Investigation of Support Materials for use in Ultrasonic Consolidation

Swank, M.L., Stucker, B.E. Mechanical and Aerospace Engineering Department, Utah State University, Logan, UT 84322

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Abstract

This paper provides an overview of the need for supports and what characterizes a good support material for Ultrasonic Consolidation. The goal is to look at a broad range of possible support material choices and the benefits and drawbacks of each. By manually depositing support materials during a build, each material is evaluated for its performance for three different configurations: an enclosed pocket, freestanding rib, and open channel. These configurations represent commonly seen features that often need to be built using Ultrasonic Consolidation, but currently cannot be well constructed. The builds are constructed with 3003 Aluminum tapes at room temperature. Microstructures are also studied to evaluate the consolidated material.

1. Introduction

Support materials play a vital role across the field of additive manufacturing (AM). Specifically, support materials have greatly expanded the geometric capability of many different AM processes and allowed many new applications. Most AM processes use some sort of support structure that is deposited simultaneously with the build to create a framework for subsequent layer deposition. Certain AM processes such as selective laser sintering (SLS) do not require an additional support material since the unmelted build powder acts as one. Not all AM processes, however, have enjoyed benefits from the addition of support materials. One such process which currently has no support materials system is ultrasonic consolidation.

Ultrasonic consolidation is a direct metal AM process that combines ultrasonic welding and CNC milling [1]. A cylindrical ultrasonic welding head or sonotrode ultrasonically welds or consolidates thin metal foils (around 150µm) in layers to create the rough part shape. Contours or other features are then milled into the metal layers at specified intervals to create the final part. UC has advantages over other AM processes in that it is a low temperature direct metal process which requires limited post processing. It is therefore well suited for embedding electronics and other temperature sensitive devices. Also, unlike other direct metal additive manufacturing processes which rely on liquid to solid transformations, UC only reaches up to 50% of the melting temperature locally [2]. UC has been successfully applied to create tooling, conformal cooling channels, honeycomb satellite structures, embedded sensors, metal matrix composites, and fiber embedment [1, 3-8]. UC also has the benefit of working with multiple materials. Many different aluminum alloys as well as copper, stainless steel, titanium, brass, and nickel have been shown to be weldable using UC [9-12].

The ultrasonic consolidation process consists of several important input parameters which combine to create a metallurgical bond. These parameters are substrate temperature, vibration amplitude, welding speed, and normal force. If any of the parameters for a given material are too low a bond will not occur. If the parameters are too high then the material may still bond but it will be severely work hardened and brittle or weld itself to the sonotrode. It is therefore very important to use the appropriate parameters for a given material as they have a direct influence on the bond quality.

During the ultrasonic consolidation process two metal surfaces are brought into close contact under a normal load provided by the sonotrode. The top layer is vibrated transversely to the weld direction at high frequency (20 kHz) and low amplitude (generally 16µm). This provides differential motion between the two layers which breaks up the oxide layer on the surfaces. This creates the ideal condition for creating a metallurgical bond between the layers.

Generally a part constructed using ultrasonic consolidation will contain some unbonded regions along the foil interfaces. In order to characterize these defects a term called 'linear weld density' or LWD is used [12]. Linear weld density is the percentage of bonded area to unbonded area along the weld interface regions. This valued is measured by using optical micrograph images of the weld interface throughout the part. A higher linear weld density corresponds to more contact points across the weld interface and generally a stronger bond. Parts fabricated using a technique called 'surface machining' in UC have been produced to achieve near 100% linear weld density [13].

Support materials are extremely important to the UC technology because of the benefits that can be geometrically achieved. Without an integrated support materials system many geometries and features will be impossible to create as shown in figures 2-5. This includes large overhangs and open channels or cavities over which the sonotrode cannot span. For the Solidica Formation ultrasonic consolidation machine this means any support dependent feature greater than the sonotrode width of 1 inch. However, even for smaller sizes down to 50% of the sonotrode width or less, a support is almost always required. This is due to the fact that bonding over any unsupported channel or cavity is very poor and often the material above these features is not significantly bonded but simply held in place due to good bonding in adjacent areas. A phenomena called recovery is characterized by increased bonding after each layer over a small unsupported area until enough stiffness is acquired by subsequent layers to achieve full bonding again. This can be easily seen visually by observing the surface change roughness layer-by-layer after welding over such a feature.

Figure 1: Ultrasonically welded part where the dark regions represent unbonded areas over a milled channel and the light areas correspond to bonded regions.

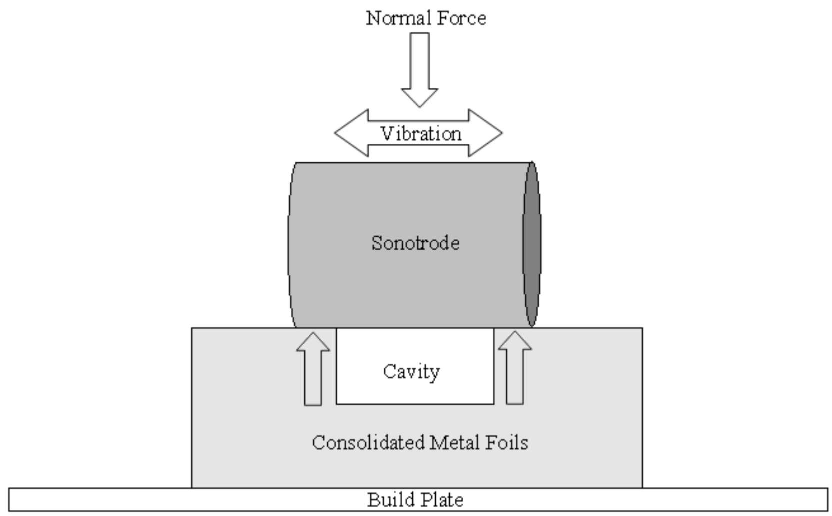

Figure 2: Enclosed cavity feature in UC will be supported by edges which bond, but areas above the cavity will not bond well during subsequent layer deposition. A support material in the cavity enhances bonding above it.

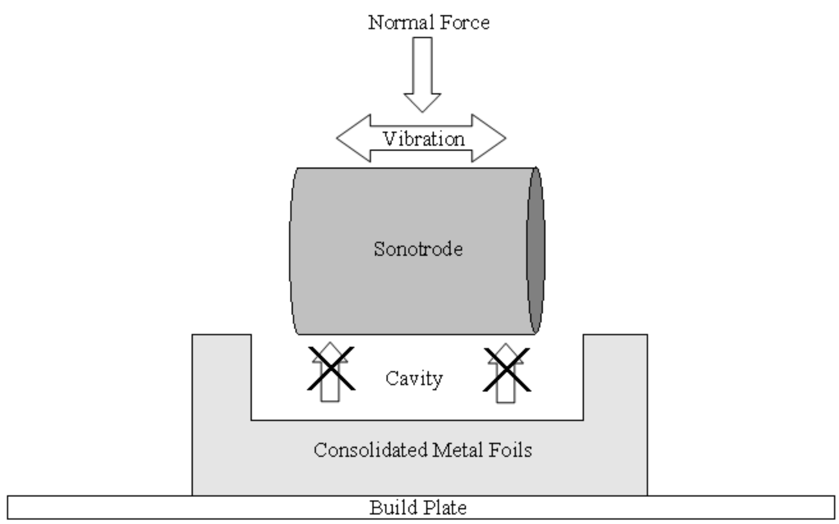

Figure 3: Building above an open channel/cavity feature larger than the sonotrode width is not possible using UC, without a support material.

Builds requiring an overhanging feature in ultrasonic consolidation will always need support. This is due to the normal force exerted by the sonotrode during UC. Unless overhanging layers are sufficiently constrained, differential motion will not take place between layers and bonding will not occur. Despite this need UC has been used to create small overhangs in which the foil layers did not bond together, but simply mechanically supported each other as cantilevers. This approach works for small overhangs up to about 0.1" but it is important to note that these overhanging foils will not be bonded together.

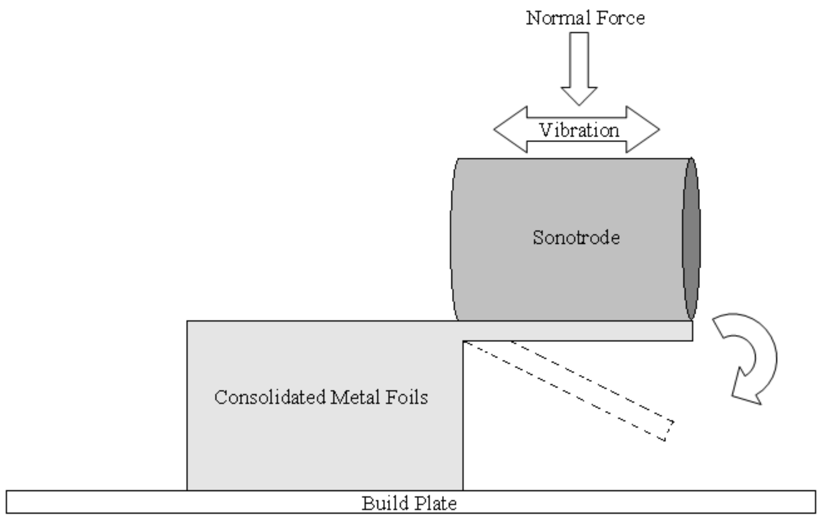

Figure 4: Large overhanging features in UC will collapse without support.

After a certain aspect ratio has been reached during a build a support material may be necessary to restrict part vibration. When a part grows taller it loses its ability to resist motion and therefore the entire part may vibrate with the sonotrode motion as shown in figure 5[14]. Using a support material around tall ribs and thin walls will prevent this motion and allow taller and thinner ribs to be constructed.

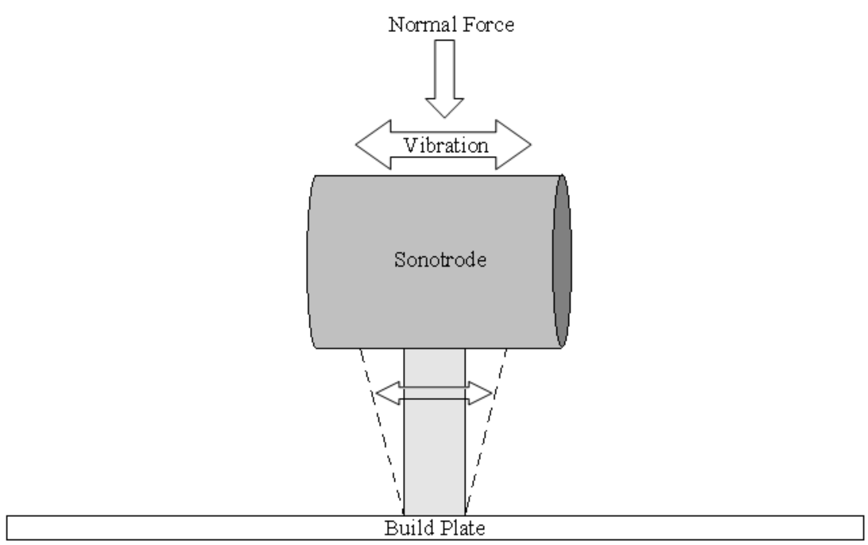

Figure 5: High aspect ratio features in UC, such as thin ribs or walls, may vibrate with the sonotrode unless supported. Lack of support causes limited or no bonding to occur.

When choosing a support material for use in UC there are several special requirements to be considered. Specifically a support material in UC needs to withstand compressive loads, be removable (unless it is used as a potting material), be stiff enough to inhibit structure vibration, and be relatively heat resistant. The normal force exerted by the sonotrode can be up to 2000N spread across a small contact area of the build. If a support material cannot support this load the material will both deform and cause the machine to fault or it will crack and not support the subsequent layers above. The support also needs to be removable so that once a part is complete it can be removed leaving the desired component. If the support is being used as a potting material to encapsulate electronic components then it does not need to be removable. A support material is generally removed using heat, dissolving solution, or mechanically by hand. As a component becomes taller during UC it can begin to have the tendency to vibrate with the sonotrode, therefore the support material must provide sufficient stiffness to resist this vibration to ensure differential motion between the sonotrode and build. Due to the heat generated locally at the weld interface a support material may need to withstand a temperature up to about 50% of the melting point of the metal. Additionally it would be beneficial if a support material was also machinable, cost effective, and non-toxic; however these are not absolutely essential.

Until this point there has been no information provided in the literature, except a UC process patent, as to suitable materials for use in the ultrasonic consolidation process [15]. It is unknown how the addition of a support material will affect the machine operation for various configurations; therefore this paper serves to provide a foundational preview of support materials for the ultrasonic consolidation process.

2. Experimental Work

2.1 Geometry Design

In order to investigate and compare a broad range of possible support materials a series of three support requiring geometries were created. These geometries represent similar types of features which may be desired to be built using ultrasonic consolidation. The three geometries used were a pocket, rib, and open channel as shown in figures 6 and 7.

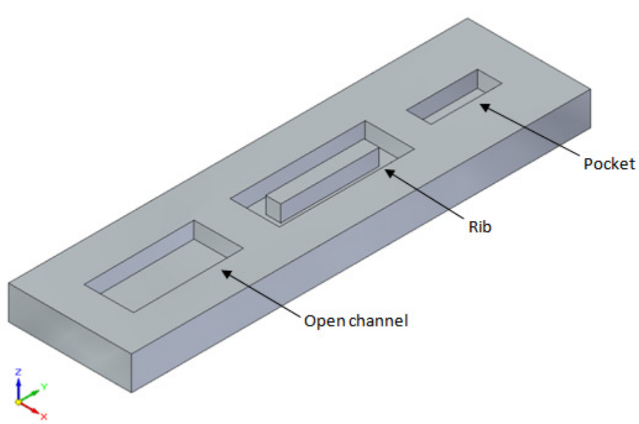

Figure 6: Three different geometries used to test support materials. Support material was manually deposited into features.

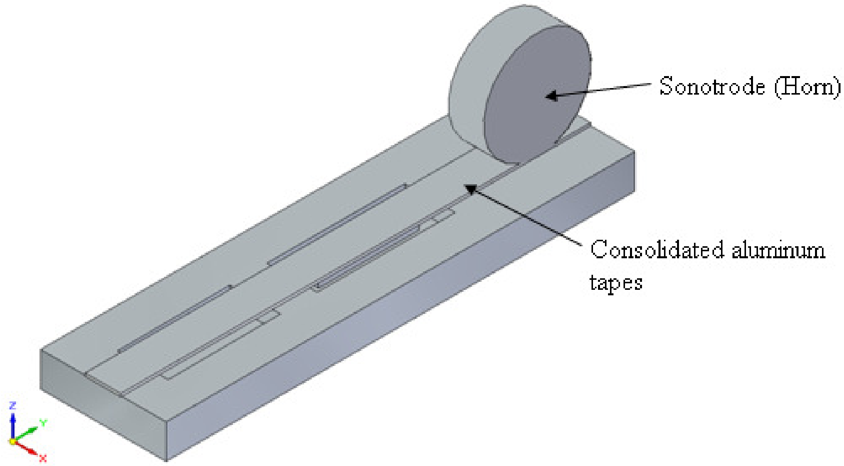

Figure 7: Tapes consolidated over three types of features: pocket, freestanding rib, and open channel.

The geometries were milled into a UC build plate of Aluminum 3003-H14. The pocket has a width of 0.7" which represents approximately 75% of the sonotrode and tape width. The freestanding rib is a 1:1 height to width ratio which represents the tallest buildable rib height in UC without a support material [3]. The open pocket measured 1.5" wide which means the sonotrode will be completely supported by the support material. The depth of all the features measured 0.25".

Figure 8: Milled features in aluminum substrate.

2.2 Support Material Options

The following list describes the materials chosen for a support application to UC:

Metal alloy (Tin-Bismuth)

Tin bismuth was chosen due to its low melting point (302°F) and positive coefficient of thermal expansion. This allows the material to completely fill any support-requiring regions without shrinkage during cooling. It is also very easy to pour and mold, especially into a metal plate. Tin bismuth is also easily machined and poured; however dust and fumes are slightly toxic. A low melting point alloy such as tin bismuth could be removed simply by heating the completed part above the melting point and pouring out the support material.

Thermoplastic (WaterWorks™)

Waterworks™ is Stratasys' proprietary water soluble support material used in fused deposition modeling (FDM). It is suitable for a support material because it is water soluble and very rigid. Waterworks™ is also a desirable choice since a dependable automatic deposition system (FDM) already exists.

Thermoset (Leco quick cure (QC) epoxy)

Epoxies are potential support materials because of their high strength and temperature resistance. They have also been successfully used in UC as a potting material for electronics. They, however, prove difficult to remove due to irreversible crosslinking which occurs during the curing process.

Wax (Water soluble casting wax)

Certain high strength waxes are candidates for support material because they are both easily deposited and removed. A high strength water soluble casting wax was used due to its ease of pouring, machining, and removal. It also had the least amount of shrinkage of various waxes from cooling in the mold.

Organic (Aluminum filled sucrose)

Similar to peanut brittle, an organic hardened sucrose filled with aluminum powder can provide a very stiff support which can be easily be poured and easily removed with water. In this experiment a 20% volume of aluminum powder was used as a filler. This option could also prove to be the least costly of all the materials tested.

Each material, except WaterWorks™, was poured in excess into the features on the aluminum build plate and allowed to cure/cool. Since the WaterWorks™ material could not be melted and poured; the shapes needed to fill the features were built using a FDM machine as shown in figure 9. The resulting blocks were then inserted and fixed into the plate using a small amount of high strength epoxy.

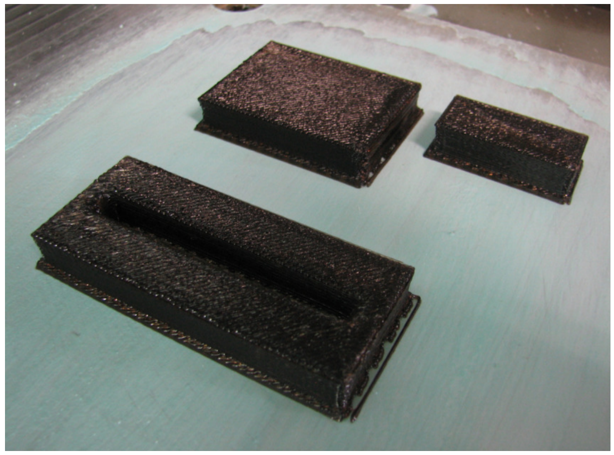

Figure 9: WaterWorks™ blocks built using FDM.

Once all of the features were filled the build plate was mounted into the ultrasonic consolidation machine. Next the plate z height was found using the normal machine program and excess support materials were milled off. A small amount of the aluminum build plate was also removed during this process to ensure that both the plate and the support materials were at an identical height.

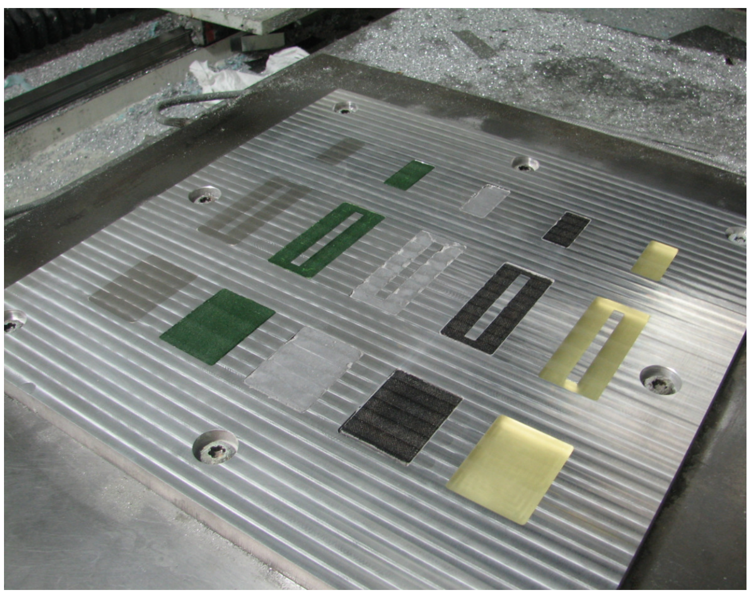

Figure 10: Milled support materials in aluminum substrate. From left to right: tin bismuth, casting wax, sucrose, WaterWorks™, and epoxy.

2.3 Ultrasonic Consolidation Machine Parameters

The UC machine parameters were chosen based on extensive work with the aluminum 3003 alloy and honeycomb structures. The parameters used were: 18µm amplitude, 28ipm welding speed, 1750N normal force, and room temperature build plate (75°F). Tapes of aluminum 3003 H18 of width 0.94” and thickness 0.006” were consolidated lengthwise along the center of each geometry for all five support materials. Deposition occurred for 15 layers (0.09”) or until a machine fault or debonding occurred. The UC machine will fault if the sonotrode detects a change in z height due to excessive support material deformation.

2.4 Material Problems Encountered

While using the various support materials several difficulties were encountered with their use. The sucrose material was highly prone to chipping during machining due to its brittle nature. Several speeds and feeds were used during the milling operations with little improvement.

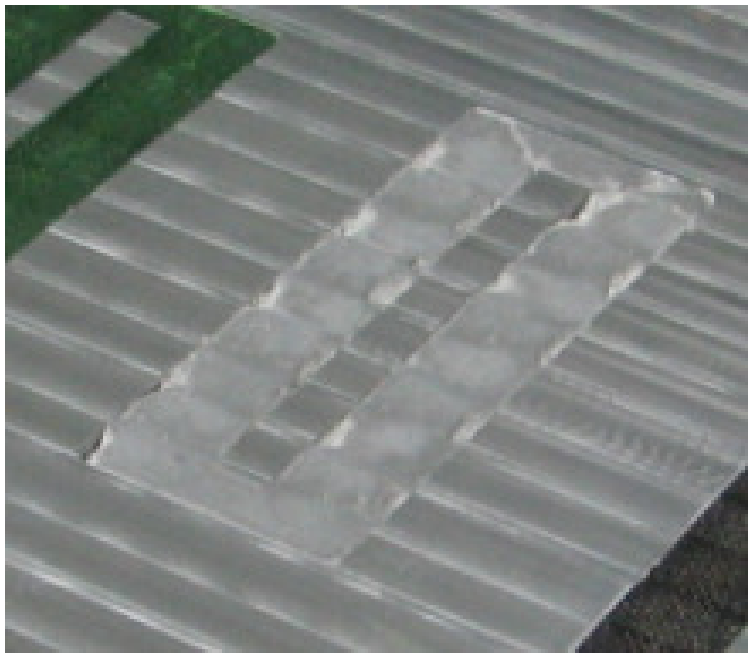

Figure 11: Chipping and cracking of sucrose observed around rib feature after milling.

The casting wax proved somewhat difficult to use because it had a tendency to shrink away from the plate and warping occurred for the open channel feature. The pouring temperature was reduced and this helped the problem significantly. The tin bismuth, WaterWorks™, and the epoxy were found to be the simplest and most straight forward materials for filling the three geometries.

2.5 Brinell Hardness Testing

Brinell hardness tests were performed using an Aktiebolaget Alpha machine with 4000 kgf capacity on each support material and the aluminum build plate according to the ASTM E10 standard. Two indentations were performed on each material using a 10mm ball indenter and 125kgf test force. The indentation diameters were measured using computer image analysis software on 1x optical microscope images taken of the indentations.

2.6 Optical Metallographic Studies

A small section from each successful deposition was cut and mounted to observe the bonding between the layers. Also a sample was made from layers deposited on the plate without any support to provide a standard for comparison. The samples were prepared according to standard mounting and polishing procedures for metallography.

3. Results

3.1 Foil Bonding

The following figures, 12-16, show the bonding over the various support materials.

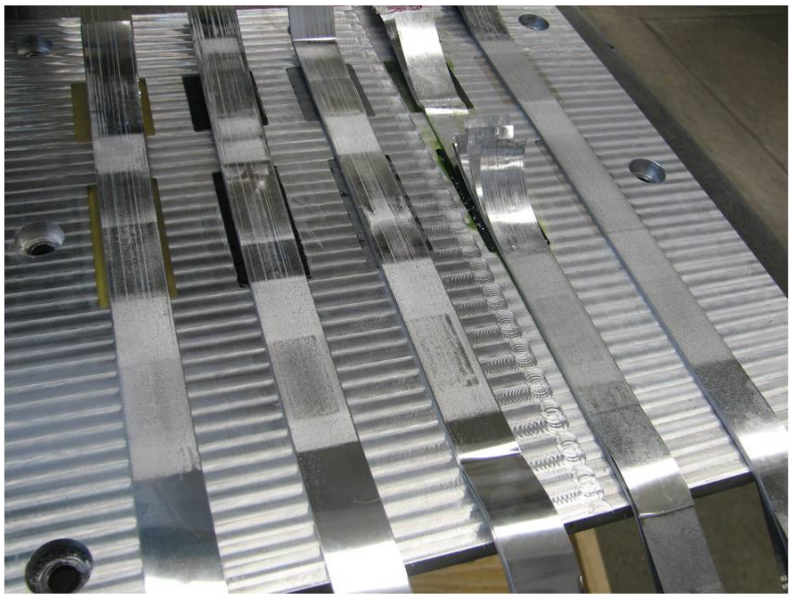

Figure 12: Aluminum tapes after consolidation over support materials. From left to right: epoxy, WaterWorks™, sucrose, casting wax, and tin bismuth.

The tin bismuth was the only material which enabled deposition over all three geometries.

Figure 13: Aluminum tapes after consolidation over tin bismuth.

The foils were only lightly bonded across the rib and channel features for the WaterWorks™, epoxy, and sucrose.

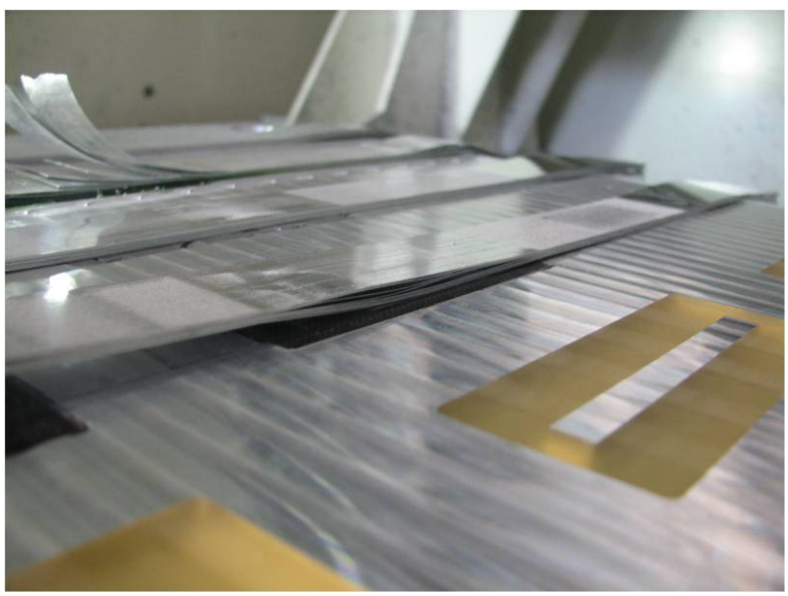

Figure 14: Delaminated foil layers over the rib and channel with WaterWorks™ support material, which also occurred with the epoxy and sucrose.

The sucrose and wax materials were melted and deformed by the sonotrode during the UC process. Melted and resolidified material was also found between the metal foils and build plate.

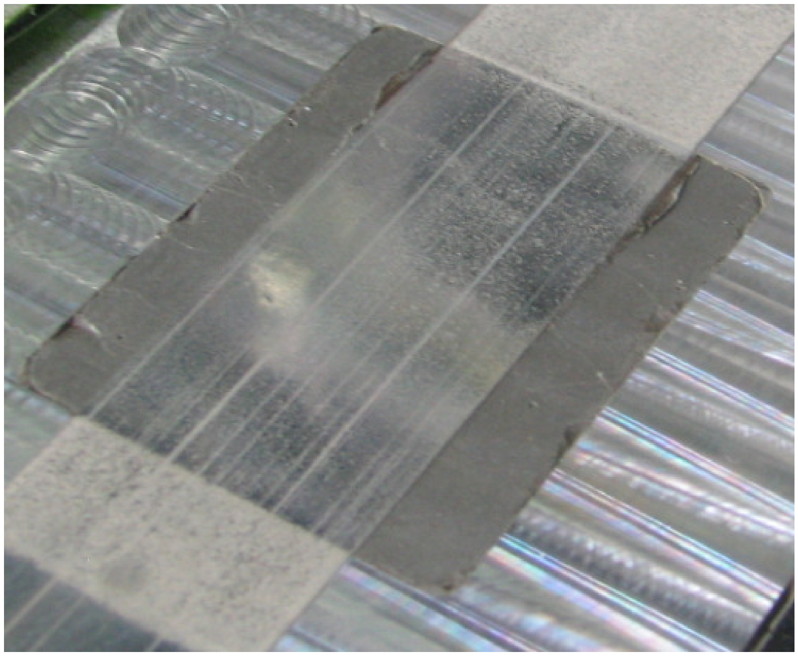

Figure 15: Sucrose material was melted and squeezed out along tape edges.

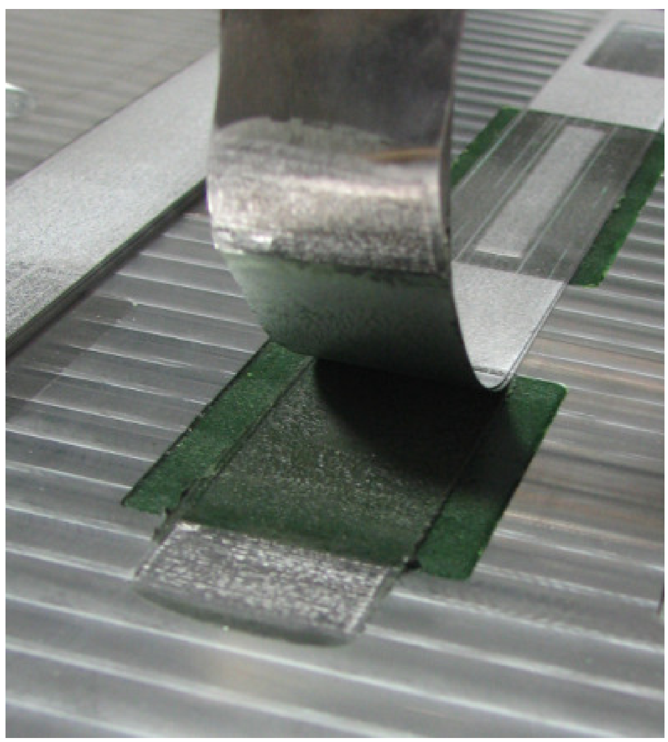

Figure 16: Casting wax was melted and squeezed out along tape edges and between the foil and build plate.

3.2 Brinell Hardness

Tables 1 and 2 show the results of the Brinell hardness tests on the support materials as well as the aluminum build plate. The water soluble casting wax was fully penetrated by the indenter and therefore a hardness value could not be calculated.

Material Type	Hardness 1	Hardness 2	Average
Al 3003-H14	46.9	46.9	46.9
Sucrose+Al	33.1	30	31.5
WaterWorks™	20.6	18.9	19.7
Leco® Epoxy	17.5	19	18.2
Tin Bismuth	15.4	16.6	16

Table 1: Brinell hardness measurement values for each material and aluminum build plate.

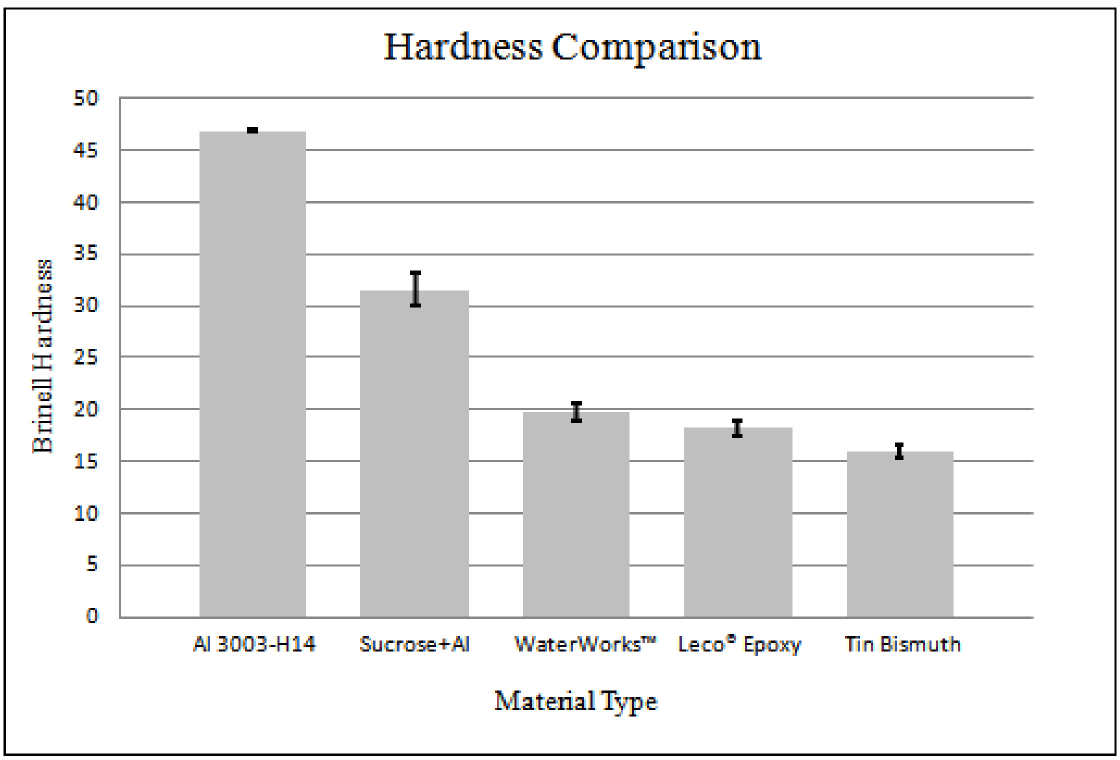

Table 2: Brinell hardness measurements with error bars for the aluminum build plate and support materials.

3.3 Microstructures

The following are micrographs taken of the layer interfaces for the different support materials. The dark voids within linear regions are areas where the foils have not been bonded between layers. Each foil layer is approximately 150µm thick.

Aluminum foils to aluminum build plate

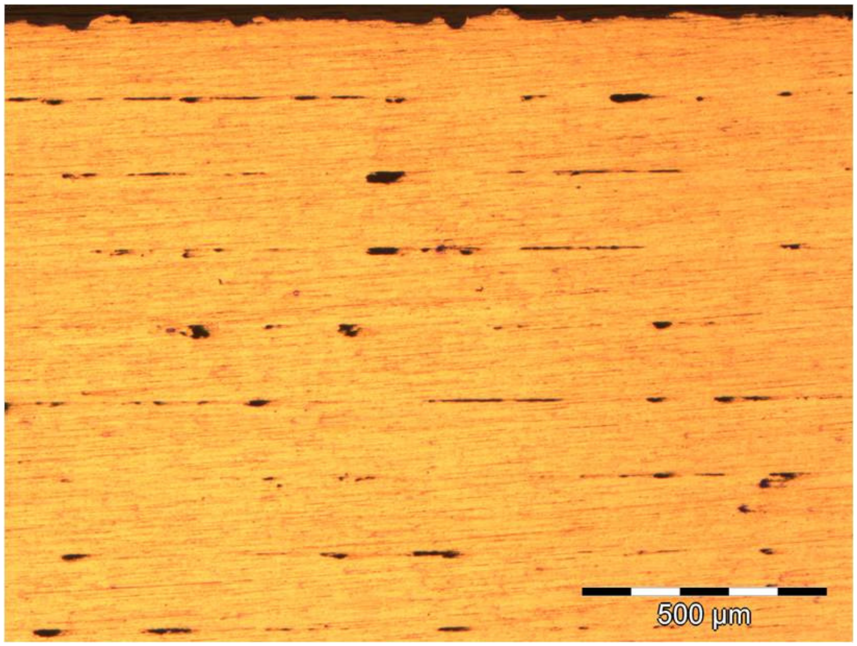

Figure 17: Top aluminum foil layers near the center of the unsupported specimen.

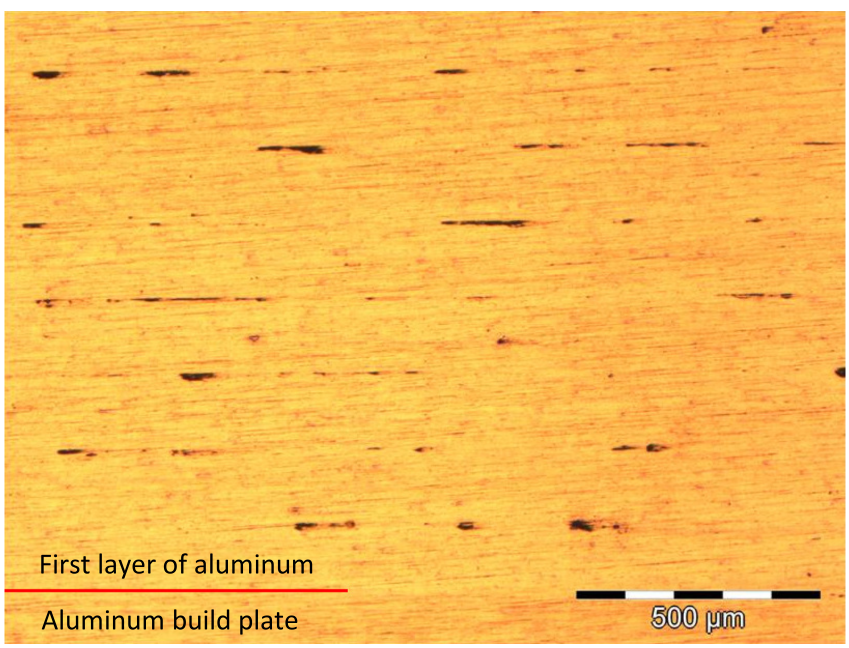

Figure 18: Bottom aluminum foil layers near the center of the unsupported specimen.

Aluminum foils over tin bismuth

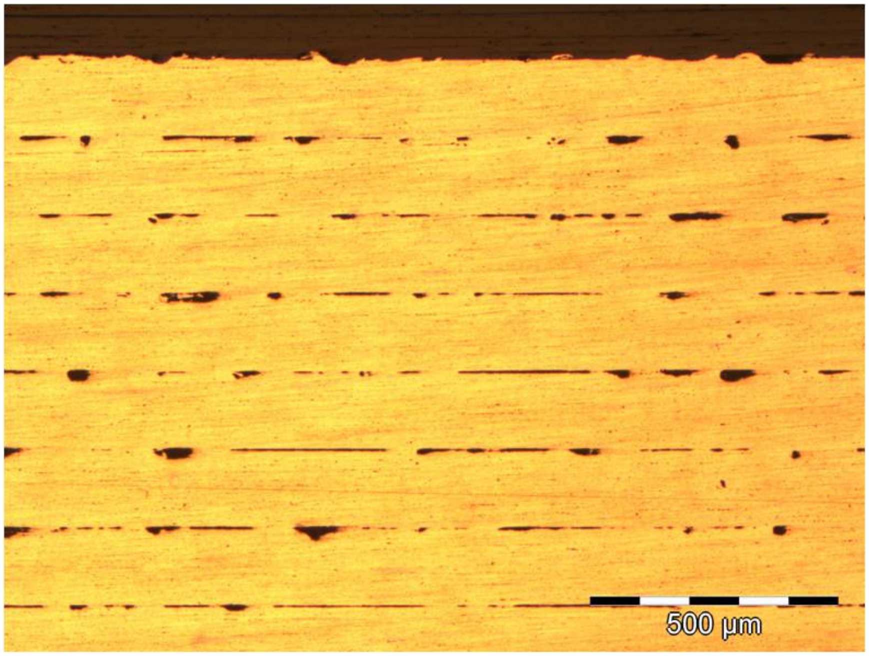

Figure 19: Top aluminum foil layers near the center of the tin bismuth pocket specimen.

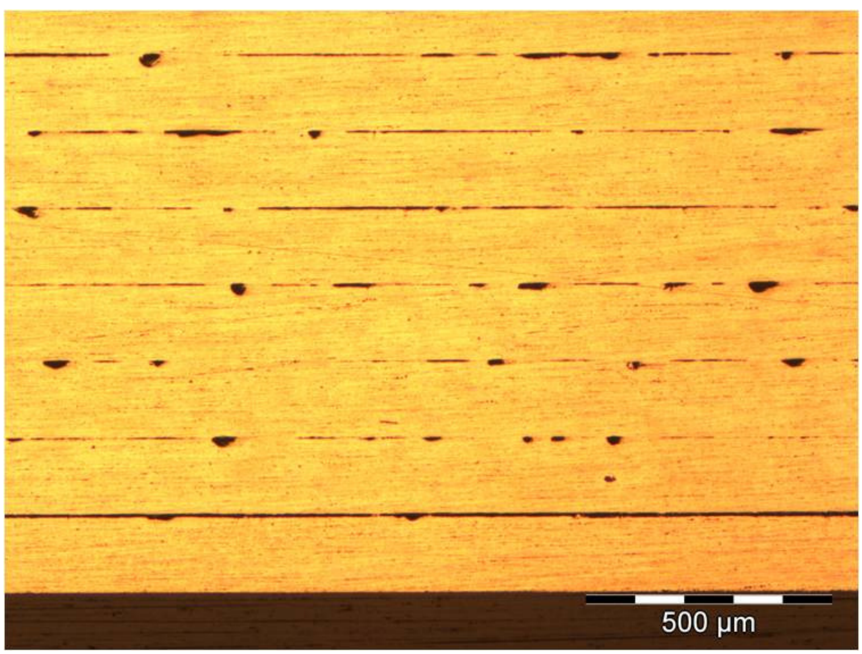

Figure 20: Bottom aluminum foil layers near the center of the tin bismuth pocket specimen.

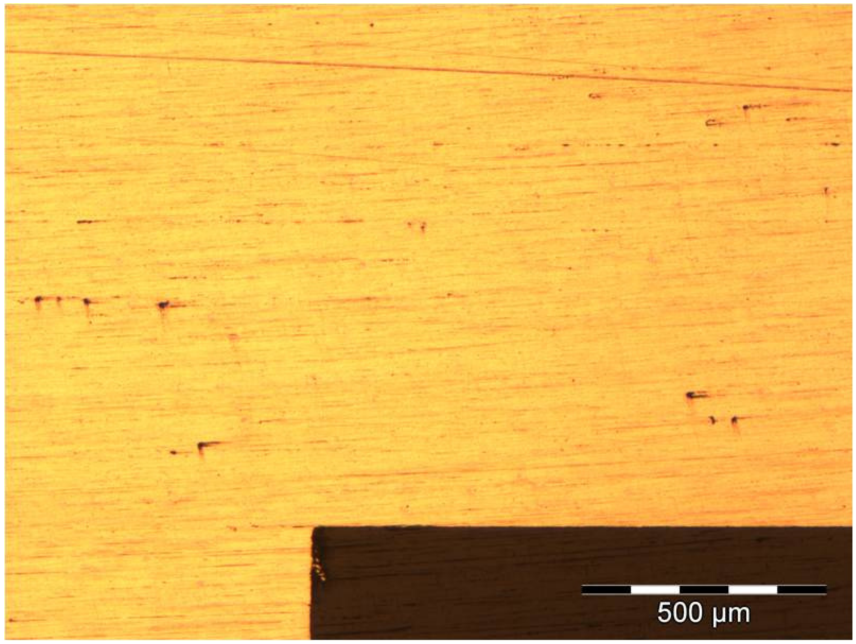

Figure 21: Foil aluminum layers near the center of the tin bismuth rib specimen.

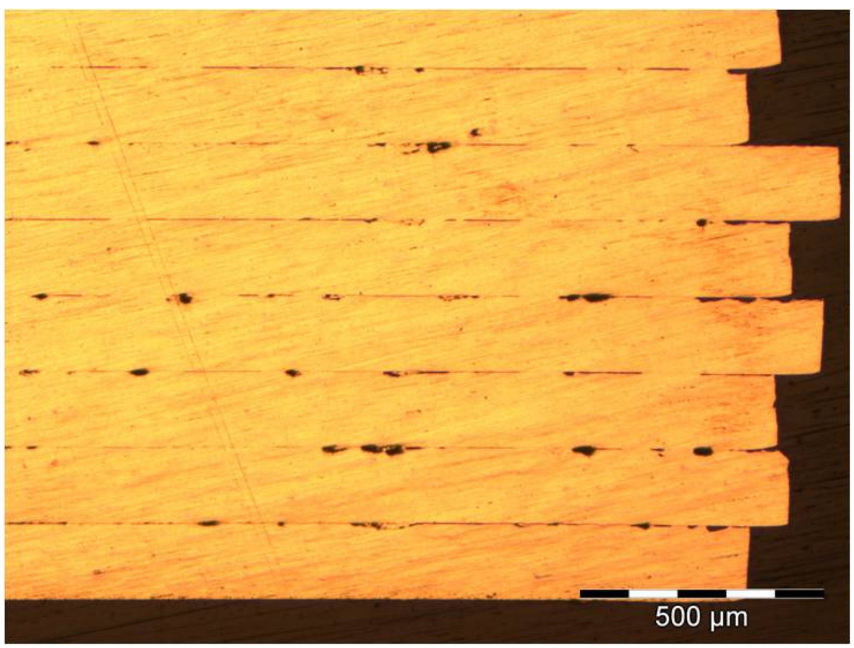

Figure 22: Aluminum foil layers at the far edge of the tin bismuth rib specimen.

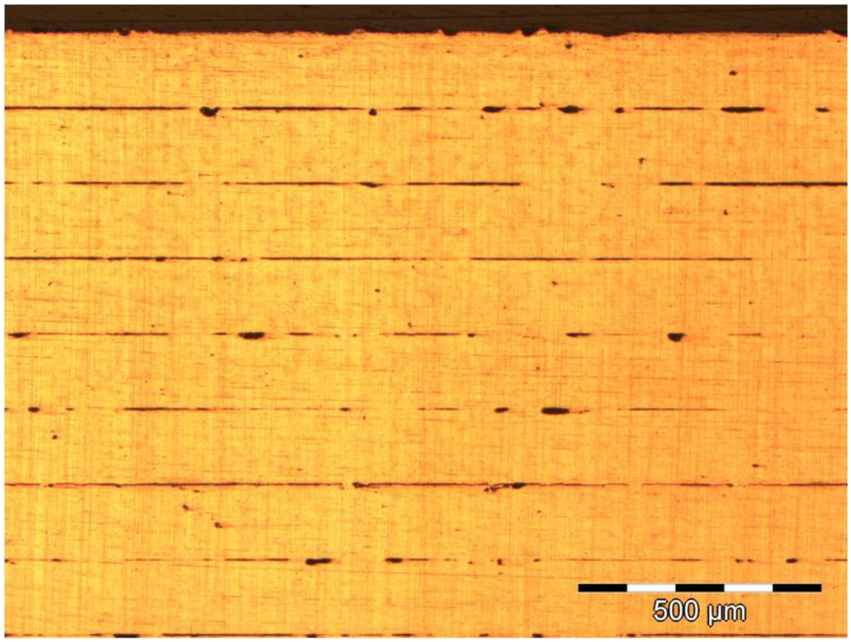

Figure 23: Top aluminum foil layers near the center of the tin bismuth channel specimen.

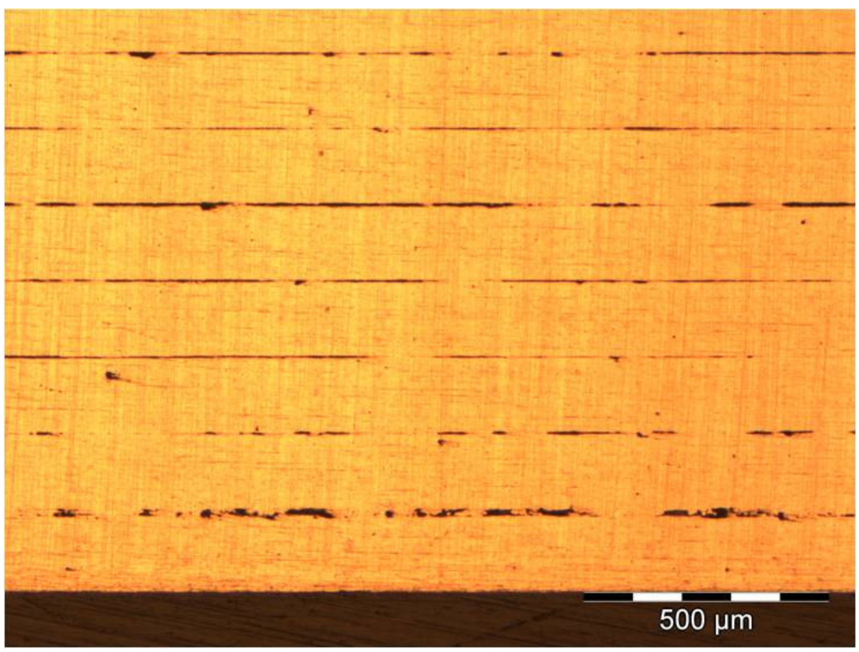

Figure 24: Bottom aluminum foil layers near the center of the tin bismuth channel specimen.

Aluminum foils over water soluble casting wax

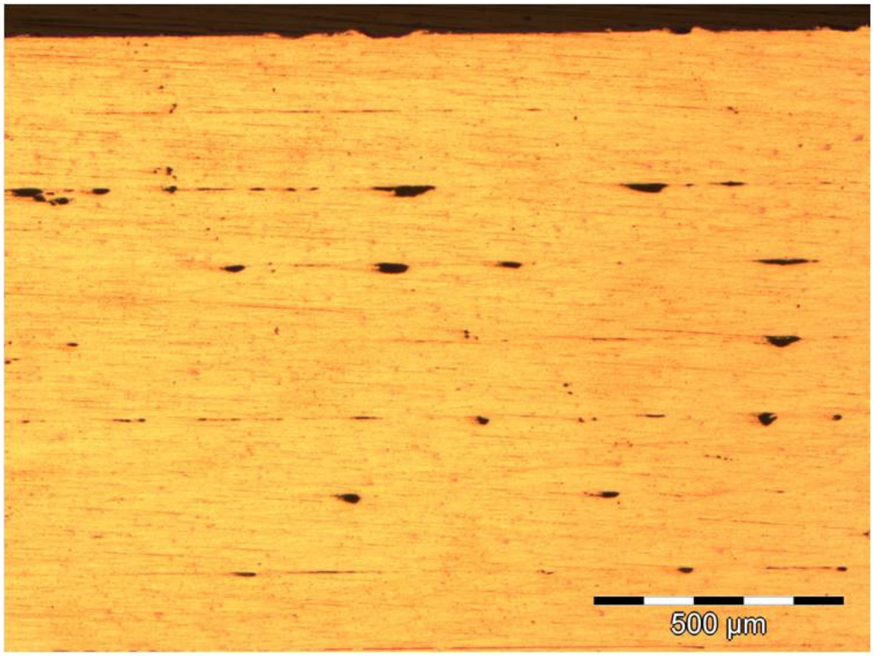

Figure 25: Top aluminum foil layers near the center of the wax pocket specimen.

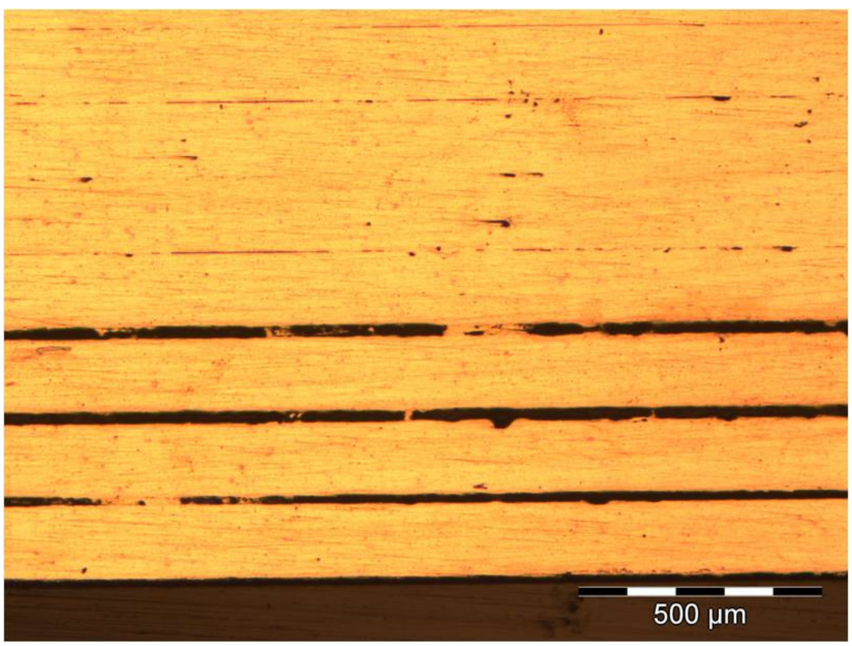

Figure 26: Bottom aluminum foil layers near the center of the wax pocket specimen.

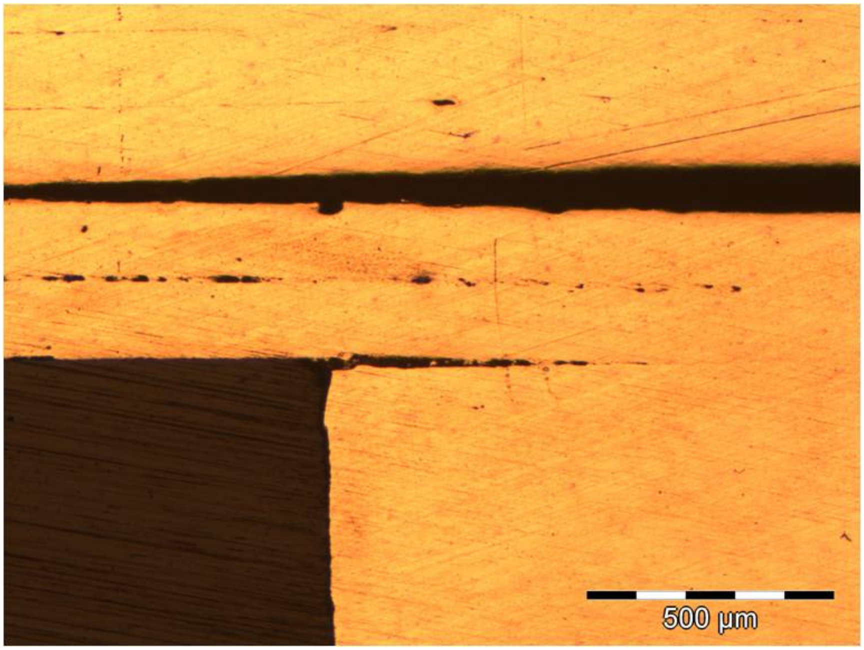

Figure 27: Foil aluminum layers near the edge of the wax pocket specimen with large defects and a crack at the sharp corner.

Aluminum foils over sucrose

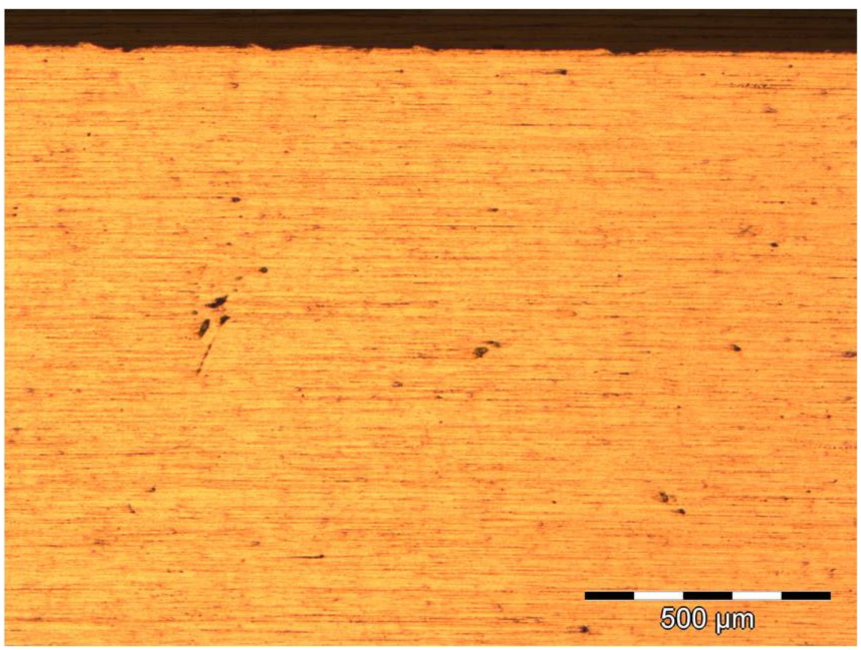

Figure 28: Top aluminum foil layers near the center of the sucrose pocket specimen.

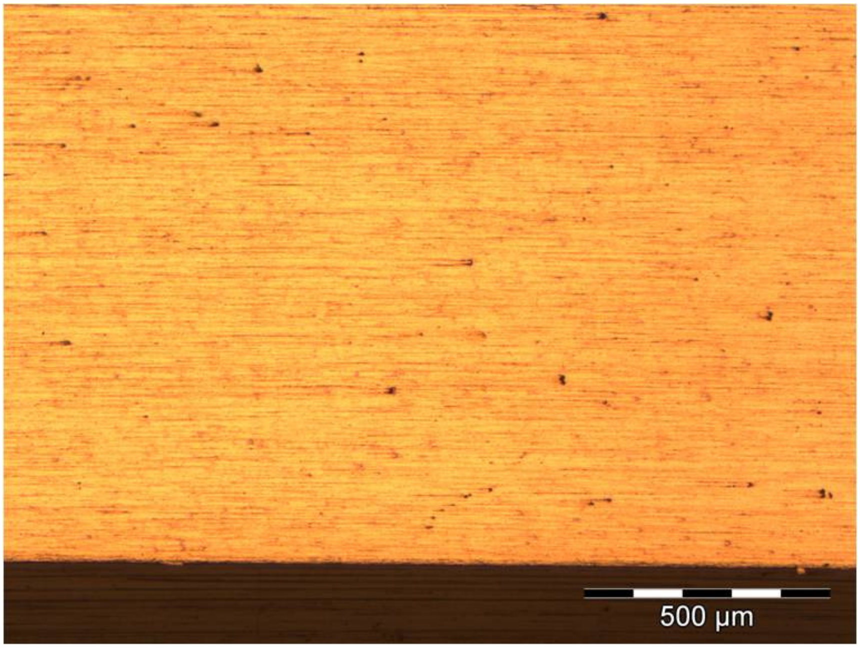

Figure 29: Bottom aluminum foil layers near the center of the sucrose pocket specimen.

Aluminum foils over WaterWorks™

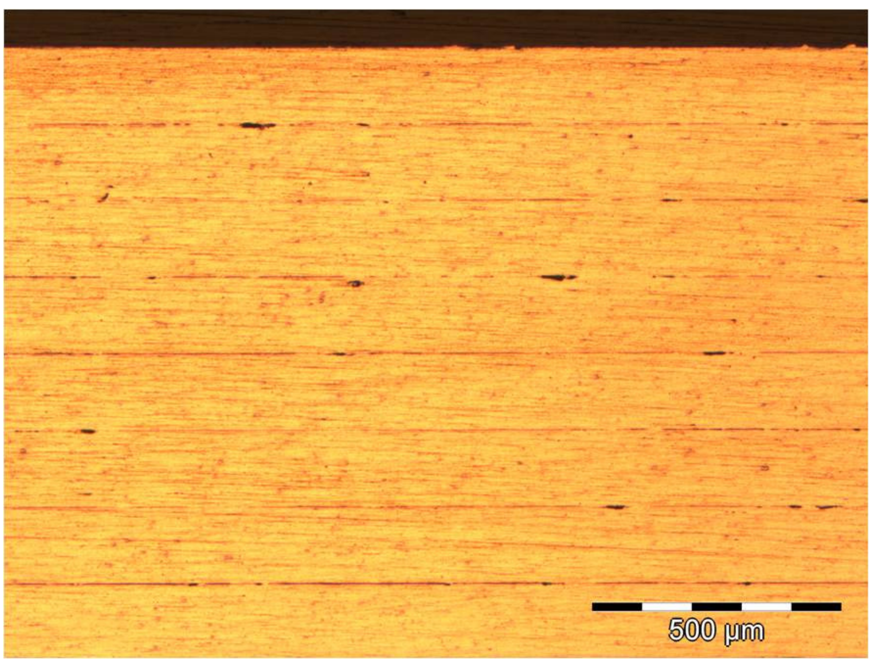

Figure 30: Top aluminum foil layers near the center of the WaterWorks™ pocket specimen.

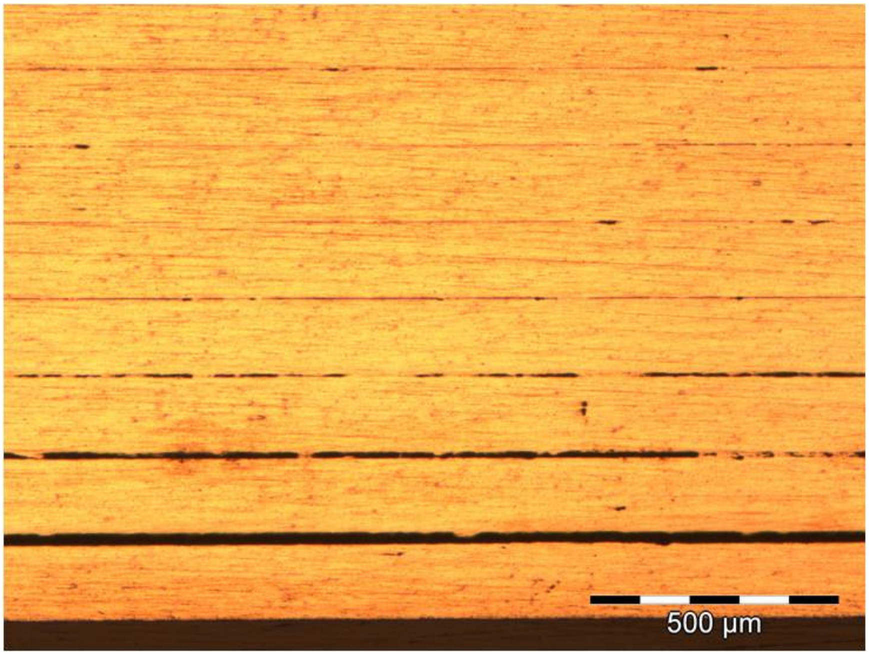

Figure 31: Bottom aluminum foil layers near the center of the WaterWorks™ pocket specimen.

Aluminum foils over Leco® QC epoxy

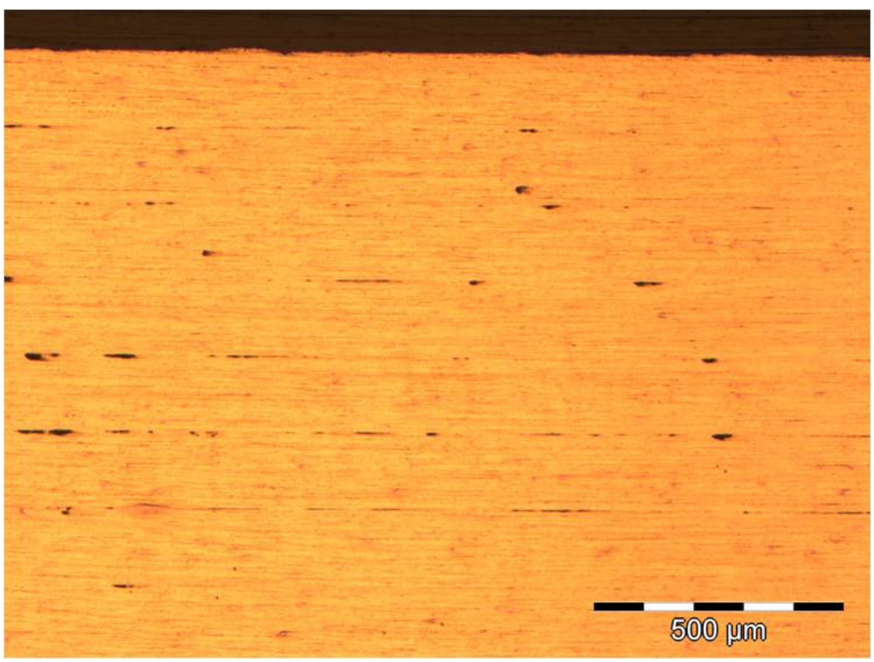

Figure 32: Top aluminum foil layers near the center of the epoxy pocket specimen.

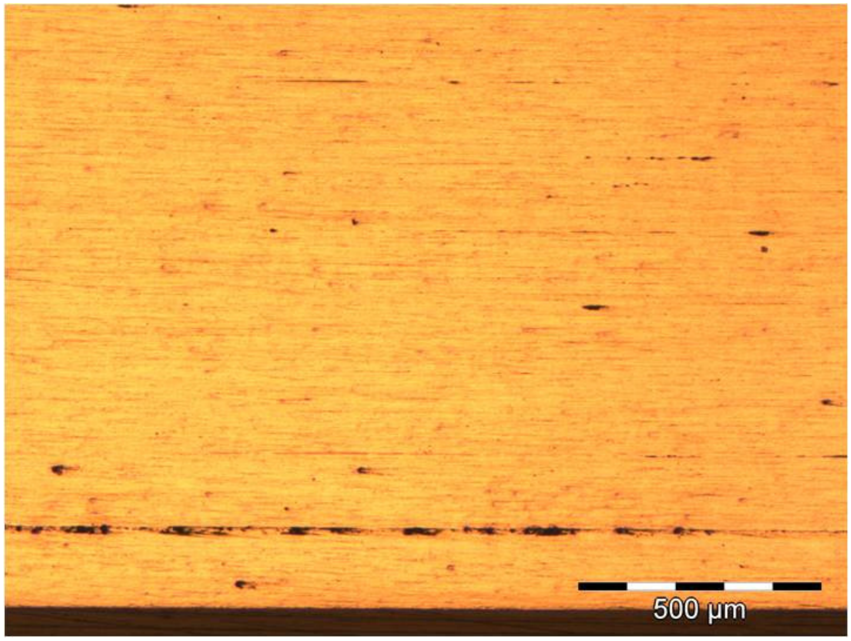

Figure 33: Bottom aluminum foil layers near the center of the epoxy pocket specimen.

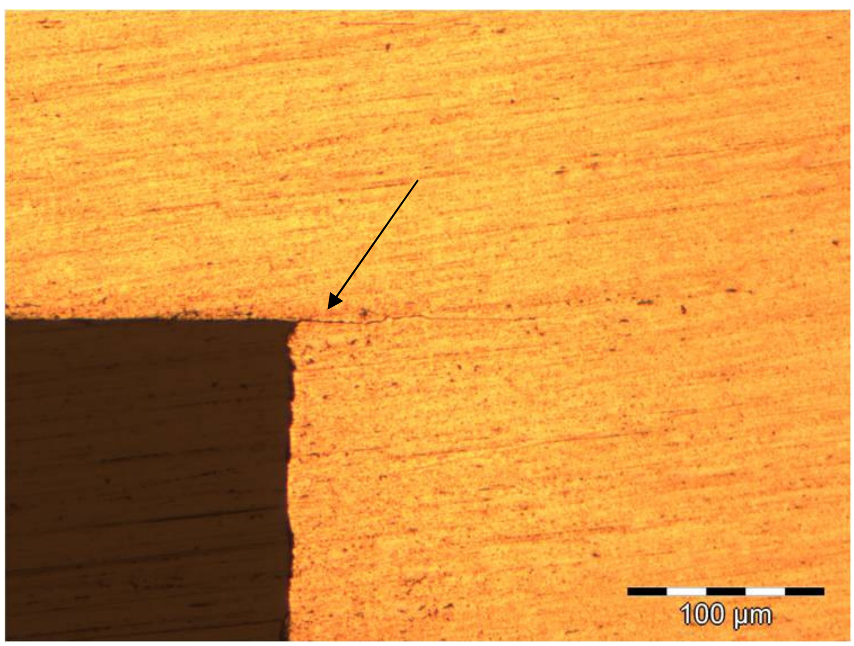

Figure 34: Aluminum foil layers near the edge of the epoxy pocket specimen with a crack at the interface.

All of the support materials were easily removed from the build plate except for the epoxy material and WaterWorks™. The epoxy had to be mechanically cut out from the plate. The WaterWorks™ was difficult because the solution used to dissolve the material contains sodium hydroxide, which is very corrosive to the aluminum.

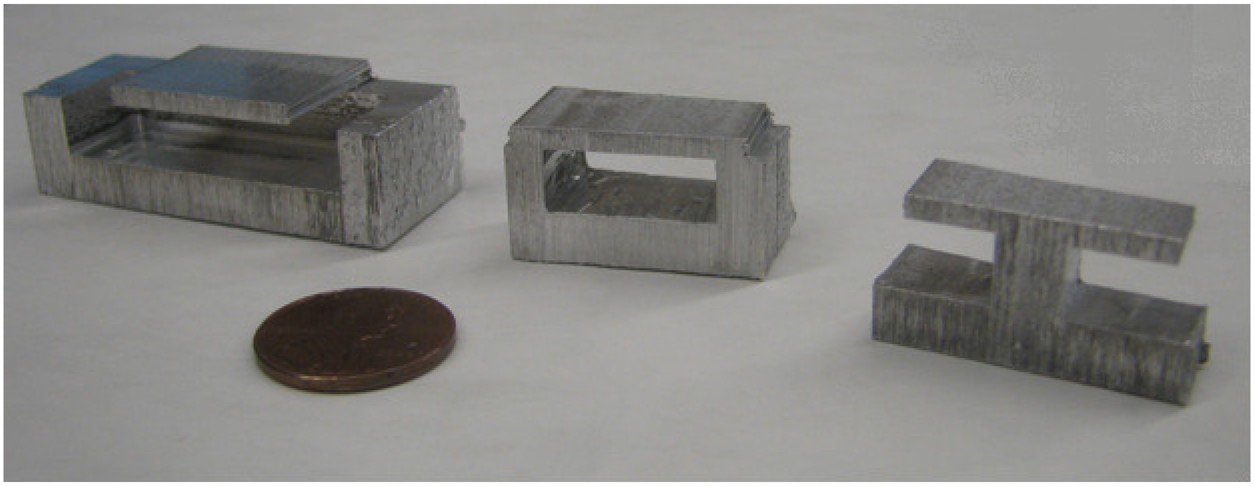

Figure 35: Channel, pocket, and rib (left to right) geometries after support material has been removed.

4. Discussion

4.1 Support Material Performance

All of the attempted support materials were successful for building over the pocket feature. This indicates that it was the simplest geometry to provide a support for. The rib feature was completed for all materials except the water soluble casting wax, which caused the UC machine to fault due to the wax deforming. However, for the sucrose, WaterWorks™, and epoxy the foils were only lightly bonded over the rib and were easily removed. During deposition over these three materials several layers were welded successfully, however after approximately 10 layers the entire deposition became delaminated. This indicates the layers were only weakly bonded initially. The tin bismuth support material was the only material which enabled a successful build for all three of the geometries. It is also the only metal support material of all the materials tested. This success may have to do with the way vibration is transferred through the plate, which may have been essentially damped by the other materials. Since the tin bismuth is also a metal it may have enabled some amount of metallurgical bonding between support and build material during deposition, but then delaminated during later foil deposition or post-processing.

None of the support materials were found to bond with the first tape layer above. However each support material did enhance the ability of the subsequent layers to bond and full recovery was seen after around 10 layers. During the consolidation of the foils the sucrose material and the wax were seen to be slightly melted from the localized heat generated by the ultrasonic consolidation process. This was apparent due to the support material being squeezed out from the sides of the tape when the sonotrode was in contact. The tin bismuth also seemed to be slightly melted or deformed since the milling marks were erased from the surface. The

WaterWorks™ and epoxy materials were not melted and still had visible machining marks left in the materials.

During welding over the sucrose material, a fine dust and small fine cracks were generated due to the ultrasonic energy. Once the bonding was completed it was observed that both the wax and sucrose materials were smeared onto the aluminum surface underneath the foils, which inhibited bonding.

The aluminum 3003 H14 build plate had the highest hardness, at 46.9 HB. The sucrose filled with aluminum powder had the highest hardness of all the support materials tested, at 31.5 HB. The WaterWorks™, Leco® epoxy, and tin bismuth had similar hardness values all within the range of 15-20 HB, which is less than half of the build plate material. Since the wax material was fully penetrated by the ball indenter it had a hardness much less than all the other materials.

The layers of aluminum constructed on the build plate without any type of supports show a significant amount of unbonded regions. This however is expected due to the fact that the welding was performed at room temperature whereas the normal building temperature is 300°F.

Based on the pocket micrograph images the material hardness has some correlation with a material's ability to provide a support in UC. In general as the hardness increases the number of voids and unbonded regions are reduced. The bonding was also usually improved, for the pocket and rib feature, near the more rigid build plate. The bonding over the sucrose showed the least signs of voids and defects along the pocket interfaces. Although the aluminum filled sucrose gave good bonding results it was somewhat hindered by the material breaking up during the UC process.

A critical region for bonding using support materials is at sharp corners and edges where the consolidated layers have a tendency to form small cracks. Another somewhat difficult area lies within the first several layers above the support material, since all but the sucrose support showed signs of delamination within the first several layers.

4.2 Recommendations

In order to successfully use support materials in ultrasonic consolidation the following can be recommended based on this study.

- A lower build temperature or room temperature should be used to reduce the softening of the support material unless the material can withstand high operating temperatures.
- A support material should be used which cannot be significantly melted from the localized heat generated during UC.
- A harder support material should be used to reduce the amount of interface voids and delamination.
- Metal support materials appear to give advantages since the deposited layers can be lightly welded to them.

4.3 Future Work

This study has provided an overview of several support materials for use in UC. As a result of these experiments, we have identified the following areas for future work that may provide further insight.

- Investigate support materials in combination with build materials other than aluminum.
- Identify support materials which can withstand elevated temperatures.
- More carefully consider the use of fillers to strengthen and stiffen support materials.
- Investigate automatic deposition methods within the ultrasonic consolidation machine.

- Look into whether the location or position of the supported area on the aluminum build plate affects bond quality.
- Use heat treatment after the build to reduce the number of interlaminar defects.
- Develop better parameters for building at reduced temperatures and with a support material to increase overall LWD.

5. Conclusions

Support materials were studied because of the potential geometric benefits. Five different materials were investigated for use as a support material in the ultrasonic consolidation process. In order to test the materials three different geometries, pocket, rib, and open channel were built to observe material performance. Only the tin bismuth material allowed all three geometries to be constructed. From optical micrographs the presence of voids and delaminations were reduced as the support material hardness increased. Epoxy would suit the electronics potting purpose the best since it can be poured at low temperature, is heat/chemical resistant, and is nonconductive.

A support material must provide enough hardness to the point where the material is not deformed under the load of the sonotrode. A support material must have a sufficiently high melting point, otherwise melting and deformation will occur and interfere with the bonding interface. If sufficient resistance is not provided the material will deform and layers will have poor bonding.

This paper has shown that there are several possible options for support material, some better than others. Although not an exhaustive study it provides insight into the types of materials which may posses desired characteristics of a support material for use in ultrasonic consolidation. The effective development of an improved support material will help ensure that the applications of ultrasonic consolidation to many different industries are realized.

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