Integrating UC and FDM to Create a Support Materials Deposition System

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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.

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

2. Background

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 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. 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.

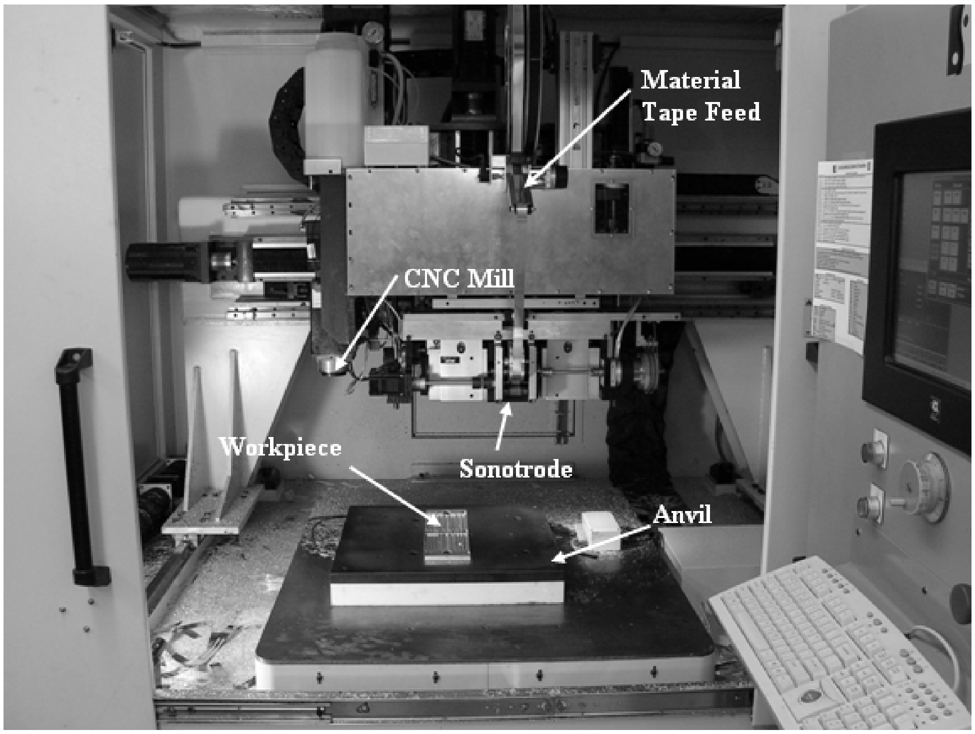

Figure 1: UC machine work environment.

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 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.

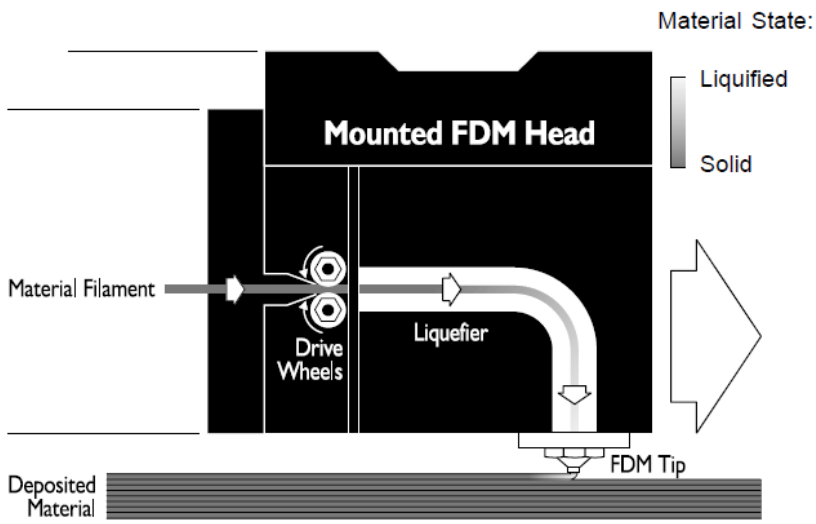

Figure 2: Schematic showing the basic FDM process [7].

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 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.

3. Machine Integration

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 as shown in figure 4 [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 3, was used to demonstrate the feasibility of the combination of processes which has not been previously demonstrated.

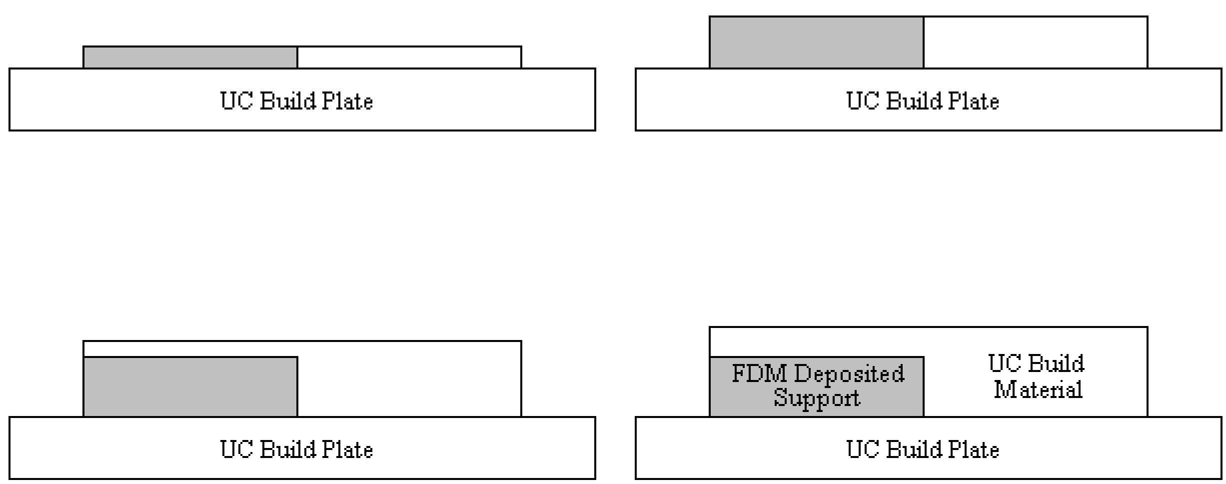

Figure 3: Basic build process sequence for a simple supported structure in UC (not shown to scale).

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 4).

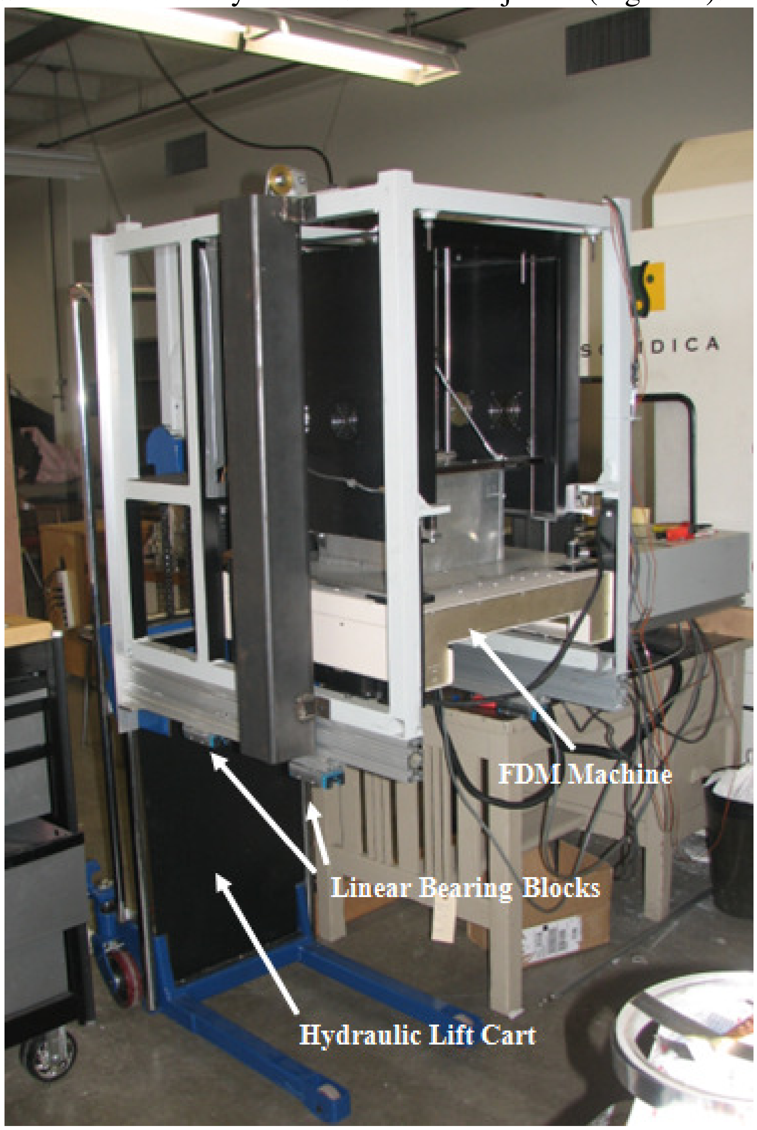

Figure 4: Flexible FDM machine lifted to be rolled inside the UC machine.

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). 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.

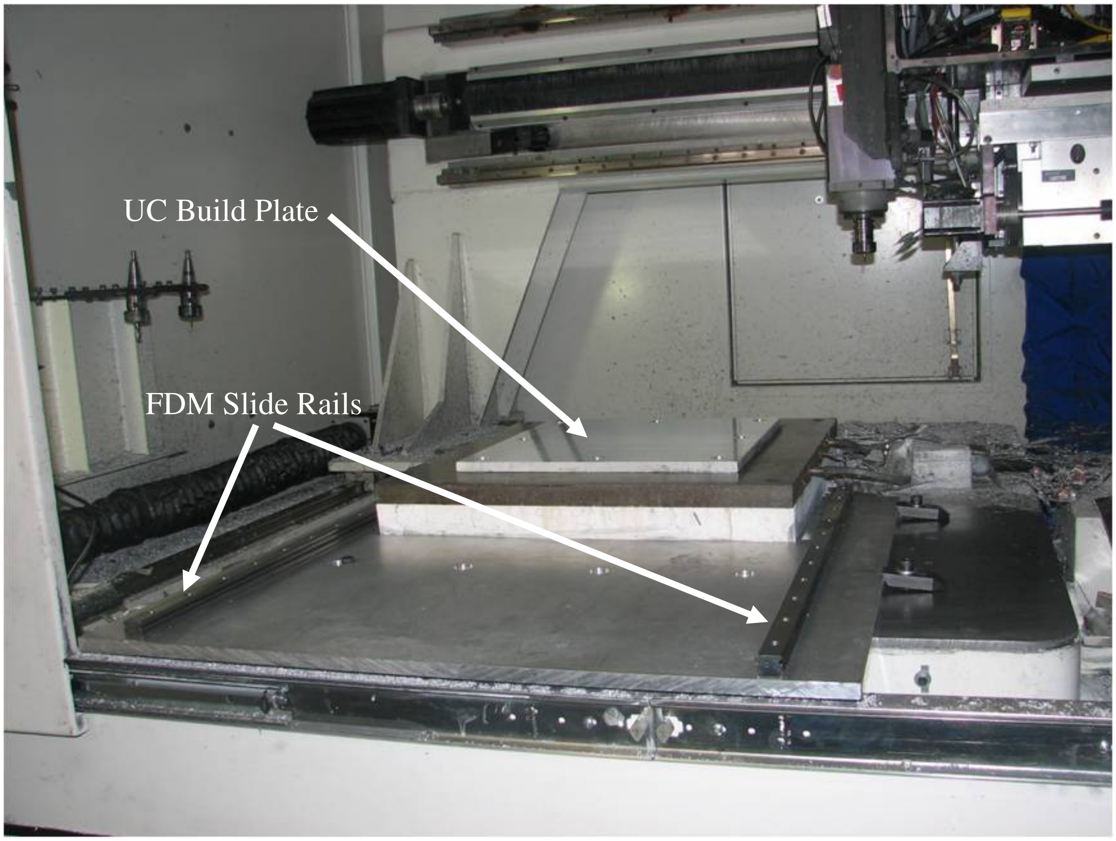

Figure 5: Inside UC build chamber showing FDM guide plate setup.

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 6-9, to ensure a proper fit and function of the integration.

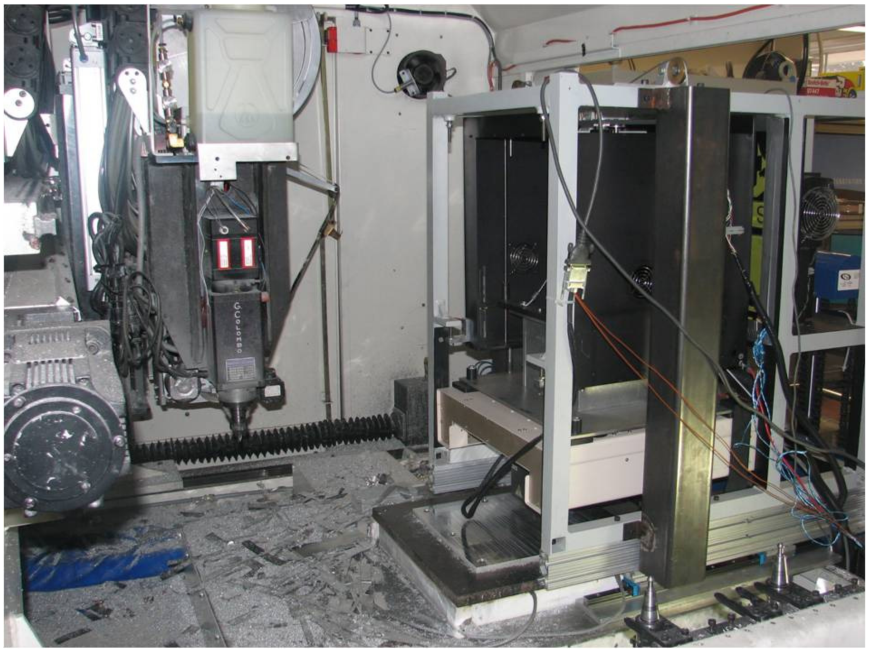

Figure 6: Flexible FDM machine slid into UC machine for deposition.

Figure 7: FDM machine positioned inside UC machine and ready for build.

Figure 8: Front view of flexible FDM deposition system showing the FDM head.

Figure 9: Combined Solidica UC machine with flexible FDM deposition system.

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. 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.

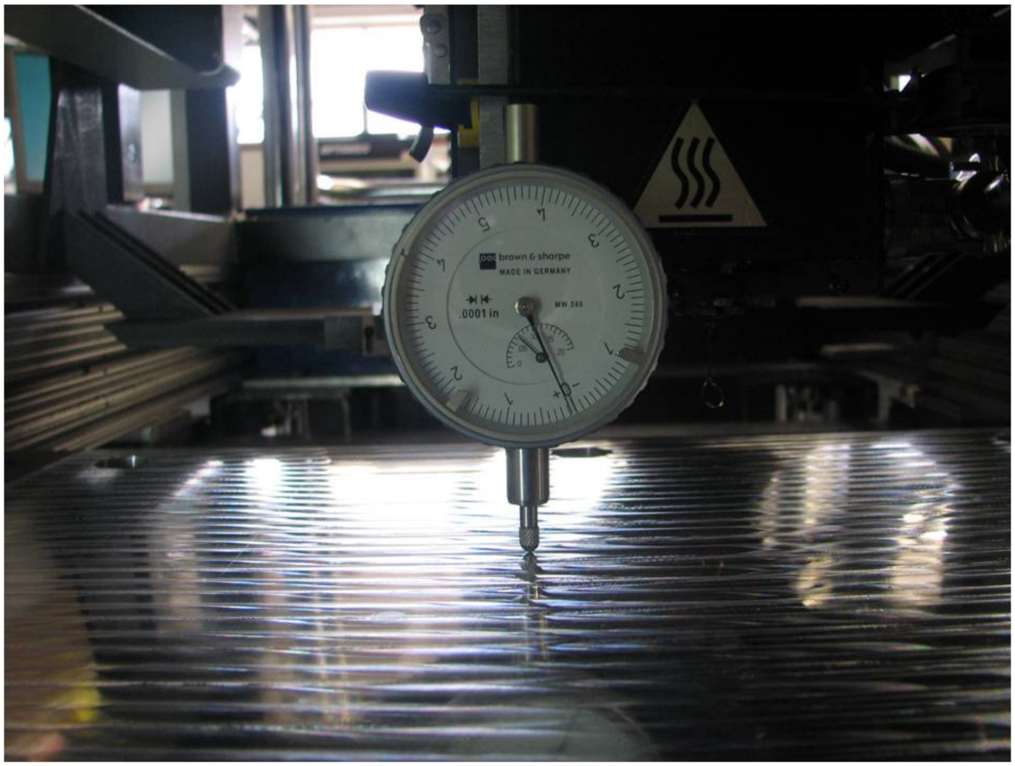

Figure 10: Using a dial indicator to level the FDM machine with the UC machine.

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.

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.

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 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.

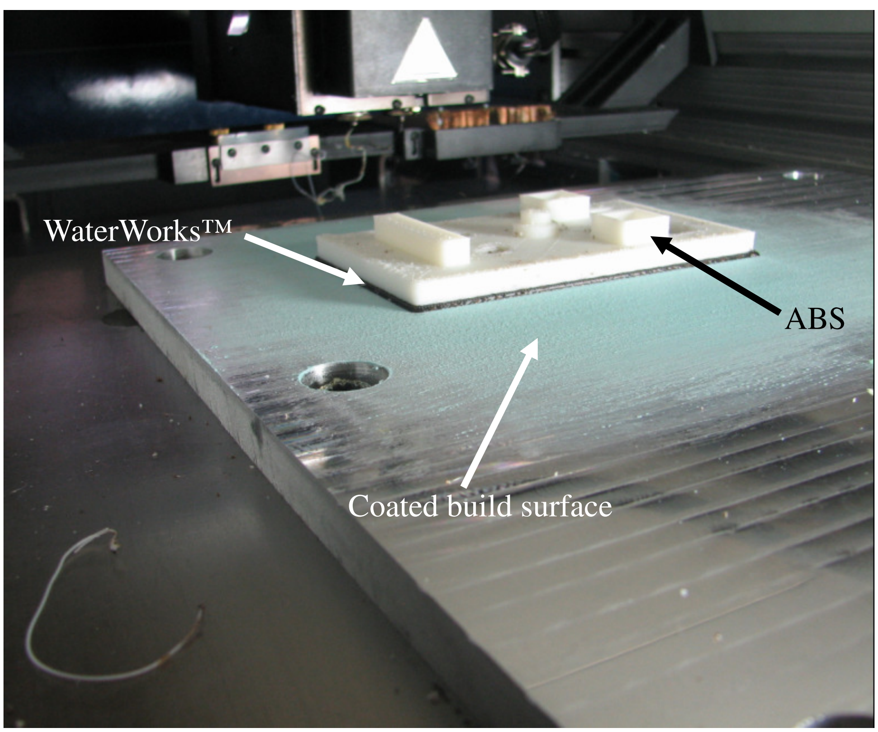

Figure 11: Complex structure built with FDM machine directly on UC build plate.

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, as shown previously in figure 3, 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.

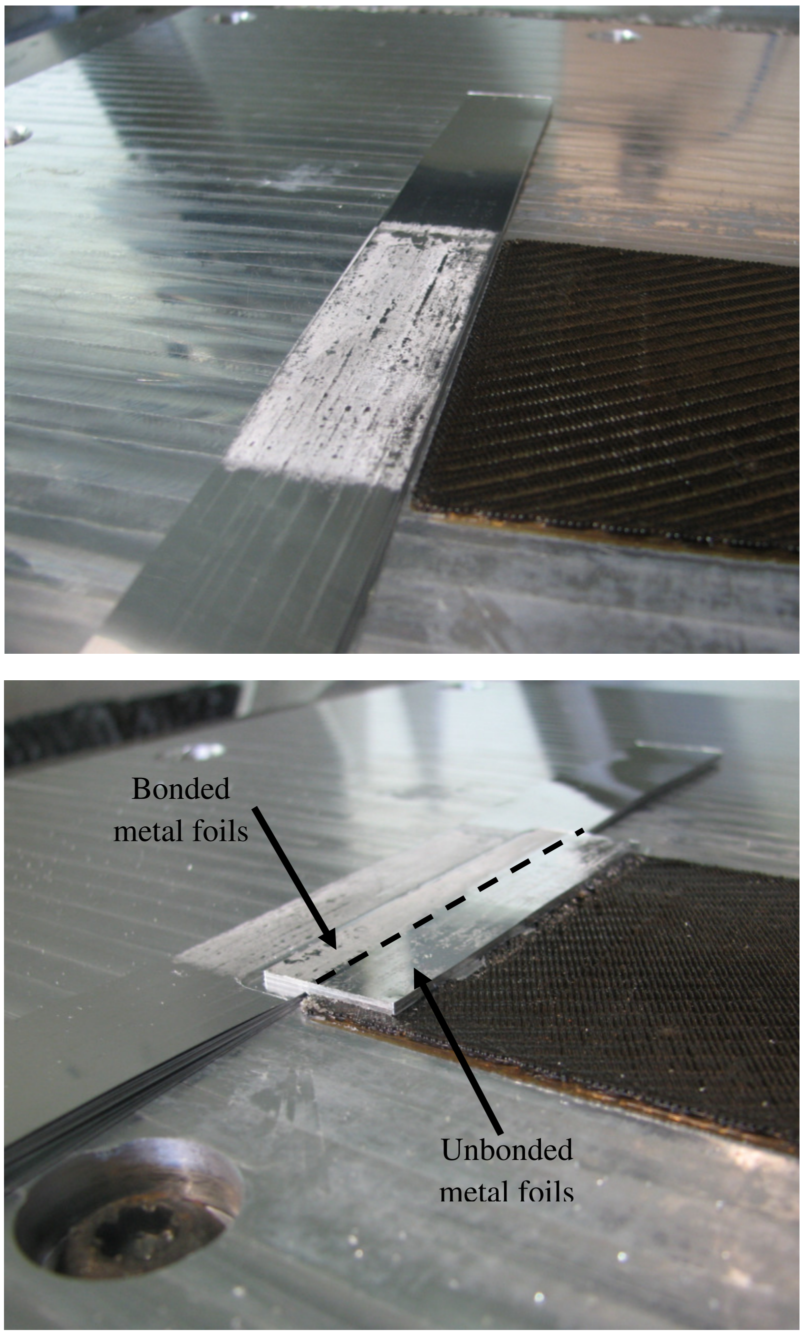

Figure 12: Overhanging structure built with UC and FDM deposited support materials.

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 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 [10]. Although the process combination worked well, this indicates that other FDM-extrudable materials need to be identified as support materials.

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.

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.

Acknowledgement

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