Support Materials Development and Integration for Ultrasonic Consolidation

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SUPPORT MATERIALS DEVELOPMENT AND INTEGRATION FOR ULTRASONIC CONSOLIDATION

by

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ABSTRACT

Support Materials Development and Integration for Ultrasonic Consolidation

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Support materials play a vital role across the entire field of additive manufacturing (AM) technologies. They are essential to provide the ability to create complex structures and features using AM. Successful implementation of support materials in ultrasonic consolidation (UC) will provide a vast opportunity for improvement of geometric complexity. Experimentation was performed to evaluate suitable support materials and their effectiveness within UC. Additionally a fused deposition modeling (FDM) system was integrated into the UC build environment to create an automated support deposition system. Finally several unique structures were built using support materials to demonstrate the improved geometric capability and to develop design rules for use in UC.

(123 pages)
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<td>Two and one half dimensions</td>
</tr>
<tr>
<td>3-D</td>
<td>Three dimensional</td>
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<tr>
<td>ABS</td>
<td>Acrylonitrile Butadiene Styrene</td>
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<tr>
<td>AM</td>
<td>Additive Manufacturing</td>
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<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
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<tr>
<td>CNC</td>
<td>Computer Numerical Controlled</td>
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<td>FDM</td>
<td>Fused Deposition Modeling</td>
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<tr>
<td>LWD</td>
<td>Linear Weld Density</td>
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<tr>
<td>ONR</td>
<td>Office of Naval Research</td>
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<tr>
<td>RpCAM</td>
<td>Solidica’s Proprietary Programming Software</td>
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<tr>
<td>SFF</td>
<td>Solid Freeform Fabrication</td>
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<tr>
<td>SLS</td>
<td>Selective Laser Sintering</td>
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<td>STL</td>
<td>STereoLithography format</td>
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<tr>
<td>UC</td>
<td>Ultrasonic Consolidation</td>
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<tr>
<td>UTEP</td>
<td>University of Texas at El Paso</td>
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<td>UV</td>
<td>Ultraviolet</td>
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CHAPTER 1
INTRODUCTION

Since the late 1980s the field of additive manufacturing (AM) or layered manufacturing (LM) has been changing the way we approach design and manufacturing. AM has profoundly impacted the way companies produce models, prototypes, and tooling. This technology has dramatically accelerated the time to market for products since the designer can now ‘feel and touch’ the prototype in order to detect and resolve errors before full production is begun [1]. Some businesses are even using AM for small production runs without tooling [2]. Additive manufacturing is a manufacturing process which utilizes additive, subtractive, and formative fabrication techniques [3]. The primary advantage of AM is that material is only added where it is needed and thus eliminates the need for complex molds or intensive machining setup. This makes AM well suited to prototyping and single or short runs of a product without long lead times. In theory the additive aspect of AM can create parts without any material waste.

Additive manufacturing involves taking a 3-D CAD model and slicing it up into thin parallel layers. These layers are then compiled into a computer program which is sent to an AM machine to be constructed one layer at a time. A sacrificial support material may also need to be added concurrently to provide support to tall structures or provide a build surface for the next layer which would otherwise droop or fall [4]. Supports particularly provide the ability to create internal cavities or channels as well as overhanging or cantilevered features. Without the capability of support materials in an AM process the geometry and strength of prototypes will be greatly limited.
Some AM processes such as selective laser sintering (SLS) require no additional supports because the unmelted build material acts as a support. However, most AM processes will require a support structure for overhanging features or internal cavities.

1.1 Additive Manufacturing

Additive Manufacturing (AM) also known as Solid Freeform Fabrication (SFF) is a process by which a 3-D computer model (CAD model) is directly fabricated or produced by constructing the part layer by layer. It is a highly flexible and cost-effective alternative to traditional methods to create prototypes and final components [5]. AM is accomplished by virtually slicing the model into thin layers, which are then constructed one at a time, from the bottom up, using an additive process. An additive manufacturing process simply adds material where it is needed instead of a subtractive process which removes all unwanted material from a block of material. However, this does not mean that subtractive fabrication is no longer necessary, because some AM technologies rely on subtractive processes to obtain a precise final finish. Therefore additive and subtractive manufacturing processes are complementary to each other.

Many different AM processes exist to produce prototypes out of metals, polymers, paper, and even sugar. The build materials consist of powder, liquid, sheet, or filament of material which is deposited in a layer-wise fashion.

Some of the main benefits to additive manufacturing include: fully functioning models, wide range of materials available, multicolor capability, extremely short lead times, ability to pause during any point during build, and embedded electronics. Some of the disadvantages to AM are: parts are generally built one at a time, large builds can take several hours or days, parts may contain porosity, parts are generally more expensive
than mass-produced parts, and final finish or dimensions may not meet design requirements.

1.2 Process Planning

Every AM process generally contains the same basic steps as shown in Figure 1.1: model generation, orientation, slicing, support generation, path planning/material addition, and post processing [6]. These steps are generally aided by computer programs, which greatly simplify the process.

The model generation is performed in a CAD program to create a virtual 3-D model of the desired part. The CAD model is then converted to the STL file format which represents the model boundary as a list of triangles each described by three vertices and an outward pointing normal vector [7].

![Process planning sequence](image)

Figure 1.1: Process planning sequence adapted from Marsan et al. [6].
Orientation operations must then be performed to determine the build position. The orientation is important, as it affects the build time, amount of supports, mechanical properties, and part surface quality [7,8]. The height in the build direction usually relates directly to the build time; the taller the part the longer the build will take. Thus it is generally desirable to lay tall parts on their side to reduce build time and ultimately cost. The amount of supports is also important with respect to orientation, because certain orientations will require different amounts of support; and some none at all. Mechanical properties will also be affected by the part orientation since AM is a layered process and the parts are not homogenous or isotropic throughout. The surface quality can be greatly altered by the orientation as well because if the layer thickness is larger than certain features, they will show poor resolution.

Ideally a part will be oriented such that the build time is reduced, the supports are minimized, the mechanical properties are the highest, and the surface finish resolution is the best, however the same position will not typically optimize all aspects therefore some compromise may need to be taken (Figure 1.2).

Figure 1.2: Various different build orientations for a given part. The shaded regions represent necessary supports [7].
The next step in the process plan for AM is slicing. The slicing procedure is very similar to the idea of a topographic map, which uses defined contour lines to define the terrain. This process enables the model to be represented as a combination of many layers and thus allowing it to be built one layer at a time.

The thinner the slice is the more detailed and smoother the part will be. This is also known as the ‘stair stepping’ effect simply because the thicker the slices are the more ridge like stairs will be apparent (Figure 1.3). A thinner slice will also allow more part detail and will capture fine features of the part that might otherwise be lost with thicker slices.

Based on the position of the model, supports must be added to hold up features which cannot support themselves. Supports may be considered either internal or external to accommodate hollow cavities and overhanging features respectively [9]. Most often supports are generated automatically by a computer program, which determines where supports are needed. Supports can also take many shapes and are not always fully dense, but may have a honeycomb-like structure, to reduce material usage.

![Stairstepping Effect](image)

Figure 1.3: Graphic showing how a model can be represented as a series of layers.
Material addition is a computer-controlled process which generally requires no human involvement. Material addition occurs one layer at a time and then progresses to the next layer. Many material addition methods are used including laser sintering, laser melting, electron beam melting, ultrasonic welding, resistance melting, UV curing, and inkjet printing.

Post processing is often required to produce the desired end product. This is generally a manual process which removes the support material and cleans the surface of the part. This can include soluble support water baths, sand/bead blasting, machining, and painting.

1.3 Ultrasonic Consolidation

In 2000 the company Solidica Inc. was founded by Dr. Dawn White based on the integration of ultrasonic metal welding and computer numerical controlled (CNC) milling technologies to create a direct metal additive manufacturing machine [10]. Ultrasonic consolidation has been successfully applied to create uniform temperature surfaces, satellite decking, embedded optical fibers, metal matrix composites, antennas, and other complex electrical and mechanical systems (Figure 1.4) [11-21].

Figure 1.4: Optical wires ultrasonically welded between metal foils [22].
It has also been demonstrated with a wide range of materials including various aluminum alloys, nickel, stainless steel, copper, brass, inconel, titanium, and MetPreg® [22-27]. Different material combinations can also be combined to create a laminated metal composite as shown in Figure 1.5 [28].

Ultrasonic consolidation is a solid state process which requires no special build environment, which makes it suitable to electronics embedment and many other unique build structures. During the UC process the material at the interface may reach up to 50% of the melting temperature of the material [29]. Operating in the solid state range reduces part embrittlement, residual stresses, and distortion.

Ultrasonic consolidation uses a continuous ultrasonic seam welding process to bond thin metal foils followed by subsequent contour machining [30]. During the welding process two metal surfaces are brought into intimate contact under a high frequency 20 kHz (ultrasonic) low amplitude vibration and normal load (Figure 1.6). Surface oxides are fractured and displaced creating an atomically clean surface for the metal to bond [23].

In order to describe the metal bond quality between the metal foils a parameter called linear weld density (LWD) is used. LWD represents the proportion of bonded interface in relation to the total interface length [23]. Therefore a high LWD part will contain very few unbonded regions throughout the foil interfaces and as a result be less porous and mechanically stronger. Ram et al. has intensively studied methods for improving LWD using different methods with the most effective being surface machining [31].
Figure 1.5: Aluminum and titanium composite material created using ultrasonic consolidation [22].

Figure 1.6: Schematic of the ultrasonic consolidation process [32].

Ultrasonic metal welding was intensively studied by H. P. C. Daniels in the early 1960s [33]. He performed many experiments to bond metal sheets, plates, wires, and non-metals in many various combinations (Figure 1.7). His work provided the foundation for ultrasonic welding and identified many important processing parameters to achieve good welding conditions. More recently ultrasonic welding has been applied to
many new applications and materials such as ceramics and metals and even underwater welding [34-35].

Ultrasonic welding has three main parts including the sonotrode, workpiece, and anvil (Figure 1.8). The sonotrode applies the specified vibration amplitude at a certain frequency to the workpiece, which is fixed and supported by the anvil. The main processing parameters of UC include: vibration amplitude, vibration frequency (fixed), normal force, build plate temperature, welding speed, sonotrode diameter (fixed), and sonotrode texture (degrades over time). Of these parameters the ones which can easily be adjusted and modified are vibration amplitude, normal force, build plate temperature, and welding speed. In addition to machine parameters the material itself can have certain characteristics which either promote or decrease bonding. These include material type, temper, thickness, surface finish, and width.

![Figure 1.7: Ultrasonically weldable material combinations [29].](image-url)
The build process in UC can be described as follows. First, Sonogel, an ultrasonic couplant, is applied to the back of a 14 inch by 14 inch by 0.5 inch thick aluminum 3003 build plate to help transmit the ultrasonic vibrations. The plate is then placed into the machine on the heating plate and heated to the desired temperature, which can be adjusted from room temperature to 400° F. After the plate has reached the desired temperature it is secured into the machine using 8 bolts torqued to 50 ft-lbs. Once the plate is bolted down the z height with respect to the plate must be found. This is achieved by running a machine program which lowers the sonotrode slowly down towards the plate until the desired resistance or force is encountered when it touches the plate surface. This z height value is recorded in the machine and used as the zero reference point for the build. Next the plate is milled using a 3/8 inch carbide end mill to
remove approximately 0.020 inches of material to ensure the work surface is flat and parallel to the sonotrode. After the plate is milled the machine is ready to start building.

The build process uses an automatic tape feeding system to lay the foil tapes in the position determined by the RpCAM program based on the geometry of the part. The standard foil tapes for the machine are 3003 H-18 aluminum with a thickness of 0.0059 inches (~150µm) and width of 0.941 inches (~24mm). The tapes are first “tacked” into place using a low energy ultrasonic weld to position them and ensure they do not move or “walk” during the actual weld. After the needed tapes for a layer are tacked into place the machine makes a final full energy weld across the tape. Once the entire set of tapes for a given layer is welded, the layer contour is milled to create the desired shape. Additionally the build process can be stopped at any point to mill special internal features or embed electrical components. This process of tape welding and trimming occurs until the final build height is reached and can be stopped and started at any point during the build. Also if a problem or design change arises, the part can be milled flat to a specified height and the build resumed from that point. If desired, finishing toolpaths can also be performed in order to create a smooth surfaced part which requires no post processing other than removing the part from the build plate. Removal of the part is accomplished by removing the build plate by milling from the backside until the part comes free. This final step can ultimately be avoided if the build plate is incorporated as part of the design.

1.4 Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) was developed in the late 1980s by S. Scott Crump and commercialized under the name Stratasys, Inc. in 1990. FDM is an additive manufacturing process which produces parts from production quality thermoplastics like
ABS and polycarbonate as well as investment casting wax. The build and support material is a continuous 0.070 inch diameter filament held on a spool that is fed through heated extrusion nozzles. The standard FDM machine has two extrusion nozzles; one for support material and the other for the build material. The material filament is heated to a semi-liquid state as it passes through the extrusion head, which is controlled by an x-y motion control (Figure 1.9). The nozzles extrude material (called roads or beads) as they follow the contours in the x-y plane based on the program generated by the CAD model. Once a layer is complete the build table moves in the z direction one layer thickness for the next layer to begin. This process is repeated for each layer until the final build height is reached.

The main process parameters for FDM include: bead width, air gap, build temperature, and raster orientation [37]. The bead width describes the thickness of the bead that is deposited, which can be adjusted from 0.012” to 0.0396” for a size T12 nozzle. The air gap is the distance between the beads of material deposited which can be

![Figure 1.9: Schematic of the fused deposition modeling (FDM) process [36].](image-url)
negative (overlapping or more dense) or positive (gaps or less dense). Build temperature is the temperature that the nozzles are heated to in order to melt the material to be deposited. The direction of the beads relative to the part is called raster orientation and is usually varied throughout the build to create a stronger structure.

The machine program is generated by Stratasys’ computer program, Insight, from a 3-D CAD model. This involves importing a model in the STL file format, which is a triangulated surface approximation of the model. Next the part is oriented in the program by the user to define the build orientation. Generally this is done so that the amount of supports required are minimized, which also usually means the build time is reduced. As shown in Figure 1.10 below, orientation (a) requires the use of supports whereas orientation (b) does not. Therefore, if possible, orientation (b) is the desired position with regards to material usage and build time.

Once the model is oriented as desired it must sliced. Slicing takes the model and cuts it into thin parallel layers usually around 0.010 inches thick. After the model is sliced the supports must be added. The program will automatically determine where the supports are needed based on the model and create the support toolpaths. Finally, after the model is supported the program creates the toolpaths for the build and support

![Figure 1.10: Different orientations for the same part [38].](image)
materials. This final generated program is then sent to the FDM machine where the build can be initiated.

1.5 Support Materials

Support materials are extremely important to AM technologies because of the benefits that can be geometrically achieved. Manufacturers and researchers of AM machines have continually faced the inherent problem of providing a support structure during additive manufacturing. Many times support structures can be eliminated by simply changing the build orientation; however this only remains true for parts with uncomplicated geometry. For most parts the use of a support material is unavoidable and a necessary requirement. Without an integrated support materials system many geometries and features will be impossible to create (Figure 1.11).

A support structure in additive manufacturing is a scaffold or dense structure which is generally built simultaneously with the part, but is designed to be removed once the entire part is built. According to Allen a support structure is needed when: material on one layer overhangs the previous layer by more than a specified amount, a floating component not attached to the rest of the part is introduced, and part stability is compromised due to orientation [4]. Support materials in AM can exist in one of two

Figure 1.11: Several geometries which require support materials [39].
ways. The first method is to rely on unused build material to provide a natural or self-supporting structure which essentially encases the entire build. The second approach involves building a support structure from CAD data generated by the build software which identifies regions that will require support. This additional build process may use the same material as the build, such as in stereolithography, however often a new material is introduced which can be easily removed. Generally support materials are removed by using water baths, heat, or mechanically breaking off by hand.

The need for a support material may be reduced or eliminated using a decomposition-based manufacturing approach [40]. This method breaks the final part into several pieces which can be constructed independently without supports and ‘glued’ together to obtain the finished part. This process also has the advantage of creating parts larger than the build chamber will allow. The disadvantage of this method however is that the joints may be very weak compared to the rest of the component and certain materials such as metals are not easily ‘glued’ or joined together. For the case of FDM this approach has proved successful simply by manually rotating the build and the subsequent build is performed directly on the previous build thus eliminating both support materials and a glued joint [38].

Ideally a good support material will be easily deposited and removed, non-toxic, relatively stiff, and low cost. However, since each AM process uses different deposition methods, a universal support material is not possible. Therefore a new method and material needs to be developed specifically for a given process and material. Sometimes similar approaches or materials for support in AM can be carried over to different technologies.
A support material developed in UC is important because it is the only direct metal technology which uses solid state processing. This means that the build material never reaches its melting point, but stays below it. Solid state AM therefore provides an ideal platform for embedding electronics, smart materials, and fibers. Support materials are necessary in UC since the lack of support materials means that certain features such as tall ribs, thin walls, overhanging structures, and wide channels are difficult or impossible to build.

Attempts have been made to use a support material in UC, but currently there has been no successful integration of support materials into the process of UC [11,16]. A support in UC presents a unique challenge because it must ultimately survive large compressive loads from the sonotrode. Also since high frequency (ultrasonic) low amplitude vibrations are applied to the material being deposited, it is important that the support material does not damp out these vibrations. If the vibration is effectively damped out by the support the build material will not bond.

Some of the suggested support options for UC include low melting point alloys, pre trimmed metal foils, high strength waxes, and water soluble ceramics [41]. Many epoxy and polymer materials have also been used as filler or potting materials for embedding electronics with limited success [11]. According to George the addition of support materials in the UC process would be the most significant improvement for creating functional complex structures [16].

Support materials for the following experimentation were chosen based on materials identified from prior research and recommendations. These included materials from the following groups: low melting point metal alloys, high strength waxes, epoxies,
thermoplastics, and organic materials. The support materials used represent a range of
different potential material types which will help indicate the desired characteristics of a
support material for ultrasonic consolidation.

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CHAPTER 2

THESIS STATEMENT

The following research is directed towards both the development and integration of support materials within ultrasonic consolidation to further the geometric capability of this AM process. This research specifically focuses on developing suitable support materials, developing design considerations, and integrating an automatic deposition system for support materials in UC. The results of experimentation and testing are supplied in the proceeding chapters.

The third chapter discusses the testing and evaluation of a wide range of materials which may be considered good candidates as a support material. Chapter four examines the complex issues encountered when building with support materials in ultrasonic consolidation and presents building guidelines based on the completion of several different features. The fifth chapter describes the completion of an integrated deposition system and provides a building process plan for successfully building within the UC build environment. Ultimately these solutions laid the foundations for future work and have led to the expansion of the geometric capability of ultrasonic consolidation.
CHAPTER 3
INVESTIGATION OF SUPPORT MATERIALS FOR USE IN ULTRASONIC CONSOLIDATION

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.

3.1 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

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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 value 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 3.2-3.5. 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 3.1).

Fig. 3.1: Ultrasonically welded part where the dark regions represent unbonded areas 
over a milled channel and the light areas correspond to bonded regions.
Fig. 3.2: 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.

Fig. 3.3: 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.

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 3.5 [14]. Using a support material around tall ribs and thin walls will prevent this motion and allow taller and thinner ribs to be constructed.

Fig. 3.4: Large overhanging features in UC will collapse without support.
Fig. 3.5: 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.

3.2 Experimental Work

3.2.1 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 3.6 and 3.7.

The geometries were milled into a UC build plate of Aluminum 3003-H14 (Figure 3.8). 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”.

![Diagram of three different geometries](image1.png)

Fig. 3.6: Three different geometries used to test support materials. Support material was manually deposited into features.

![Diagram of tapes consolidated](image2.png)

Fig. 3.7: Tapes consolidated over three types of features: pocket, freestanding rib, and open channel.
3.2.2 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 3.9. The resulting blocks were then inserted and fixed into the plate using a small amount of high strength epoxy.
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 3.10).

Fig. 3.9: WaterWorks™ blocks built using FDM.

Fig. 3.10: Milled support materials in aluminum substrate. From left to right: tin bismuth, casting wax, sucrose, WaterWorks™, and epoxy.
3.2.3 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.

3.2.4 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 (Figure 3.11). Several speeds and feeds were used during the milling operations with little improvement.

Fig. 3.11: 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 straightforward materials for filling the three geometries.

3.2.5 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.

3.2.6 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.

3.3 Results

3.3.1 Foil Bonding

Figures 3.12-3.16 show the bonding over the various support materials.
The tin bismuth was the only material which enabled deposition over all three geometries (Figure 3.13). The foils were only lightly bonded across the rib and channel features for the WaterWorks™, epoxy, and sucrose (Figure 3.14).

Fig. 3.12: Aluminum tapes after consolidation over support materials. From left to right: epoxy, WaterWorks™, sucrose, casting wax, and tin bismuth.

Fig. 3.13: Aluminum tapes after consolidation over tin bismuth.
The sucrose and wax materials were melted and deformed by the sonotrode during the UC process (Figures 3.15 and 3.16). Melted and resolidified material was also found between the metal foils and build plate.

Fig. 3.14: Delaminated foil layers over the rib and channel with WaterWorks™ support material, which also occurred with the epoxy and sucrose.

Fig. 3.15: Sucrose material was melted and squeezed out along tape edges.
Fig. 3.16: Casting wax was melted and squeezed out along tape edges and between the foil and build plate.

3.3.2 Brinell Hardness

Table 3.1 and Figure 3.17 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.

3.3.3 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.
Table 3.1: Brinell Hardness Measurement Values for Each Material and Aluminum Build Plate.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Hardness 1</th>
<th>Hardness 2</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 3003-H14</td>
<td>46.9</td>
<td>46.9</td>
<td>46.9</td>
</tr>
<tr>
<td>Sucrose+Al</td>
<td>33.1</td>
<td>30.0</td>
<td>31.5</td>
</tr>
<tr>
<td>WaterWorks™</td>
<td>20.6</td>
<td>18.9</td>
<td>19.7</td>
</tr>
<tr>
<td>Leco® Epoxy</td>
<td>17.5</td>
<td>19.0</td>
<td>18.2</td>
</tr>
<tr>
<td>Tin-Bismuth</td>
<td>15.4</td>
<td>16.6</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Figure 3.17: Brinell hardness measurements with error bars for the aluminum build plate and support materials.
Aluminum foils to aluminum build plate

Fig. 3.18: Top aluminum foil layers near the center of the unsupported specimen.

Fig. 3.19: Bottom aluminum foil layers near the center of the unsupported specimen.
Aluminum foils over tin bismuth

Fig. 3.20: Top aluminum foil layers near the center of the tin bismuth pocket specimen.

Fig. 3.21: Bottom aluminum foil layers near the center of the tin bismuth pocket specimen.
Fig. 3.22: Foil aluminum layers near the center of the tin bismuth rib specimen.

Fig. 3.23: Aluminum foil layers at the far edge of the tin bismuth rib specimen.
Fig. 3.24: Top aluminum foil layers near the center of the tin bismuth channel specimen.

Fig. 3.25: Bottom aluminum foil layers near the center of the tin bismuth channel specimen.
Aluminum foils over water soluble casting wax

Fig. 3.26: Top aluminum foil layers near the center of the wax pocket specimen.

Fig. 3.27: Bottom aluminum foil layers near the center of the wax pocket specimen.
Fig. 3.28: 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

Fig. 3.29: Top aluminum foil layers near the center of the sucrose pocket specimen.
Fig. 3.30: Bottom aluminum foil layers near the center of the sucrose pocket specimen.

Aluminum foils over WaterWorks™

Fig. 3.31: Top aluminum foil layers near the center of the WaterWorks™ pocket specimen.
Fig. 3.32: Bottom aluminum foil layers near the center of the WaterWorks™ pocket specimen.

**Aluminum foils over Leco® QC epoxy**

Fig. 3.33: Top aluminum foil layers near the center of the epoxy pocket specimen.
Fig. 3.34: Bottom aluminum foil layers near the center of the epoxy pocket specimen.

Fig. 3.35: 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™ (Figure 3.36). 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.

3.4 Discussion

3.4.1 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

Fig. 3.36: Channel, pocket, and rib (left to right) geometries after support material has been removed.
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.

### 3.4.2 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.

3.4.3 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.
3.5 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.

References


CHAPTER 4
DESIGN CONSIDERATIONS FOR ULTRASONIC CONSOLIDATION USING SUPPORT MATERIALS

4.1 Introduction

4.1.1 Additive Manufacturing

Additive manufacturing (AM) involves the building of a component directly from a 3D CAD model without using traditional methods such as molding, casting, or machining. However some AM processes may incorporate the use of machining in combination with additive techniques. By not requiring complex molds or castings both time and money are saved with AM. Currently AM provides the most benefits where limited quantities or prototypes are needed and not full scale manufacturing, however rapid manufacturing using this technology has already been developed (Wohlers, 2003).

The main thrust behind AM involves virtually slicing the desired part into paper thin parallel layers which are then constructed one at a time. These layers are deposited one on top of each other until the final height is reached. Over the past 20 years many different deposition methods have been developed for AM including laser melting/sintering, UV polymer curing, inkjet printing, ultrasonic welding, and extrusion, to name a few. During an AM build process a sacrificial support layer or layers may also be added. A support material is designed to be a temporary build surface to allow the construction of layers which would otherwise droop or fall (Allen and Dutta, 1995). Support materials are required when building enclosed cavities, cantilevers, or free floating features. The extent to which a support is required is directly related to the

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orientation of the build. Some parts may avoid the need for support materials simply by reorienting the build, however many parts will still require a support material no matter the orientation.

A support material may be considered either intrinsic or extrinsic (White et al., 2004). Intrinsic supports are those which are inherently produced during the process such as selective laser sintering (SLS). During SLS, a laser scans the powder bed, melting the desired areas while the unmelted powder remains surrounding the melted regions to provide support for the next layer. Extrinsic support materials are those where a secondary material is introduced or a scaffold structure is built along with the part. These are completely independent systems which are designed to be broken or dissolved away once the part is completed.

4.1.2 Ultrasonic Consolidation

Ultrasonic Consolidation (UC) is a solid state direct metal AM process which utilizes the benefits of ultrasonic metal welding and CNC milling (White, 2003). The process produces net shape parts by continuously ultrasonically welding thin metal foils (often referred to as ‘tapes’) to form the rough part shape while the CNC mill cuts the exact contours generated from the 3D model.

The metal foils, generally 0.006” (150um) thick and 1” (25.4 mm) wide, rolled onto a coil, are automatically fed to the machine which lightly welds or ‘tacks’ the foils into the correct position and cuts them to length. Subsequent adjacent tapes can also be added in order to cover the total area required. Once a full layer is tacked into place the machine returns once again and performs a final full power weld. To add the layer contours the CNC mill removes the unwanted material at specified layer intervals.
The UC process works by generating ultrasonic differential motion between the metal layers causing oscillating shear forces and plastic deformation which breaks up the surface oxide layer (White, 2003; Kong et al., 2003). This creates atomically clean metal surfaces which under a normal force are bonded.

The basic processing parameters include: normal force, vibration amplitude, welding speed, and substrate temperature. The vibration frequency is fixed at 20 kHz. These parameters in the proper combination provide enough energy to produce a weld. They are however very material dependent and each material or combination of materials requires careful attention to machine parameters. If too high energy is input, the materials will either strain harden and not bond or bond themselves to the sonotrode. If too low the materials will simply not be welded. It is therefore imperative that the proper parameters are used for different materials. Significant work has been established to identify processing parameters for various materials using the UC process, however it is not within the scope of this present work to deal with optimizing parameters for using UC in conjunction with support materials (Kong et al., 2003, 2004; Ram et al., 2006).

4.1.3 Applications of the UC process

The UC process operates in an open atmospheric environment at relatively low temperatures ranging from room temperature to 400°F. The standard building temperature for aluminum 3003 is 300°F. The machine is also designed in such a way that the part is highly accessible to human interaction at any time during the build. This can be utilized to install necessary components or devices along the way.

The inherent characteristics of the UC process provide a unique building capability which allows internal cavities and channels as well as embedded electronic,
thermal, and fiber components (Yang et al., 2009; George, 2006; Johnson, 2007; Siggard, 2007). Various aluminum alloys as well as copper, stainless steel, titanium, brass, and nickel have been shown to be weldable using ultrasonic consolidation (Ram et al., 2007; Tuttle, 2007; Solidica, 2009; Kong et al., 2003). In addition the layered nature of AM also allows multiple materials to be combined to create a gradient structure if desired (Ram et al., 2007).

4.1.4 Supports in UC

Support materials are needed in UC for two main reasons. The first is simply to provide the necessary building surface for overhanging layers or enclosed volumes. The second is to provide the resistance to motion required for ultrasonic bonding to occur. This second case is especially true for thin structures, walls, or ribs which otherwise lack the stiffness to resist ultrasonic motion. The maximum unsupported rib height to width ratio for UC was found by Robinson et al. to be 1:1 height to width ratio (Robinson et al., 2006), thus without supporting geometry or materials, a UC part cannot be taller than it is wide. This ratio was found to be the maximum buildable ratio for ribs longitudinal, transverse, and 45 degrees to the rolling direction.

Most of the work building advanced structures, to this point, has been limited by the lack of a support material. This is especially true where a lack of supports has hindered the development of more geometrically complex structures, which simply are not possible without some type of support. Support materials employed in UC will enable a significant geometric gain and open a new horizon of design possibilities. Successful implementation will ultimately expand and deepen the application of the UC process across many industries.
Currently no one material or method has been identified as a final solution to the issue of support materials within UC, however many have shown some success. Tin-bismuth has been successfully employed as a support material in previous experimentation; therefore it was chosen for use in the following experiments due to its ease of use. Tin-bismuth is a simple binary alloy with a eutectic point at 139°C (282°F) corresponding to 57 wt% Bismuth (Baker and Okamoto, 1992). Since a successful automated deposition system had not been developed at the inception of this research, a manual approach was taken to construct the parts. The scope of this paper is thus to consider the design ramification of the use of support materials primarily by demonstrating the types of complex geometries which were previously not possible and that are enabled using support materials in UC.

4.2 Experimental Approach

The current work seeks to develop design rules and demonstrate successful use of support materials in UC. A number of complex geometries were constructed which are not possible except through the use of support materials, including ribs with a height to width ratio greater than 1:1, demonstration of totally new geometric capability, and investigation of multi-material supported structures.

The build material used was aluminum 3003-H18 (0.006” thick) unless otherwise specified. All of the builds were performed on a 14”x14”x0.5” thick aluminum 3003-H14 build plate. The building parameters used were 1750N force, 17.5µm amplitude, and 46 ipm (inch per minute) feedrate unless otherwise specified.
4.2.1 Tin-Bismuth cooling curve

A cooling curve was constructed for the as-received tin-bismuth support material in order to determine the melting point and approximate composition. This is important in order to determine an appropriate building temperature so that the tin-bismuth is not melted during welding. It is desired that the highest possible build temperature be used since normal building operations occur at elevated temperatures to enhance bonding.

4.2.2 Ribs

In order to investigate the effect of support materials on rib height, two different sizes of ribs were constructed in the longitudinal direction (along the rolling direction of the sonotrode). The two rib widths constructed were 0.125” and 0.0625” and the lengths were a 10:1 length to width ratio. These dimensions were based on Robinson’s et al. earlier work (Robinson et al., 2006). In order to contain the poured support material a 0.25” wide channel was created around each rib. Ribs are an important demonstration of thin wall and high aspect ratio features needed to build more complex parts. It is desired that the addition of support materials will increase the capability to build taller and thinner features than currently possible.

4.2.3 Large Cavities

Large cavities, circular (1.5” diameter) and square (2.0”), were created greater than the sonotrode width of approximately 1” in order that the support material would bear 100% of the load. Without a support material these features are technically impossible in UC and will cause the machine to fault.
4.2.4 Multi-Material Bonding

Four layers of copper 110 were welded to both rib sizes and to the rectangular and circular cavities to observe the behavior with a support material. Support material interaction with various build materials is important since UC has been demonstrated with many materials and a support material should extend its function into these areas as well.

4.2.5 Support Material Alteration

Several high modulus metal powders, including stainless steel and nickel, were mixed with the tin-bismuth support in order to create a stiffer and harder support. This concept was confirmed in earlier experimentation where harder support materials yielded better overall bond quality (see Chapter 3). If the current tin-bismuth material can be stiffened the effects due to support material deformation will be reduced and bonding will be improved.

4.3 Results and Discussion

4.3.1 Tin-Bismuth cooling curve

Results from the cooling curve indicate a near eutectic tin-bismuth composition with a melting point of 273°F (134°C) (Figure 4.1). While this somewhat limits the possible building temperature during UC, it enables the material to be easily removed once the part is completed.
Since the mixture of tin-bismuth used melts at 273°F a build temperature of 240-260°F was used. It was observed that using any higher temperature above 260°F combined with the localized heat generated from the UC process caused the support material to melt out and interfere with the bonding layers. Also heat generated by the cutting tools was enough to melt and splatter or smear the tin-bismuth and interfere with the bonding layers; therefore a lower cutting speed and feed were used in addition to an alcohol coolant.

4.3.2 Ribs

Beginning with a rib greater than the 1:1 height to width ratio milled into the plate the ribs were constructed by alternating adding support material and build material. Layers of build material were added and then milling was performed to expose the rib. Tin-bismuth was then added in excess into the area around the rib and a flat pass milling was performed. This milling process, which removes some of both materials, ensured that both the tin-bismuth and aluminum build material were at the same level. Deposition
was then continued and the process was repeated until at least one additional height to width ratio of material was deposited or the layers became delaminated (Figures 4.2-4.4).

**Figure 4.2** (a) Initial rib is milled into the build plate with channel to contain the support material and (b) support material is added in excess and allowed to cool.

![Figure 4.2](image1.png) ![Figure 4.2](image2.png)

(a) (b)

**Figure 4.3** (a) Build plate is milled to ensure a level build surface, (b) aluminum layers are welded across the top of the rib, and (c) milling is performed to expose the rib and the channel.

![Figure 4.3](image3.png) ![Figure 4.3](image4.png) ![Figure 4.3](image5.png)

(a) (b) (c)
Ribs along the longitudinal or rolling direction have the least resistance to vibration since the sonotrode is vibrating perpendicular to the rib direction. This therefore serves as an important demonstration of the benefits of a support material in ultrasonic consolidation. The 0.125” rib was built to a total height of 0.49” or a 4:1 height to width ratio, while the 0.0625” rib was completed to a total height of 0.31” or a 5:1 height to width ratio (Figure 4.5).

**Figure 4.4** (a) Support material is again added in excess to fill the channel, (b) milling is performed to level the build surface, and (c) aluminum layers are again welded across the top of the rib.

![Figure 4.4](image)

(a) ![Figure 4.4](image) (b) ![Figure 4.4](image) (c) ![Figure 4.4](image)

**Figure 4.5** Completed ribs after being removed from the build plate.

![Figure 4.5](image)
In this situation using a support material increased the buildable height to width ratio by 4-5 times, however a direct comparison to Robinson’s et al. work is not possible since a different building method was used. It should however be noted that for both ribs that a material amount greater than 1:1 was deposited onto a rib already exceeding the 1:1 ratio. Additionally, with an optimized parameter set the bonding could improve further. Initially four layers of material were added and milled at a time; however the support material was ripped out due to the shallow depth. The height was increased to eight layers before milling and the support material remained in place. A potential solution to this problem would be to remelt the entire support structure by heating the plate however this would greatly increase the amount of build time.

The aluminum tapes were not found to have any visible evidence of bonding with the tin-bismuth support material. In fact the tin-bismuth was seen to be slightly melted due to the heat generated by the UC process and the low melting point of the tin-bismuth. Ideally the build material would bond to the support material to enhance bonding of subsequent layers and enable free floating features to be created.

4.2.3 Large Cavities

The cavities were constructed by milling into the plate to a depth of 0.45” and filling the area with the tin-bismuth support (Figures 4.6 and 4.7). A milling operation was then performed to remove approximately 0.003” of build plate which leveled the support material with the build plate (Figure 4.8). Next, 8 layers (each 3 tapes wide) of build material were deposited on top of the cavity in order to enclose the cavity (Figures 4.9 and 4.10). Finally, a milling operation was performed around the enclosed cavity leaving a 0.125” wall of build material (Figure 4.11).
Figure 4.6 Milled cavities for (a) circular and (b) square enclosures.

(a)                                                         (b)

Figure 4.7 Cavities filled with support material for (a) circular and (b) square enclosures.

(a)                                                         (b)

Figure 4.8 Milled build plate with support material for cavities for circular and square enclosures.
**Figure 4.9** First layer tape deposition over square cavity.

**Figure 4.10** Completed tape deposition over the square cavity.
Several times during the welding of the middle first layer of aluminum over the support material in the cavity, the tape was observed to be severed where the aluminum build plate and support material come together. This only occurred however for the middle tape which is the only one which spans the cavity without any contact with the aluminum plate. Therefore this tape is completely supported by the tin-bismuth which indicates that under a high enough load the support material may actually be deforming. This deformation can allow the sonotrode to cut the aluminum tape by shearing it at the edge of the aluminum cavity (Figure 4.12). A reduced force of 1300 Newton was used instead for the first layer and the problem was resolved. Several of the tapes also bubbled up after welding, again indicating that the support material is slightly deforming under
the sonotrode load leaving a slight excess of material in the middle (Figure 4.13). In this case though subsequent layers above were unaffected and no errors or welding faults occurred. In other instances such as larger cavities this problem may become more problematic.

**Figure 4.12** Illustration demonstrating how support material deformation can lead to the shearing of the tape at the edge of a cavity.

**Figure 4.13** Bubbled tape deposition over the square cavity.
The tin-bismuth support material was removed by milling a 1/8” hole into the structure and heating the part in a melting pot (Figure 4.14). The tin-bismuth flowed very well from the parts; however some small pieces of tin-bismuth adhered to the aluminum and had to be scraped away. Most likely some of these pieces also remain inside the cavity but would be difficult to remove.

4.2.4 Multi-Material Bonding

Two different sets of parameters were used based on previous experimental work. The parameter sets used were: 1750N force, 28µm amplitude, and 46 ipm (inch per minute) and 1750N, 16 µm amplitude, and 25 ipm (inch per minute). The higher amplitude parameter set used with copper resulted in the tin-bismuth melting at the bond interface and no bonding was achieved (Figure 4.15). This demonstrated the energy

Figure 4.14 Completed hollow structures before support was removed (dotted line indicates the approximate wall thickness).
input intensity can have a significant effect on localized heat generated during the UC process which penetrated the full layer of copper. However, when the amplitude and welding speed were reduced bonding was successful although probably a weaker bond was formed (Figures 4.16 and 4.17). In order to overcome this issue it may be feasible to increase the parameters once the first layer has been deposited and welded.

**Figure 4.15** Melted tin-bismuth support on the copper foil after welding.

**Figure 4.16** Completed (a) multi-material rib and (b) cavity structures with outer wall machined.
4.2.5 Support Material Alteration

Attempts to mix several metal powders, including stainless steel and nickel with the tin-bismuth were unsuccessful. In all cases the powder simply balled up on the surface and could not be wetted by the molten tin-bismuth matrix. This method was therefore not further pursued as a feasible method for stiffening the tin-bismuth. Both tin and bismuth were used independently since they have higher melting points than the combined mixture. This independent use however was also abandoned due to the high temperatures required for removal.

4.4 Design Considerations

Based on the completion of the previous parts design considerations have been developed for UC using support materials.
• Large cavities can experience support material deformation which can cause tape bubbling or warping leading to difficult bonding conditions for subsequent layers.

• Part orientation should be such that the stiffness is maximized with respect to the sonotrode vibration. Orientation should also account for sharp edges which can shear the tape. Every part will be different and therefore a certain amount of compromise will have to be made.

• The optimum welding parameters including welding amplitude, temperature, welding speed, and normal force will vary depending on the amount and location of the support material.

• Welding more difficult materials such as copper will require both reduced amplitude and federate to avoid support melting or possibly a lower build temperature to obtain bonding.

• The build temperature should be optimized to maximize bonding taking into account both bonding in the presence of support materials and in regions where supports are not used.

While tin-bismuth served as a sufficient support material there are several potential drawbacks. Since the part must be reheated to over 273°F to remove the tin-bismuth, this may cause difficulties when constructing parts with electronics or delicate instruments which cannot withstand high temperatures. Also since tin-bismuth is an excellent electrical conductor parts with electronics could easily be shorted out. Currently in order to overcome these difficulties it may be required to use two different support materials depending on the application required. Tin-bismuth therefore would be
most beneficial for parts requiring geometric complexity without electrical or temperature sensitive components.

While it was not explicitly tested it should also be noted that support materials may reduce the inherent porosity over enclosed features that can cause leaks in thermal parts. This can potentially be an issue because without a support material it can take many layers to regain the stiffness required for bonding. This problem was observed by Johnson in which parts required a sealant in order to be functional (Johnson, 2007).

4.5 Build Recommendations

The following is a compilation of specific build recommendations helpful for successful part completion.

- Components should be built to the tallest z height possible before machining is required to maximize structure rigidity and minimize operations.
- A containment wall should be maintained around the structure to withhold tin-bismuth.
- Containment walls provide additional bonding surface areas for the tape to be held in place which is especially helpful for smaller features.
- Working temperature should not exceed 260°F when working using tin-bismuth as a support material otherwise the heat generated during the UC process will melt the support material.
- A reduced normal force may be required to limit support material deformation and its effects.
- Smaller cutting tools can be used to minimize forces on more intricate features.
4.6 Future Work

As a result of these experiments, several areas have been identified for which future work is essential. The major limiting factor thus far has been a lack of sufficient bonding between the support material and the build material which would enable free-floating features to be constructed. In order to achieve this it may be required to identify lower temperature bonding parameters so that the energy can be increased to obtain a bond without melting the support. Additionally if either metal or ceramic particles could be added to increase the support material stiffness, the effects due to support material deformation would be reduced and the bonding would be improved. Finally more work is needed to explore the limitations with respect to building a fully three-dimensional part incorporating numerous complex features into one component.

4.7 Conclusions

Novel geometries were built with ultrasonic consolidation utilizing support materials. These include tall ribs which exceeded the 1:1 height to width ratio, large open cavities, and multi-material parts. These types of structures represented features which were previously impossible to create in ultrasonic consolidation. They also demonstrated the geometric improvement possible with the combination of support materials into ultrasonic consolidation. Each geometry provided a unique building challenge, however design guidelines were developed to overcome many of the issues encountered. These guidelines enabled the successful completion of the features described and will ultimately provide a foundation for future work involving support materials and their integration. While tin-bismuth is not an ideal support material it enabled the structures to be completed successfully. It was found that the support
material may be slightly melting, which hinders bonding above the support material; however subsequent build layers were bonded together. When welding copper, or other materials requiring more energy, the tin-bismuth support can be melted out especially at higher amplitudes. This highlights the need for a more robust support material which has a higher melting point and/or stiffness, but that can still be easily removed, for working with materials other than aluminum.

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CHAPTER 5
INTEGRATING UC AND FDM TO CREATE A SUPPORT MATERIALS DEPOSITION SYSTEM

Abstract
Currently there is no automated deposition system available for support materials in Ultrasonic Consolidation. Support materials are 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. This paper describes the approach taken to integrate UC and FDM in order to automatically deposit materials as a support in a UC machine. This includes the process setup, design, and planning. Finally a build process integrating the two machines is shown to demonstrate that automated support material deposition in UC is possible.

5.1 Introduction
Many different additive manufacturing (AM) processes exist today based on a layered build approach. New applications are continually being investigated and applied to change the way we approach manufacturing. Sometimes multiple AM processes may also be integrated to create a specialized manufacturing platform. As processes are integrated we can also move towards a direct manufacturing system where complex parts are built on one machine without interruption.

One application of machine integration involves ultrasonic consolidation (UC) and fused deposition modeling (FDM). This paper provides an overview to the approach taken to integrate both technologies in order to provide a support materials delivery

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system. The task involved significant process planning and design in order to demonstrate a successful integration.

5.2 Background

5.2.1 Ultrasonic Consolidation (UC)

Ultrasonic consolidation (UC) is a direct metal additive manufacturing process developed by Solidica Inc. in 2000 [1]. The Solidica Formation UC machine uses a continuous ultrasonic seam welder (sonotrode) to consolidate thin metal foils (approximately 150µm thick) into the rough part shape (Figure 5.1). Layer contours are then cut using an integral CNC milling head. Complex internal features and geometries may also be milled in a similar fashion.

Fig. 5.1: UC machine work environment.
UC is a unique process since it uses solid state processing. 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]. Solid state AM therefore provides an ideal platform for embedding electronics, smart materials, and fibers. The process was developed extensively for use with aluminum 3003 however since then UC has been demonstrated with various other aluminum alloys, stainless steel, copper, nickel, titanium, inconel, brass, and MetPreg® [3- 6].

During the ultrasonic consolidation process thin metal foils are automatically fed from a coil above the machine to the sonotrode where they are welded into place. The sonotrode rotates in contact with the metal foil while providing ultrasonic vibrations transverse to the weld direction. These high frequency (20kHz) low amplitude (~16µm) vibrations break up surface oxides at the foil surface and enable a metallurgical bond. Deposition occurs on a tightly bolted 0.5” thick by 14” (~12.5 mm by 355 mm) square build plate which generally consists of the same material as the foils being deposited. The machine is controlled by a program generated by RpCAM, Solidica’s proprietary machine software. This software utilizes information from the 3D solid model to create the correct layer contours and foil arrangement. The main processing parameters for ultrasonic consolidation include vibration amplitude, welding speed, normal force, and substrate build temperature.

5.2.2 Fused Deposition Modeling (FDM)

Fused deposition modeling is an additive manufacturing (AM) process which produces parts from thermoplastic filaments. The build and support materials are a continuous filament held on a spool that is fed through heated extrusion nozzles. The
FDM head contains two nozzles; one for support material deposition and the other for the build material. The material is heated to a semi-liquid state as it passes through the extrusion head, which is controlled by an x-y motion control as shown in Figure 5.2. The nozzle extrudes material as it follows the contours in the x-y plane based on the program generated by the CAD model. Once a layer is complete the build table moves in the z direction one layer thickness for the next layer to begin. This process is repeated for each layer until the final build height is reached. Water soluble support material, if used, may then be removed by placing the structure into a water bath. The machine program is generated by Stratasys’ computer program, Insight, from a 3D CAD model. This program enables the user to define part orientation as well as processing parameters such as slice height, road width, build temperature, raster orientation, and many others.

5.2.3 Support Materials in AM

During an AM build process it often becomes necessary to provide a support structure to provide a build surface for subsequent overhanging or independent portions of layers. It is often possible to eliminate the need for a support material simply by reorienting the build; however for more complex geometries a support is almost always necessary.

![Fig. 5.2: Schematic showing the basic FDM process [7].](image)
required. In order to fulfill this requirement the support structure must be built either simultaneously with the build or after a feature is created. This is most often accomplished by depositing a sacrificial material, in addition to the build material, to be removed once the build is complete. This sacrificial or support material provides the necessary foundation to create more complex or otherwise impossible geometries. Generally a support material may then be removed by using water baths, heat, mechanically breaking them off by hand, or machining.

An automated support material deposition system for UC is important because features such as tall ribs, thin walls, overhanging structures, and wide channels are currently difficult or impossible to build. It is desired in ultrasonic consolidation for a support to be as stiff as possible to act as an effective support. This is due to the large normal forces exerted during the UC process which the support material must withstand. Using negative or minimal air gaps or overlapping contours in the FDM build structure will create a more dense part and therefore a stiffer structure with FDM. It is recommended that no more than -0.002” gap be used to reduce the amount of material buildup on the tip and the build [8]. Increasing the overlap (more negative gap) any further would also degrade the surface finish and dimensional tolerance.

5.3 Machine Integration

5.3.1 Overview

FDM was chosen as the support material delivery system for ultrasonic consolidation because it can be a mobile and flexible way to accurately deposit 3D structures. In order to accomplish this integration, an FDM-3000 machine was
reconfigured and modified into a flexible deposition system [9]. The purpose of this machine is to provide a mobile FDM unit that does not require a special build chamber or build surface. Therefore a build can be performed on virtually any surface in any location. Unlike standard FDM machines which have a moveable z build stage; this machine has been modified so that the nozzle head is controlled directly by the z stage. This allows the x-y build surface instead to be stationary, which is what is required for integration with the UC machine.

The flexible FDM system will allow a material to be deposited where it is needed to fill channels or provide overhanging support. With this capability it will be possible to extrude common FDM materials such as ABS, investment casting wax, and WaterWorks™ (Stratasys’ proprietary water soluble support) or any other material which can be supplied in a filament form.

In order to create a support structure for a UC part, a mirror image of the supported regions must be created by the FDM machine. This is easily achieved for simple structures, however as the models become more complex, specialized software is required to automatically generate the supports. For experimentation purposes a simple geometry, as shown in Figure 5.3, was used to demonstrate the feasibility of the combination of processes which has not been previously demonstrated.

5.3.2 Machine design

The flexible FDM machine has been integrated with Solidica’s ultrasonic consolidation machine to provide a support deposition system. The FDM machine is attached and held by a portable hydraulic lift which can be easily maneuvered and adjusted (Figure 5.4).
Fig. 5.3: Basic build process sequence for a simple supported structure in UC (not shown to scale).

Fig. 5.4: Flexible FDM machine lifted to be rolled inside the UC machine.
The FDM machine is positioned within the UC machine through the use of a bolted guide plate with high precision linear slide rail bearings (Figure 5.5). The guide plate allows enough room that the FDM machine slides back and forth without completely removing the machine from the guide rails. This helps maintain a consistent z height registration. This also enables the machine to slide out of the way so that the UC machine will be able to deposit material when needed. The plate is positioned in the UC machine with two 1/8” guide pins and securely bolted to the build table. The linear slide rails are bolted to the guide plate while the bearing blocks are mounted to the FDM machine.

Fig. 5.5: Inside UC build chamber showing FDM guide plate setup.
The FDM control box, which was originally located on top of the FDM machine, had to be relocated next to the UC machine so that the unit would fit inside the doors of the UC machine. This also allowed for easy cable connection to the FDM machine and computer while it is rolled in and out of the UC machine. The flexible FDM was then test fit into the machine, as shown in Figures 5.6-5.9, to ensure a proper fit and function of the integration.

Fig. 5.6: Flexible FDM machine slid into UC machine for deposition.
Fig. 5.7: FDM machine positioned inside UC machine and ready for build.

Fig. 5.8: Front view of flexible FDM deposition system showing the FDM head.
5.3.3 Leveling

In order to produce an accurate and successful build the UC machine build surface and the FDM depositing head must be leveled relative to each other. This was accomplished by using a dial indicator attached to the FDM head, as shown in Figure 5.10. First the UC build plate was mounted into the machine and heated to the desired build temperature (generally 300°F). Next the build plate was milled flat using the integrated CNC mill on the UC machine to create a flat build surface. These first steps
are the same steps used for a normal UC build in the machine. Once the plate was milled
the FDM machine was slid into the UC machine as described previously. A dial indicator
with 0.0001” increments was attached to the FDM head and lowered slowly onto the
build plate. With the indicator tip slightly depressed the indicator was zeroed for a
reference point and first moved in the +/- x direction. Using this information and the
three point leveling system on the FDM machine the build platform was adjusted until the
readings were within 0.001” of each other. Next the FDM machine was moved in the +/-
y direction and adjusted in the same manner. Once this was complete this ensured that
the build plate was parallel to the machine motion for successful deposition and so that
the head would not gouge the build plate during deposition of the first layer.

Fig. 5.10: Using a dial indicator to level the FDM machine with the UC machine.
5.3.4 Coordinate Control

The most significant difficulty encountered with integration of FDM and UC is coordinate control. The UC machine has a built in coordinate system which makes it easy to locate a part or move to a specified position. The FDM machine however cannot be controlled through the software to specific x-y-z coordinates. This means that the user specifies the start build position, but exact coordinates are not identified. This approach works well for a stand-alone machine, however it makes machine integration difficult. In order to overcome this obstacle the home position of the FDM machine was recorded with respect to the UC machine build plate. This allows the user to position parts in the solid model to ensure correct placement between the two machines. While this method does work it can be tedious and is not a practical long-term solution, therefore further integration of both machines’ coordinate systems is an area for future improvement.

5.3.5 Process Building Plan

The deposition process can be described as follows:

1. The aluminum build plate inside the ultrasonic consolidation machine is heated to 250°-300° F and rigidly fastened to the heated platen. If the build plate is not sufficiently hot, the FDM materials will not adhere as well to the build plate and to each other.

2. The build plate is flat passed with the CNC mill to create a level work surface.

3. The surface of the build plate is coated with a thin layer of water soluble polymer to provide adhesion between the FDM materials and aluminum. Without this polymer layer the FDM build and support materials will not adhere to the smooth aluminum build plate.
4. The FDM model head is located to 0.006” gap from build plate using a feeler
gauge to set build z-height. If the gap is too large the material will not adhere to
the plate. If the gap is too small the FDM machine will encounter a torque limit
error due to the tip clogging.

5. The FDM build program is begun, with machine code pauses inserted at each
layer or after several layers to allow ultrasonic machine deposition.

6. Once the desired height is reached with both the aluminum build and FDM
support materials the surfaces are milled flat with respect to each other to create a
level work-plane.

7. UC material can now be deposited across the support material.

5.3.6 Building with the FDM Machine inside the UC Chamber

In order to test the FDM machine operation inside the UC machine several
different geometries were constructed. Using the WaterWorks™ support material 0.3”
 thick rectangular test blocks were built in the ultrasonic consolidation machine with an
air gap of -0.002”. This caused the material to build up excessively on the FDM
deposition tip and cause a torque limit error. Therefore the air gap was increased to
0.000” and the builds completed successfully. Another more complicated geometry, as
shown in Figure 5.11, was also completed using ABS and a standard WaterWorks™
base. These builds confirmed that both basic and more complex geometries could be
completed within the UC build area and on the aluminum build plate using the modified
FDM system.
5.4 Performing a Supported Build

In order to demonstrate the use of the FDM machine as a support deposition system for the UC machine a simple overhanging build, shown in Figure 5.12, was performed. The FDM machine was programmed to build using only the WaterWorks™ material so that it could be completely dissolved once the build was complete.

Two different materials, aluminum and WaterWorks™, were alternately built next to each other with the UC and FDM machines respectively. Once the desired height was reached both materials were machined flat to create two level build surfaces. The WaterWorks™ demonstrated a strong bond to the aluminum build plate by withstanding the machining forces. The UC machine was then used to deposit material overhanging
Fig. 5.12: Overhanging structure built with UC and FDM deposited support materials.

the support material, but still in partial contact with the aluminum. A total of 8 aluminum layers (~0.0472”) were consolidated on top of the support material. The part was removed from the plate without dissolving the support material and the overhanging
metal layers were found to be unbonded to each other. The layers directly above the aluminum were well bonded to the plate and to each other. The WaterWorks™ survived the ultrasonic deposition process, but based on previous experiments the WaterWorks™ was demonstrated to be a non-ideal support material [see Chapter 3]. Although the process combination worked well, this indicates that other FDM-extrudable materials need to be identified as support materials.

5.5 Other Applications

The flexible fused deposition modeling system can also have other applications within the UC machine besides a support materials delivery system. Essentially the two machines have been combined to create a combined metal and plastic AM process. This integration could also be used to automatically create insulated surfaces for electronics embedding, insulated direct write build surfaces, and other complex multi-material structures.

5.6 Conclusions

This paper describes initial work to automate deposition of support materials inside a Solidica ultrasonic consolidation machine using FDM. In this effort a flexible fused deposition modeling system was integrated into an ultrasonic consolidation machine to provide a support materials delivery system. The result of the UC and FDM machine integration is a direct manufacturing process which requires no special build atmosphere and temperatures between room temperature and 150°C. Complex and simple geometries can now be constructed within a UC build environment to provide a support structure, however more work on developing FDM-compatible support materials
is required. The combined UC/FDM machine enables different metal and plastic materials to be automatically deposited together. The benefits from this integration have only begun to be explored.

References


CHAPTER 6
CONCLUSIONS AND FUTURE WORK

Ultrasonic consolidation is an important technology within the realm of AM. This is because it is a direct metal solid state process which eliminates both tedious post processing and effects due to phase transformations. It is also highly desirable since the process is performed in an atmospheric environment at relatively low temperatures.

Support materials serve an important function throughout the field of additive manufacturing. They are essential to provide the ability to create complex and advanced geometries which would otherwise be difficult or impossible to build. To this point ultrasonic consolidation has been limited by the lack of support materials. Successful use of support materials in UC has opened a new level of design capability and applications never seen before.

The main thrust behind this current work was to investigate, develop, and integrate support materials for use in ultrasonic consolidation. In the end these objectives were met and the geometric capability of UC process was furthered. This was not a simple task, but rather complex which required several different approaches. Ideally a fully functioning and integrated system would be the end result, however small steps were made to solve this complex issue. This work therefore has both laid the foundations for future work as well as demonstrated the current capability through the use of support materials.
6.1 Support Materials

Various support material options were investigated including tin-bismuth, casting wax, aluminum filled sucrose, WaterWorks™, and epoxy in three different geometrical configurations. While this was not an all inclusive list of materials it was representative of a range of different distinct material types. It was observed that as support material hardness increased the overall bond quality and weld density was improved. The tin-bismuth material was most straightforward to work with and was the only material which enabled deposition for pocket, rib, and channel geometries. Epoxy was found to be a suitable electronics potting support material since it could be poured at low temperature, is heat/chemical resistant, and is nonconductive.

Ultimately it was found that a support material must provide enough hardness to resist significant deformation under the load of the sonotrode. Additionally a support material should not melt or deform due to the localized heat generated which would interfere with the bonding interface. Furthermore it would be beneficial if a support material was also machinable, cost effective, and non-toxic; however these are not absolutely essential.

6.2 FDM-UC Integration

In order to provide a support materials deposition system a flexible fused deposition modeling system was incorporated into the ultrasonic consolidation machine. A deposition process plan was also developed for use of the combined UC and FDM machines. This provided a consistent building process with which FDM structures could be accurately and repeatedly deposited within the UC environment. Complex and simple geometries can now be constructed within a UC build environment to provide a support
structure. While the current FDM materials were found to be unsatisfactory as a support in UC it now provides a platform in which new materials may be deposited as a support with FDM. UTEP has begun development with extruding low melting point alloys such as tin-bismuth with FDM which could prove useful in the future. This however highlights the need for further development of FDM materials which could be used as support materials.

6.3 Geometric Capability

Several different novel geometries were built with ultrasonic consolidation utilizing tin-bismuth as a support material. Based on this construction, design guidelines and recommendations were established to provide solutions to the difficulties encountered when building with UC and support materials. Most notably was the effect of the localized heat generated from the UC process which was enough to melt and deform the support material. These guidelines led to a building capability which had before proved difficult or technically unattainable. These build geometries included tall ribs which exceeded the previous maximum 1:1 height to width ratio, large hollow shells, and multi-material parts. These parts encompassed the geometric roadblock within UC, specifically overhangs, cavities, and high aspect ratio features. These structures are important because they demonstrated the geometric improvement possible with the combination of support materials into ultrasonic consolidation. The guidelines developed also provide a foundation for future work involving support materials and their integration.
6.4 Relevant Properties

The following discussion emphasizes the relevant properties of support materials and their practical implications identified from the preceding research. They are designed to highlight the desired support material characteristics and classify what makes a good support material. The results are highlighted in Table 6.1.

6.5 Melting Point

The energy provided during ultrasonic consolidation can be enough to significantly melt support materials. The main operating parameters such as build plate temperature, vibration amplitude, welding speed, and bonding material type are all interrelated factors that collectively determine the temperature achieved during the UC process. Therefore, a support material should be chosen based on the combination of machine parameters and bonding materials to ensure the support melting point is in excess of the temperature generated during bonding. The actual temperatures reached during the ultrasonic consolidation process have yet to be successfully measured, however during experimentation both the water soluble wax and tin-bismuth were in

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Brinell Hardness (HB)</th>
<th>Stiffness Rating (1=highest)</th>
<th>Melting Point (°F)</th>
<th>Ultimate Tensile Strength Rating (1=highest)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tin-Bismuth</td>
<td>16.0</td>
<td>4</td>
<td>273</td>
<td>4 (55 MPa)</td>
</tr>
<tr>
<td>WaterWorks™</td>
<td>19.7</td>
<td>2</td>
<td>455</td>
<td>2</td>
</tr>
<tr>
<td>Epoxy</td>
<td>18.2</td>
<td>3</td>
<td>N/A**</td>
<td>3</td>
</tr>
<tr>
<td>Casting Wax</td>
<td>N/A*</td>
<td>5</td>
<td>150***</td>
<td>5</td>
</tr>
<tr>
<td>Sucrose</td>
<td>31.5</td>
<td>1</td>
<td>200***</td>
<td>1</td>
</tr>
</tbody>
</table>

*A hardness measurement for casting wax was not obtained due to full indenter penetration.

**Epoxy will soften or burn at elevated temperatures.

***Both casting wax and sucrose soften significantly before the melting point is reached.
some cases significantly melted. The degree of melting was greatly driven by the
vibration amplitude. As the vibration amplitude increased the amount of melting was
also increased. Generally the entire build plate is elevated to temperatures in the 300-
400° F range, however lower build temperatures were shown to be successful to
incorporate lower melting point support materials such as tin bismuth and wax. With this
information the melting point was found to be an extremely important factor to consider
for a support material.

6.6 Stiffness

Stiffness measures a materials’ resistance to bulk deformation or changes in shape
under an applied force. Stiffness calculations can be made through the use of tensile or
compression tests. The support material stiffness in ultrasonic consolidation is an
important characteristic since without sufficient stiffness the material will be deformed
under the load of the sonotrode. The amount of deformation will be determined by the
type of support material, machine normal force, and geometry of the supported region.
Depending on the extent of the support deformation several problems can arise; the most
serious being a machine fault which is caused by excessive z height travel. In this case
the sonotrode dips down and either causes the machine to stop welding or if it completes
the weld the excess tape forms a bubble. Additionally, the support stiffness is important
to maintain an even force distribution across the sonotrode and the supported build
region. Without this even distribution more force is applied to certain areas causing some
regions to bond well and other regions to bond poorly or not at all, which compromises
the part’s integrity. Although this property is important for a support material in
ultrasonic consolidation it was not measured due to the difficulty in testing.
6.7 Hardness

Hardness measures the ability of a material to resist localized plastic deformation. This is a quick, easy, and well established test which can quickly provide information about a material. Hardness tests are also very useful when tensile or compression tests are not practical for the given material. They also enable a wide range of materials to be mechanically compared without the need for different test parameters. Experimentation identified a better bond quality with fewer defects for harder support materials. This observation was most likely due to the support material providing enough stiffness to minimize deformation and maintain a relatively even force distribution across the sonotrode width. With an even force distribution the welding energy was maintained across the entire bonding area and the number of unbonded regions was reduced. Based on these observations the hardness test would be well suited as a screening test for support materials and their viability for the ultrasonic consolidation process.

6.8 Material Compatibility

Good bonding compatibility between the support material and build material will enable free floating features as well as a more unified build structure. This is because when the build material is welded to the support material it is held rigidly in place and enables the next layer to bond above. When underlying layers are not sufficiently restrained they will vibrate with the upper layer resulting in weak or no bonding. This problem can be somewhat minimized by depositing build material such that the sonotrode remains in contact with other areas of the build and thus restraining the tape, however large cavities or free floating areas will require bonding between the deposited material and the support material. For this reason the ultrasonic consolidation process would most
likely favor a metal support material since the build materials are also metals. To this point experimentation has shown no bonding between dissimilar materials and no conclusive bonding evidence for tin-bismuth.

6.9 Damping

Damping is the energy dissipated by a material or system which experiences cyclic stresses or vibrations. Within the ultrasonic consolidation process damping will affect the types of geometries that can be built. Depending on the type of support material used each material will influence the way the entire build, including the substrate, vibrates under the sonotrode. Thus using a support material will alter the damping characteristics of the system and may enable new geometric features to be built. Previous research has indicated undesirable height to width build ratios without a support material, which may be overcome by changing the damping characteristics with a support material.

6.10 Future Work

In order to further the use of support materials in ultrasonic consolidation and improve upon them there are several different areas for future experimentation.

6.11 Multiple and New Materials

The current work only looked at aluminum as a build material and briefly with the use of copper. Future work should therefore explore the use of multi-material bonds and other new materials which are currently being developed for the UC process. As more and more materials are widely used in UC it will be important that a support material is compatible with them.
6.12 UC Process Modeling

A better fundamental understanding of the UC process is still needed. With this understanding it would be easier to understand the interaction between a support material and the bulk build.

6.13 FDM Materials

New materials, both polymers and metals, developed for the FDM process are essential. This would pave the path to a fully integrated and automated process to build complex parts within UC. The current polymer FDM materials were ineffective and it seems that a metal material may serve the purpose the best. It should however be noted that FDM polymers can effectively be used in UC to create novel multi-material parts and serve as insulators for direct write materials.

6.14 Further Geometric Improvement

The greatest obstacle with using support materials in UC is the difficulty in achieving a bond with the support material. Ideally a bond would be facilitated between the support material and the build material as well as subsequent layers above. This would ultimately lead to an ability to build free-floating features which to this point still has not been achieved. With this added capability nearly any geometry would be possible with UC.
APPENDIX
Date  11/03/2009

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Address    1145 View Point Dr. #C204
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        Sandy, UT 84094
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