo on Al 3003-H14 substrate

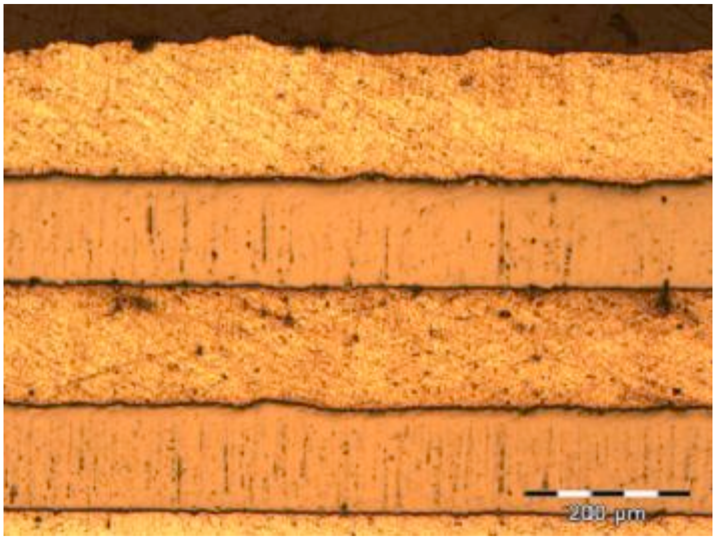


c: Al 6061/Mo/Al 6061 on Al 6061-T6 substrate

Figure 3: Micrographs of Molybdenum welded to different aluminum alloys

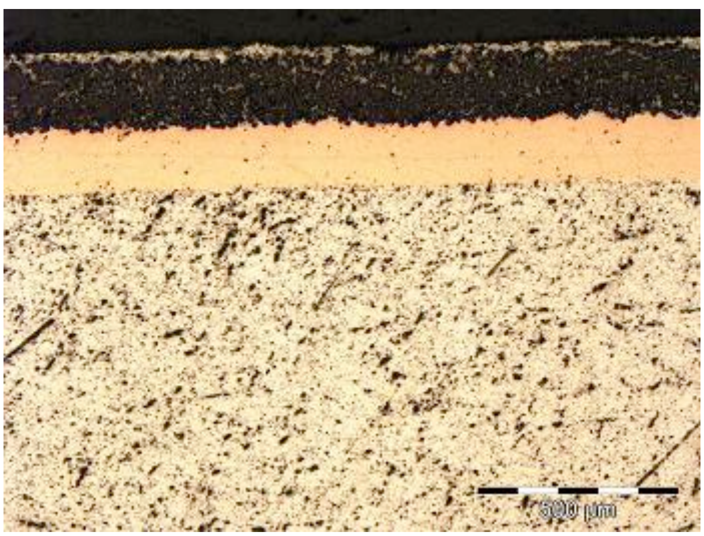


a: Ta/Al 3003/Ta on Al 3003-H14 substrate

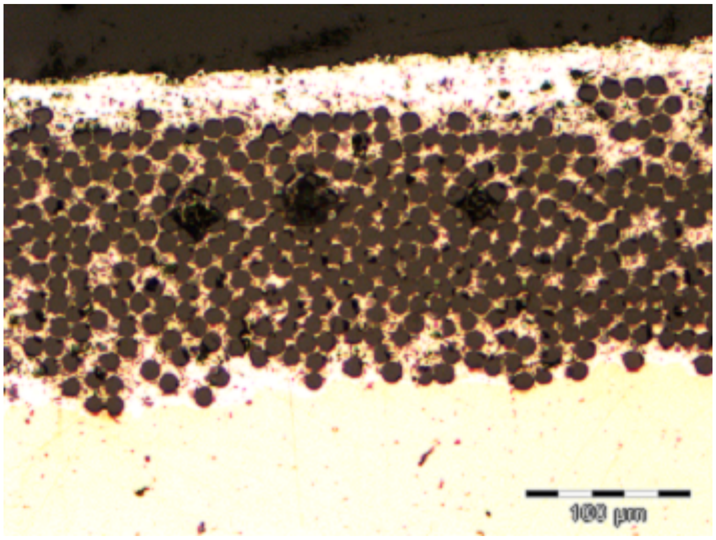


b: Ta/6061/Ta/6061 on Al 6061-T6 substrate

Figure 4: Micrographs of tantalum welded to Al 6061-O on Al 6061-T6 substrate

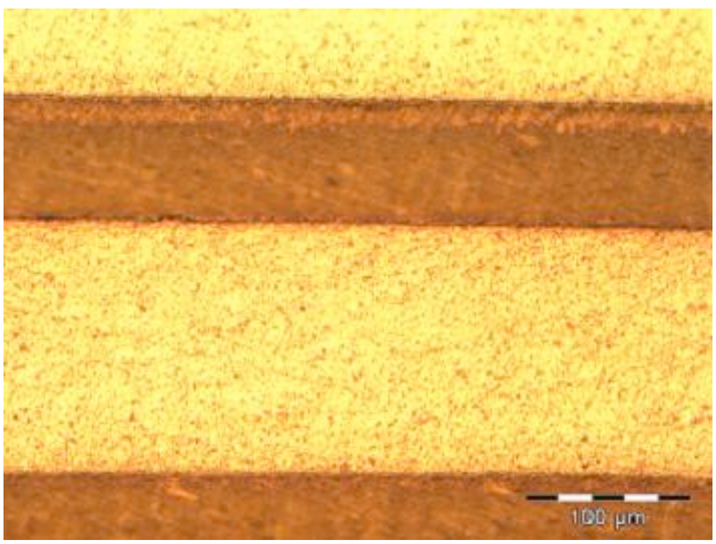


a: Cu/MetPreg on Al 3003-H14 substrate

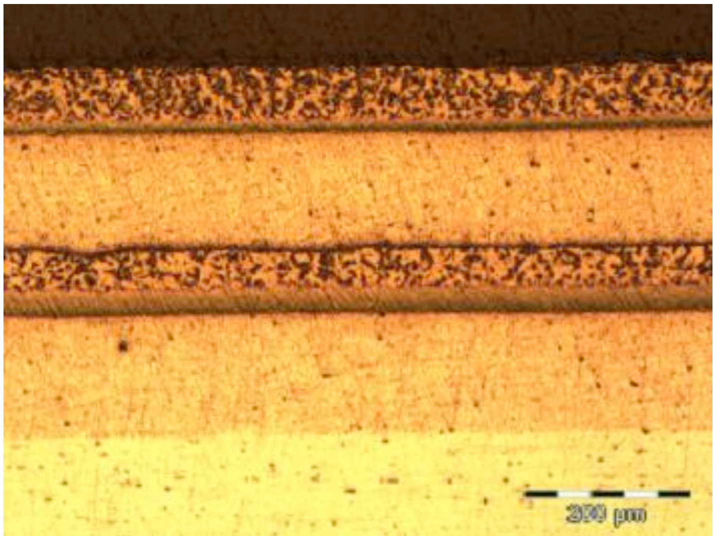


b: Higher magnification of Cu/MetPreg on Al 3003-H14 substrate

Figure 5: Micrographs of MetPreg welded to Copper on Al 3003 H14 substrate

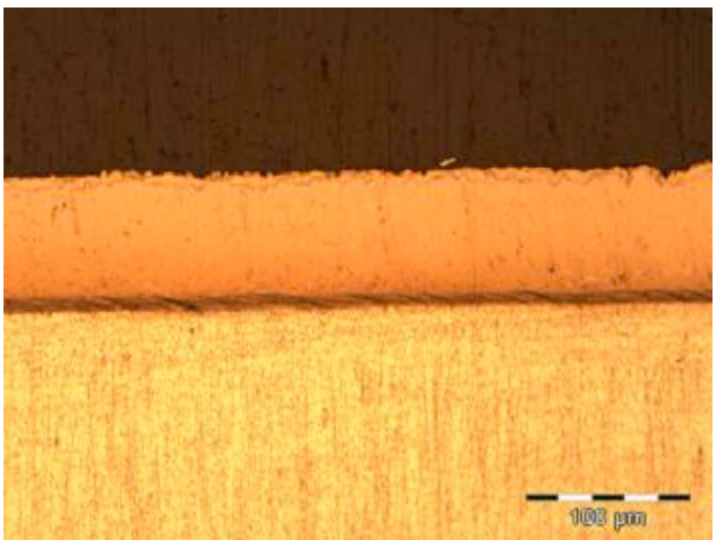


a: Ti/Al 3003/Ti on Al 3003-H14 substrate

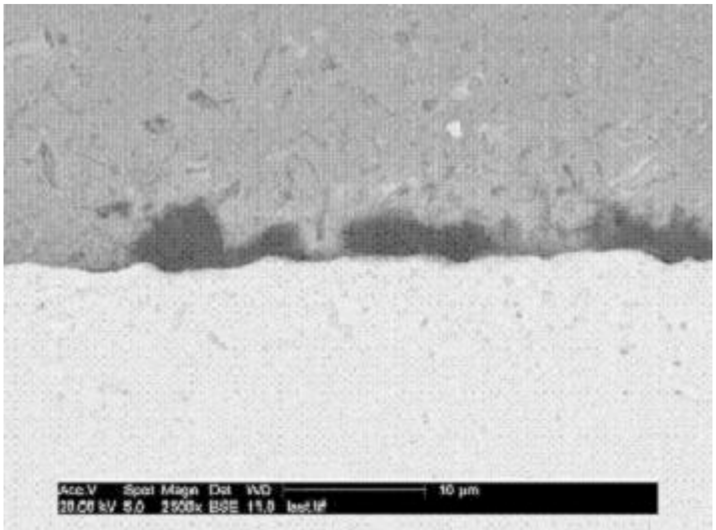


b: Al 6061/Ti/Al 6061/Ti on Al 6061-T6 substrate

Figure 6: Micrographs of Titanium welded to Al 3003 Al 6061



a: Titanium/Al 3003 with elemental boron powder at the interface



**b: 2500x magnification SEM micrograpgh of boron
powder at the interface between Ti and Al 3003 foils**

Figure 7: Titanium/Al 3003 with elemental boron powder at the interface

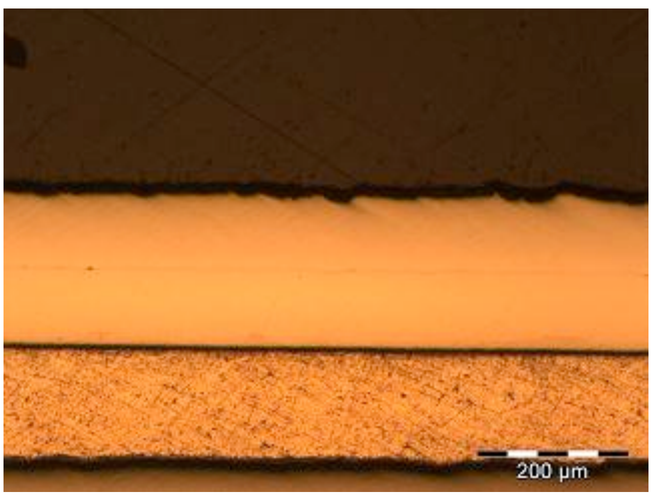


Figure 8: Nickel/Stainless steel 316L welded on Al 6061-T6 substrate

4 Discussions

The bonding mechanisms of ultrasonically consolidated foils as explained by Janaki Ram *et al*. [11] highlighted the dominant factors influencing good bonding between two foils of materials. The ability to plastically deform the foils under the action of the normal and oscillating shear forces acting at the interface of the mating foils is of paramount importance as it helps in breaking the hard surface oxides and repeatedly deforming the surface asperities thereby exposing atomically clean surface for metallurgical bonding between the mating foils during the weld cycle. Successful welding between two mating foils can be a measure of how well the surface oxides of the foil materials can be removed as well as the ease of surface deformation. From the results presented, it can be observed that the relatively soft materials generally bonded well to each other. This is because, their surface oxides were easily broken up and displaced along with the fact that they were relatively easier to deform under the influence of the operating forces. It is also worthy of note that most of these softer materials have face centered cubic (FCC) crystal structures while the harder ones have body centered cubic (BCC) and hexagonal close pack (HCP) structures at UC processing temperatures. So far limited success has been achieved in bonding softer materials to hard ones. All the aluminum alloy series used in this experiment bonded well with all the hard materials tried, whereas silver, copper and nickel did not bond well with molybdenum and tantalum directly. Thus, in addition to welding parameters, material composition and combinations play an important role in determining good bonding. Attempts to bond molybdenum and tantalum, representing hard materials to themselves both as similar and dissimilar materials, have been unsuccessful. Observations from welded material combinations are discussed in the following subsections.

4.1 Silver/Copper/Nickel welding

In this combination of materials, two silver foils were successfully welded to each other on the Al3003 base plate as shown in Fig.2. Copper foil also bonded well to both silver at the bottom and nickel at the top. From the micrograph, it can be seen that the silver to silver weld has a very good linear weld density (a measure of bond quality [3]), as there are no visible interfacial defects between the two layers. Silver welded well at 150^{o}F as well as at 300^{o}F, although it underwent a high rate of oxidation at 300^{o}F. Except when bonding with materials that will significantly conceal the surface from atmospheric oxygen, it is better to weld Silver at 150^{o}F. Copper to silver and copper to nickel foils also bonded very well to each other, as can be seen in Figs. 2a and 2b. From the micrographs, good welds were obtained between copper and nickel both at the top and bottom. In Fig.2c, nickel, copper and silver are shown individually sandwiched between aluminum alloy 6061-O foils to demonstrate their good weldability to this aerospace grade material using UC. Al 6061-O foil bonded well with the Al 6061-T6 substrate material with no visible defects. All the materials welded in Fig. 2 show good bond qualities.

4.2 Molybdenum/Al 3003-H14/Copper Welding

Figure 3 shows the micrographs of moderately bonded combinations. Molybdenum welded to aluminum alloy 3003 H18 is shown in Fig.3a, copper with aluminum alloy 1100-O as an interlayer material in Fig.3b and to aluminum alloy 6061-O in Fig.3c. Molybdenum is a hard, wear and corrosion resistant refractory metal with high temperature strength, and resistance to plastic deformation. As can be seen in Fig.3a, molybdenum bonded well with Al 3003 with either material at the top or bottom. It is also bonded well to copper when using an Al 1100 interlayer material. Within the limits of the welding parameters of the UC machine used, molybdenum could not be successfully joined to copper directly. With the interlayer material however, very good joining was achieved. Molybdenum-copper laminated materials have applications in thermal management for electronics packaging [13]. The bond between molybdenum and Al 6061-O shown in Fig.3c is not as good as those in Figures 3a and 3b.

However, with further welding parameter optimization, there may be a possibility of achieving good bonding between these two materials.

4.3 Tantalum/Aluminum Welding

Micrographs of tantalum foils ultrasonically welded with aluminum alloys 3003-H18 and 6061-O are shown in Fig. 4. The tantalum foils were in the as-rolled and tempered form. The micrographs show very good linear weld densities between tantalum and the two aluminum materials. The sandwiched tantalum between the two aluminum alloys show that good bonds are achieved with either material at the top or bottom of the welds. Tantalum is a refractory metal with good wear and corrosion resistance. It can be ultrasonically welded to a material for surface protection against wear and corrosive environmental conditions. Tantalum is also used for radiation shielding in nuclear applications [14].

4.4 MetPreg/Copper Welding

MetPreg was fully bonded with copper on an aluminum 3003 substrate, as shown in the micrographs in Fig. 5. The deposit is a combination of an aluminum metal matrix material with very hard reinforcing alumina fibers, joined to copper, a good electrical and heat conducting material. The dual material deposit can be used in applications requiring good heat or electrical conductivity underlying materials with a hard, wear resistant surface. The micro-hardness of the as fabricated surface of the MetPreg on copper is 600Hv.

4.5 Titanium/Aluminum Welding

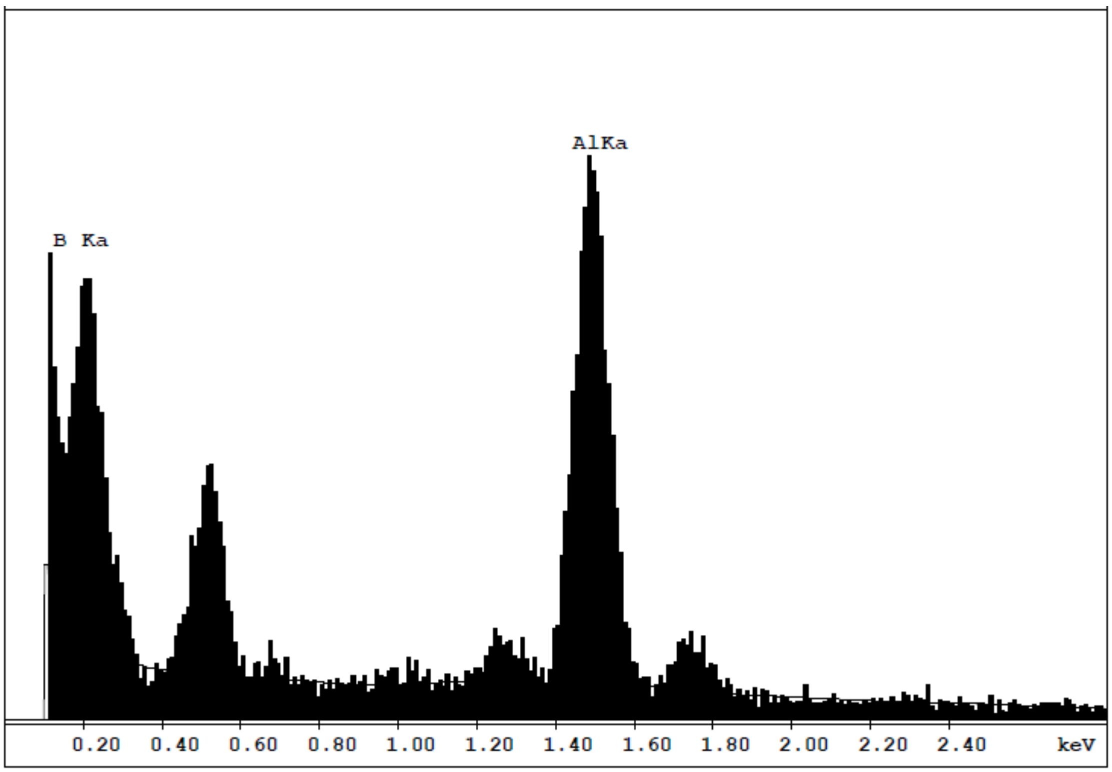
Titanium was successfully joined to aluminum alloys 3003-H18 and 6061-O by ultrasonic consolidation as shown in the micrographs in Fig. 6. The micrographs show good bond qualities between titanium foils and the aluminum alloys with either material at the top or bottom position. Titanium and aluminum have a wide range of applications in the aerospace industry. As such; ultrasonic consolidation provides a unique fabrication technique for their dual material freeform fabrication for functional structures in the aerospace industry, especially with aerospace grade Al 6061 materials.

4.6 Titanium/Aluminum Welding with Embedded Boron Particles

Titanium and aluminum alloy 3003-H18 welded well with embedded boron powder at the interface as shown in the micrographs in Fig.7. The boron powder used has particle size less than 5μm diameter. Plastic flow of aluminum and titanium foils around the boron particles is crucial to obtaining good bond. During welding, the oscillating motion of the vibrating sonotrode redistribute the particles at the interface of the welded foils, as such, uniform particle distribution will be difficult to achieve. Embedded powder can be used to achieve local property control within a structure. It can also be used to fabricate particle reinforced composite materials, especially in cases where the UC particle embedment is an initial fabrication step before post deposition heat treatments. The deposition shown in Fig.7 was subjected to post process annealing at 480^{o}C for two hours and oven cooled. The result of Energy Dispersive X-ray (EDX) spot analysis, shown in Table 3 below at a 1μm point distance on the aluminum side from the boron powder, reveals that significant boron diffusion into the aluminum matrix took place.

4.7 Nickel/Stainless Steel 314L Welding

Figure 8 shows a good bond between stainless steel 316L and nickel. The austenitic stainless steel material with an FCC crystal structure demonstrates good weldability with nickel. The dual materials have applications in areas where strength and corrosion resistance is a major requirement.



EDAX ZAF Quantification (Standardless)
Element Normalized
SEC Table : Default

Element	Wt %	At %	K-Ratio	Z	A	F
B K	75.38	88.43	0.4872	1.0172	0.6354	1.0000
AlK	24.62	11.57	0.2324	0.9435	1.0003	1.0000
Total	100.00	100.00				

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
B K	34.54	14.40	3.26	2.40
AlK	71.38	6.36	1.82	11.22

Table 3: Result of EDX spot analysis of a point in the aluminum side of the matrix

5 Concluding Remarks

The multi-material capabilities of ultrasonic consolidation have been further demonstrated in this work. All FCC crystal structure materials used welded well with each other. Among the materials used, only aluminum alloys 1100, 3003, and 6061 welded well with molybdenum, tantalum and titanium; the only non-FCC crystal structured materials. With further optimization of the welding parameters for most of the material combinations, functional multi-material structures can be fabricated by ultrasonic consolidation.

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