EXAMINATION OF BUILD HEIGHT IN ULTRASONIC CONSOLIDATION FOR FOIL WIDTH SPECIMENS USING SUPPORTS

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ABSTRACT

Ultrasonic consolidation (UC) is a novel, solid-state, additive manufacturing fabrication process. It consists of ultrasonic joining of thin metal foils and contour milling to directly produce functional components in a variety of geometries. The bond between layers forms when an ultrasonic horn creates a local oscillating stress field at the mating surfaces. It is commonly theorized that the high frequency vibration under pressure produces a metallurgical bond without melting the base material. The mechanism behind the bond is believed to be due to interfacial motion and friction that disrupts surface contaminants, arguably allowing direct metal to metal contact, and producing sufficient stress to induce plastic flow and promote the growth of grains across the mating surfaces. Ignored in this explanation is the role of substrate dimensions on the quality and strength of the joining process. Researchers have previously examined the effective height limitations of the build process, i.e., the limiting height to width ratio of one of the component features being fabricated. This paper extends the experimental work on using support materials to extend build height on specimens using two different candidate

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materials, tin bismuth, and a mixture of sugar, corn syrup, and water, referred to as "candy". Tin bismuth and candy the represent the extremes of a tradeoff between convenience and stiffness that a support material must possess.

INTRODUCTION

Ultrasonic consolidation (UC) also known as Ultrasonic Additive Manufacturing is an innovative, solid-state, rapid manufacturing fabrication process. Solidica, Inc. originally developed the process, which is composed of ultrasonic joining of thin metal foils and contour milling to directly produce functional components. The process has been utilized in applications ranging from embedding electronics into armored vehicles, embedding shape memory alloys within structures, fabricating injection mold tooling and fabricating lightweight structural panels for satellites [1].

DESCRIPTION OF ULTRASONIC CONSOLIDATION

The UC process begins with a thin metal foil being placed on a sacrificial base plate. The base plate is bolted downward and heated to 300°F (approximately 150°C). The ultrasonic horn compresses the foil while simultaneously vibrating transversally at a nominal frequency of 20 kHz and at amplitudes ranging from 1.97×10^{-1} to 1.18 mils (5-30 μm) while simultaneously rolling over the foil. The foil is typically 5.90 mil (150 μm) thick and 0.94 inches (23.88 mm) wide. After the foil is bonded, the process is repeated for additional foils across the width of the build plane for each layer of the desired end component. The consolidated foils are machined as needed throughout the build process to produce the desired final part geometry. Figure 1 illustrates the process.

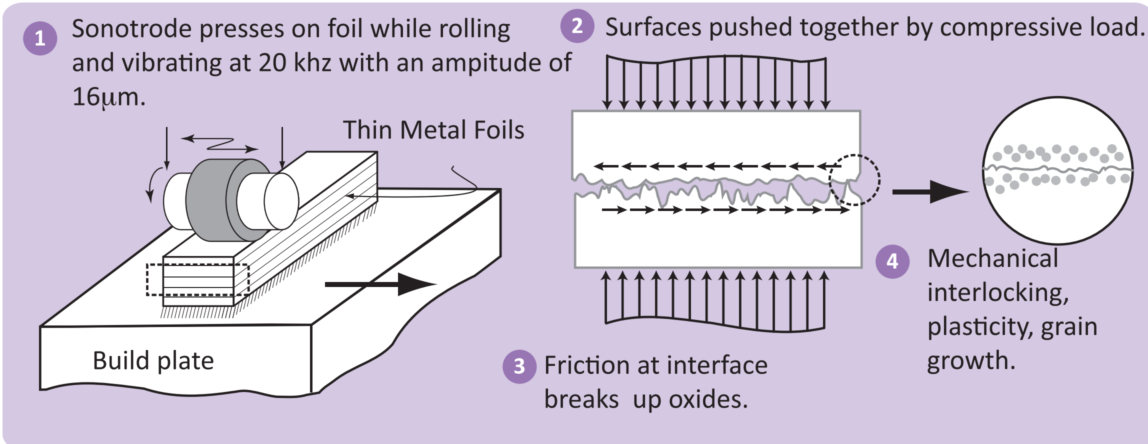

Figure 1: Overview of the UC process

PREVIOUS RESEARCH ON BUILD HEIGHT LIMITATION

Robinson *et al*. [2] found that an apparent limit on build dimensions exists through a series of experiment where they varied the width and orientation of the specimen with respect to the vibrating sonotrode and consolidated layers until failure occurred. Specifically, they examined five specimens at the following widths: 0.94 inches, 0.5 inches, 0.25 inches, 0.125 inches and 0.063 inches. Each specimen has a length-to-width ratio of 10:1. The failure of the smaller width specimens was attributed to insufficient bonding area. Conversely, for specimens of larger widths they concluded that layers couldn't be bonded to a feature if its dimensions reach a critical value, specifically, if its height-to-width ratio (*h/w*) is approximately 0.7 to 1.2, hereafter referred to as high aspect ratio features. They attributed the inability to bond, to the substrate becoming increasingly compliant, i.e., lowering its stiffness and reducing the amount of differential motion between the specimen and bonding tape. This assertion supports anecdotal evidence by Solidica, Inc. that support material added to high aspect ratio (height-to-width) features, extends the height to which the feature can be built and bonded successfully. Solidica demonstrated that utilizing a support material could achieve high aspect ratio features of over 20 (figure 2).

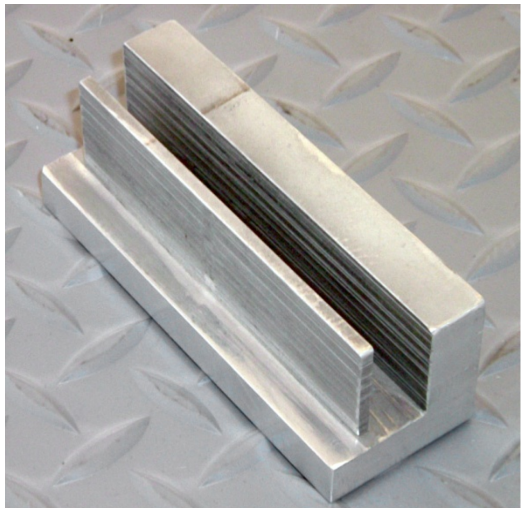

Figure 2: High aspect ratio feature produced with the use of support material

Zhang and Li [3] attempted to explain the findings of Robinson *et al*. [2] through numerical simulations. The researchers performed a fully transient, dynamic, finite element analysis that allowed for elastic, plastic and thermal strain. The simulation showed that, as *h/w* approaches unity and beyond, the magnitude of the frictional stress decreases, and that concentrated bands of high shear strain appear in the substrate as *h/w* approached one. They attributed this to positive wave interference that resulted in minimum interfacial displacement. The researchers later refined their model [4] to clarify how the waveform causes bonding degradation through a two-dimensional model of a quarter domain of the substrate. The researchers modeled the wave motion using a Rayleigh Ritz analysis. They argue that in steady state shear; stress concentrations appear on the substrates edge. After half a vibration cycle the concentrations switch locations resulting in wave interference and in minimal shearing stress due to the two waves interfering. The interference results in insufficient elastic plastic deformation to promote bonding. Relating both the wave interference model and the ratio of energy transferred into the bonding area to the frictional energy, they conclude that an *h/w* equaling one results in a limit on bonding energy. However, it is unclear from their work why this geometry results in wave interference.

While Zhang and Li [4] used a Rayleigh-Ritz model, the first use of this technique to understand the UC process was by Gibert *et al*. [5] . They showed that for features built at the nominal tape width with high aspect ratios, several modal frequencies of the feature approach the 20 kHz excitation frequency of the sonotrode. They also showed that these modes are only weakly dependent upon the length of the build piece. They postulated that the increase in compliance of the build feature could be due to an excitation of a modal frequency by the sonotrode. In a follow up study [6] the researchers experimentally verified their hypothesis for nominal tape width specimens. Using both lumped parameter and finite element modes of the UC process they accurately predicted trends in vibration that can be correlated to the build height limit at nominal tape widths based on examining differential motion at the interface. Both models indicated that once the region of experimentally observed regions of bond degradation due to height are passed it is possible to re-initiate bonding. Experimentally, they verified the models' predictions by consolidating a large stack; milling it down to a high aspect ratio feature and then resuming the consolidation process, see Figure 3. In this manuscript we expand on the tests, conducted by Gibert *et al*. [6], by testing the effectiveness of support materials in extending the limiting build height in the UC process.

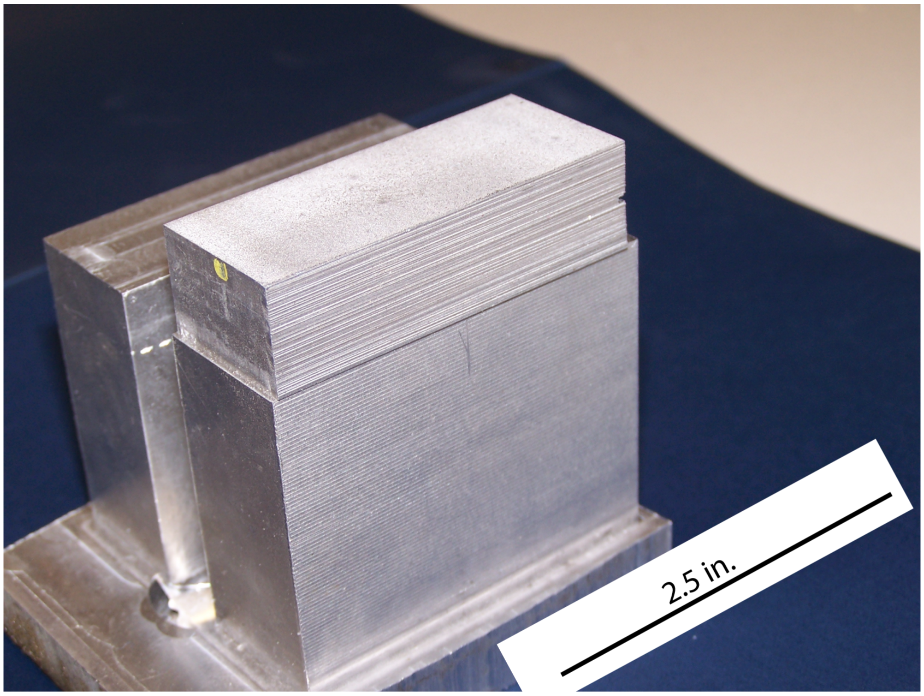

Figure 3: Welding of additional layers on specimen of 2.00 X 0.94 X 2.50 inches (50.80 X 23.88 X 63.50 mm) [8]

PREVIOUS RESEARCH ON THE USE OF SUPPORT MATERIALS

The use of support material is not original in Ultrasonic Consolidation; their use was motivated by anecdotal evidence by Solidica, Inc. indicating that the addition of supports increases the build height of freestanding features. Additional work conducted by Solidica with support from the US Department of Defense and the National Center for Manufacturing Sciences in 2005 and 2006 established the earliest methods for the automated delivery of a tin-bismuth support material within an Ultrasonic Consolidation platform.

The first published use of support materials in UC that included an investigation of feature building effects was by Swank and Stucker [7]. They examined the effect of support materials using three build configurations: an enclosed pocket, freestanding rib, and an open channel. In addition, they used five candidate support materials: metal alloy (tin-bismuth), a thermoplastic (Water Works™), a thermoset (Leco quick cure (QC) epoxy), a wax (water soluble casting wax), and an organic (aluminum filled sucrose). They found that only tin-bismuth allowed all geometries to be built. In addition, they proposed several guidelines for the use of support materials. The recommended that one use a lower build temperature to reduce softening of the support material. They noted that harder support materials reduce the amount of interface voids and delamination, and metal support materials are preferable to other materials in that they allow deposited layers to be welded to their surface. Metals allow subsequent layer bonding on the support material. They also found that localized heating during the UC process can melt support materials. However, left unanswered is the exact improvement of support materials on extending the build height in the process.

This paper examines the effect of support materials on the maximum build height obtainable for the 0.94-inch width specimens. In our work, we differ in both support geometry and material than those used by Swank and Stucker [7]. They used enclosed cavities. In this study, we use semi-enclosed support materials, i.e., two faces of the material are free, and the support material is not flush with the build specimen's height. We considered this geometry for several reasons. First, this arrangement may be seen as the limiting configuration of applying the support material that would allow it to stiffen the build specimen. Second, it is easily foreseeable that during the use of UC one may want to produce components where the enclosed cavity would be problematic. Thirdly, by varying height we prevent localized melting of support materials that can occur if the material is directly below the sonotrode. Finally, this geometry is of particular interest considering the work of Gibert *et al.* [6]; it adds only side supports to free standing features.

ROLE OF SUPPORT MATERIAL

In simple mechanical terms, the stiffness of the build piece can be represented by springs, Figure 4, through which forces are transmitted to the ground. The support material can be viewed as a spring in parallel to build feature stiffness.

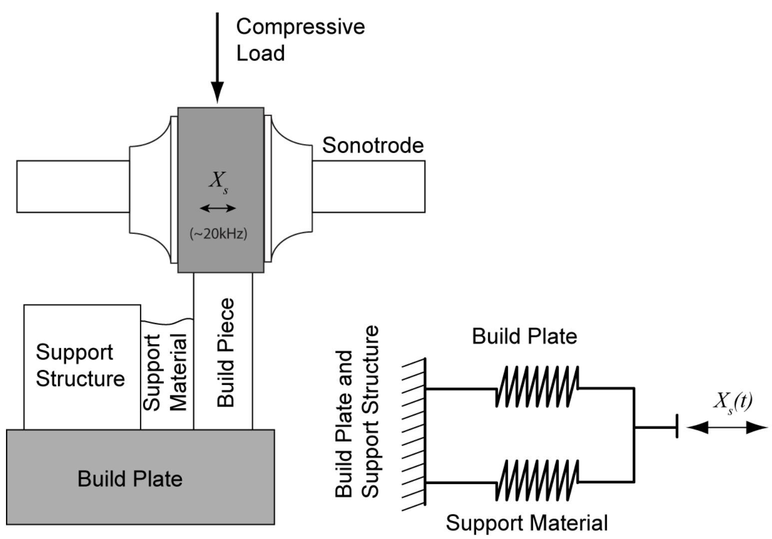

Figure 4: Conceptual model of the effect of support material

The addition of support materials has two possible effects on a free standing build feature: 1) changes the lateral stiffness of the build feature resulting in changes of modal frequencies of vibration of the build feature if the support material adheres to sides of the feature, and 2) increases dampening in the structure. However, the ideal support material must do more than change the structural characteristics of the build piece. It must convenient to remove when the consolidation process is complete. Figure 5 shows a hypothetical tradeoff between stiffness and convenience. In our studies, we examined the two extremes of the tradeoff, SnBi, and a mixture of hardened sugar, water and corn syrup we call “candy”. Material characterization shows that they have modulus of 60.8 GPA and 16.14 GPA, for SnBi and candy, and Brinell Hardnesses of 3, and 15, respectively [8].

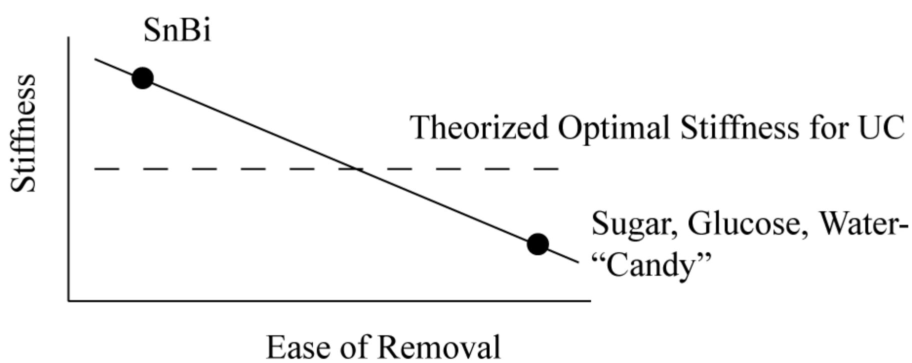

Figure 5: Tradeoff between stiffness of support material and ease of removal

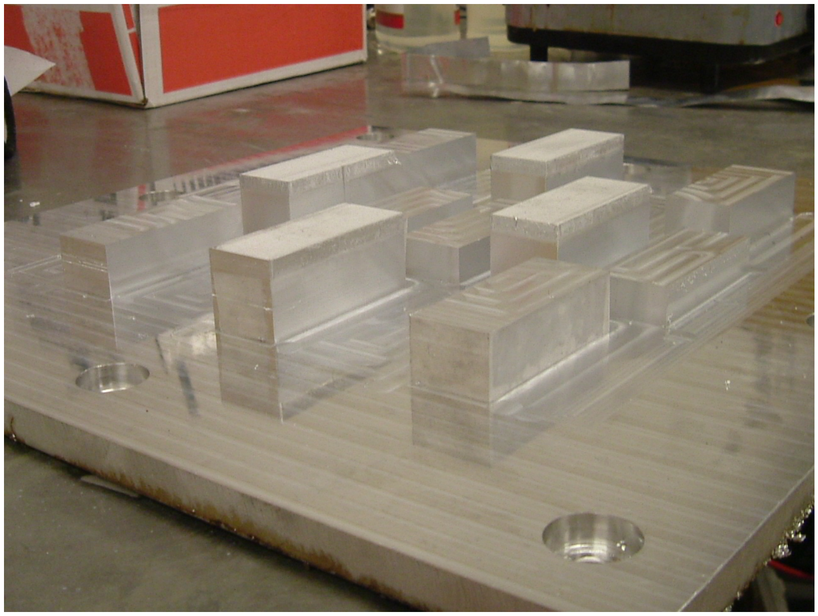

Figure 6: Specimens before filling used in support material characterization

BUILD SPECIMENS MATERIAL AND GEOMETRY

The build specimens were constructed from aluminum foil 3003-H18 provided by Solidica, Inc. The dimensions of the build plates were 14.00 x 14.00 x 0.51 inches (356 x 356 x 13 mm) thick 3003 H-18 plates, again provided by Solidica, Inc. The specimens were milled to a height, width and length of 0.94 x 0.94 x 2.50 inches, i.e., at the problematic aspect ratio for nominal tape width specimens.

SUPPORT MATERIAL COMPOSITION, GEOMETRY AND SPECIMEN PREPERATION

We chose three geometries for the support material: 0.25 x 0.25 x 2.50 inches, 0.50 x 0.50 x 2.50 inches, and 0.75 x 2.00 x 2.50 inches. This was a preliminary study and these geometries would give us two points to quantify the effect of support height on build limit and one extreme point in examining the effect of an oversized support. We conducted the test for all the geometric configurations using both SnBi and the candy support material totaling six tests. The SnBi ingots were heated in a furnace to melting, roughly 450 °F. The candy was made of a mixture of sugar, corn syrup, and water. In terms of mass the candy consisted of 82 % percent household sugar, 15% corn syrup, and 3% water. The mixture heated to roughly 300 °F for 20 minute. Each support material was poured in its molten state and bracing material was used to ensure the edge of the supports remained flush with both the build specimen and the support bracing. The candy material proved to be somewhat unwieldy and the material overfilled the trough. We were able to ensure that SnBi was flush with the bracing. In each case the support trough was totally filled. Figure 7 and 8 show the filled specimens before welding. After the specimens were placed on the machine, we waited two hours before beginning the test to allow the specimens to reach thermal equilibrium.

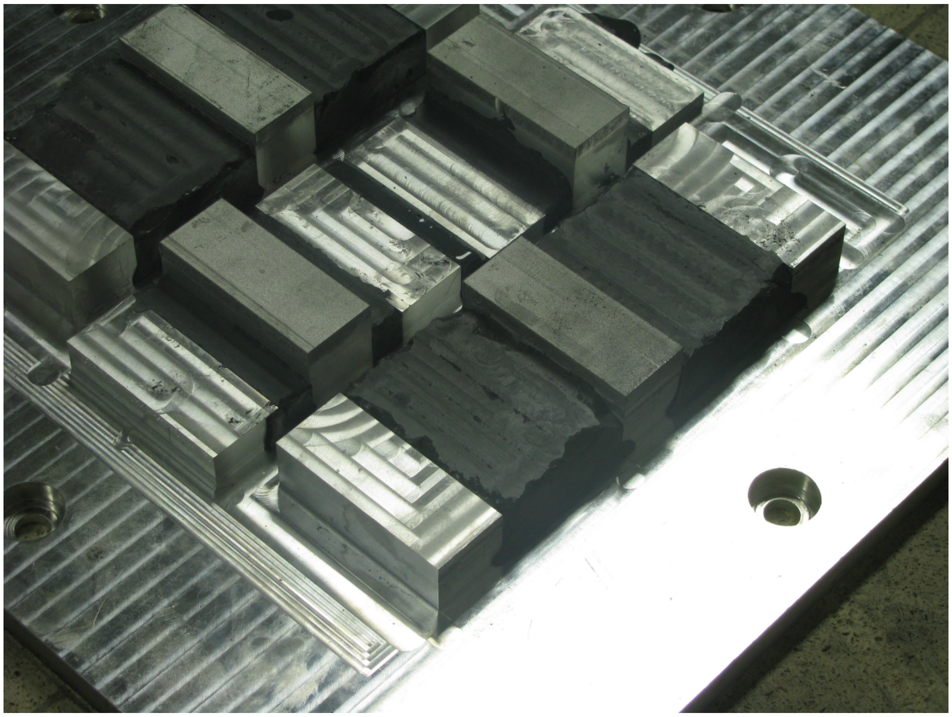

Figure 7: SnBi used in support material characterization

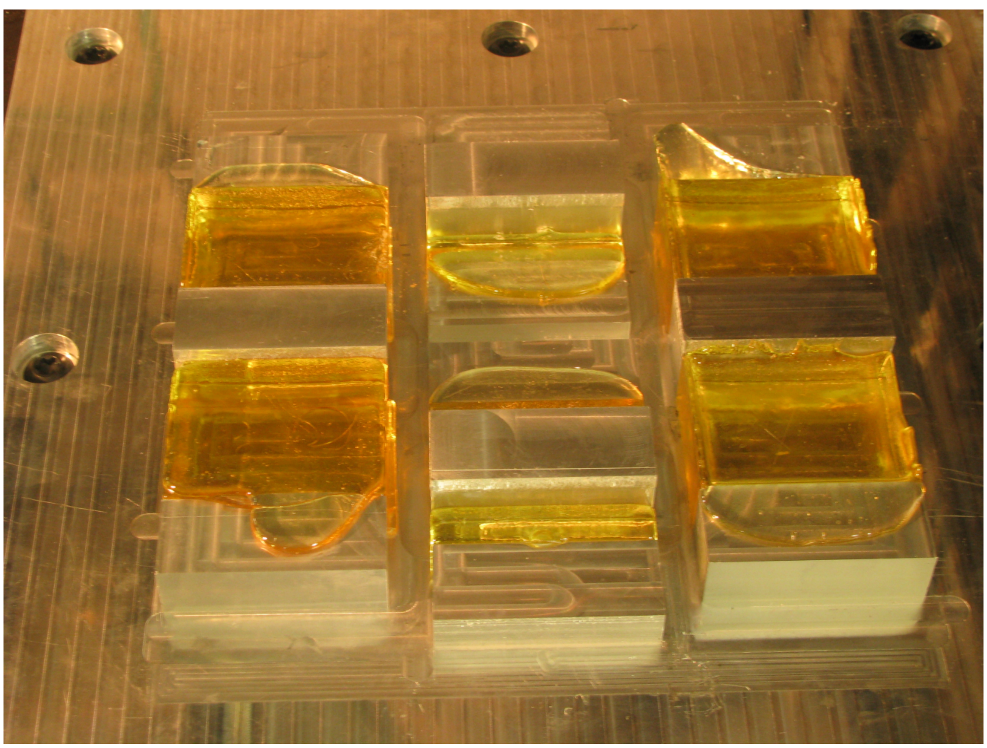

Figure 8: Candy used in support material characterization

PROCEDURE

Table 1 presents the geometry and UC process parameters for the tests. The base plate was heated to 120 °F (50 °C) for the candy and 200 °F (93 °C) for SnBi. The lower base plate temperature was used to avoid exceeding the melting point for both materials which would occur at the standard operating temperature 300 °F (150 °C) [7]. In addition, the normal load had to be lowered for each support material. Initially, the normal load was set to 1400 N (314.7 lbs.). This proved to be problematic since the power supply would short out and additional layers could not be welded over the specimen; the same behavior was observed when welding over the freestanding specimens of this dimension by Gibert *et al*. [6]. We systematically reduced the normal load until bonding occurred at a load of 269.8 lbs. (1200 N) and 179.8 lbs. (800 N), for the SnBi and candy, respectively. The amplitude was set to 9.84×10^{-4} inches (25 μm) and the rolling speed of 100 in/min (42.33 mm/s). Each specimen was then welded for up to 55 layers or until bond failure was observed.

Table 1: Test Specimens and process parameters used in support material test with a rolling speed of 100 in/min (42.33 mm/s) and amplitude of 9.84x10^{-4} inches (25 μm)

CFG	Support Height	Support Width	Support Material	Base Plate Temp.	Normal Load
1	0.25 in	0.5 in	Candy	120 °F	179.8 lbs. (800N)
2	0.50 in	0.5 in		(50 °C)	
3	0.75 in	2.0 in			
4	0.25 in	0.5 in	SnBi	200 °F	269.8 lbs. (1200N)
5	0.50 in	0.5 in		(93 °C)	
6	0.75 in	2.0 in			

RESULTS OF SUPPORT MATERIAL TESTS

Table 2 presents the results of the support material test. Although the use of the candy required a drastic reduction in normal load, its performance was superior to SnBi. In two of the three configurations, specifically, 1 and 3, the candy showed no signs of failure at 55 layers. Conversely, only one specimen of SnBi, configuration 5, showed no sign of failure. The candy was observed to progressively fracture as successive layers were welded, Figure 9.

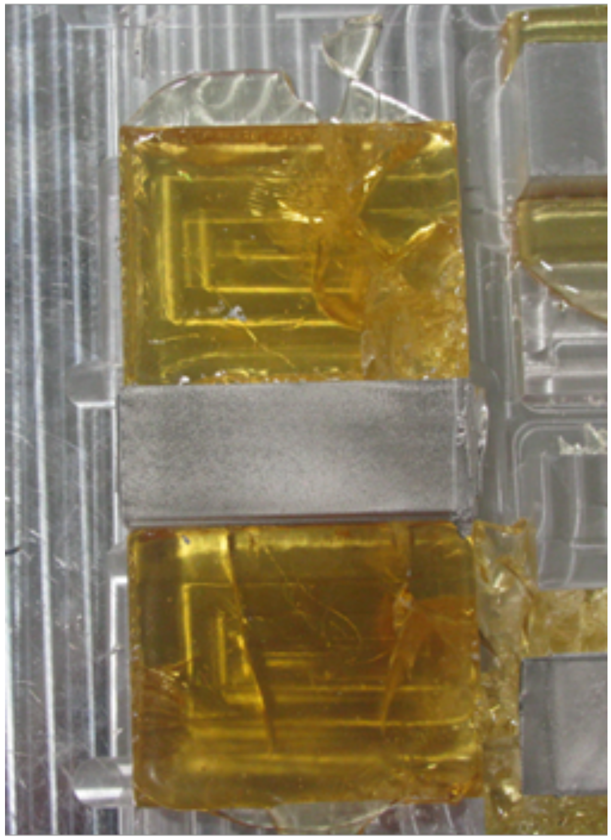

Figure 9: Cracking of candy support material

This was expected due to the much greater brittleness of the candy compared to the relatively soft and ductile SnBi. Despite cracking, the candy specimens remained attached to the build feature for the duration of the UC process. In contrast, the SnBi specimens showed no signs of cracking in their bulk. Figure 10 shows that support structures did not remain “wedged” between the specimen and the support bracing but were vibrated loose and shifted during the weld process. Note that the height or width of the support material was not a factor in the performance of the candy. Surprisingly, the tallest and widest SnBi sample refused to bond.

Table 2: Test results of observed failure for candy (sucrose mixture) and tin bismuth (SnBi) support materials

CFG	Support Height	Support Width	Method of Failure	Layer at Failure	Total Height	Support Material
1	0.25 in	0.50 in	No Failure	55	1.27 in	Candy
2	0.50 in	0.50 in	Crack Formed	48	1.22 in	
3	0.75 in	2.00 in	No Failure	55	1.27 in	
4	0.25 in	0.50 in	Crack Formed	28	1.11 in	SnBi
5	0.50 in	0.50 in	No Failure	55	1.27 in	
6	0.75 in	2.00 in	Detachment of 1st layer	24	1.08 in	

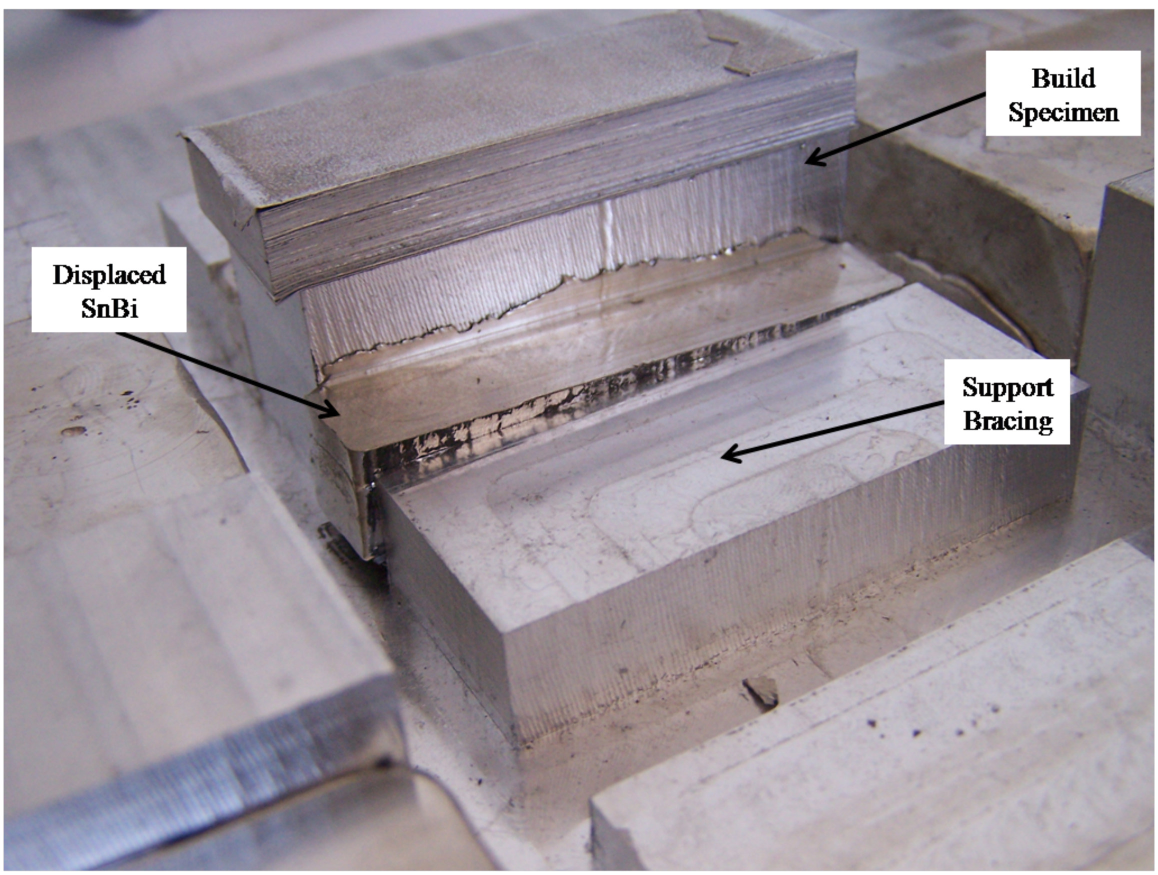

Figure 10: Displaced SnBi support material

DISCUSSION OF SUPPORT MATERIAL RESULTS

We hypothesize that the superior performance of the candy is primarily due to two factors: 1) propensity oft the candy to wet to the aluminum, and 2) a mismatch in the thermal properties between SnBi and aluminum that may have left a gap after initial heating cooling and reheating. These two factors outweigh the relative hardness or stiffness of the materials; thus, SnBi's stiffening effect could not be fully realized.

ADHESION OF SUPPORT MATERIALS TO ALUMINUM

The wetting depends on the relative surface energies of the molten liquid support material and the aluminum build specimen. When the surface energy of the liquid is greater than that of the solid; the liquid will have a large contact angle and appear as a bead. The surface energy also known as surface tension is a function of many variables including surface roughness and temperature; thus, obtaining the precise values for the surface energy of the material would be difficult to obtain. Lee *et al*. [9] shows that the equivalent surface tension of the molten SnBi is approximately 340 dynes/ cm much larger than the surface tension of the solid aluminum which is 35-45 dynes/cm depending on the alloy. The best estimates of the surface tension of the sucrose mixture are near 65 dynes at room temperature [10]. While the authors did not specify the size of the capillary tube used to perform the test. Estimating the tube width to be roughly 2 to 4 cm gives surface tensions of 16.25 dynes/cm to 32.5 dynes/cm very close to the surface energy of aluminum.

THERMAL PROPERTIES OF SnBi

Candy's superior wetting ability may not be the only the reason behind its performance. The coefficients of thermal conductivity and thermal expansion of the material also play a significant role in how well each support the build specimens. This relationship can be explained by considering the following simplified problem. Assume the heat flow and the change in length lie primarily in one-dimension, then using Fourier's law and the simple definition of one-dimensional thermal expansion, the change in length due to heating is

$$\Delta L = \frac{\alpha L^2 Q}{\kappa A}, \tag{1}$$

where α, κ, L, A, Q, are the coefficients of thermal expansion, conductivity, length in direction of heat flow, the cross-sectional area, and the heat flowing in the specimen. Fixing the geometry and input heat, the ratio of thermal conductivity to thermal expansion determines the change in length. Table 3 presents the thermal properties used for aluminum and SnBi. The ratio of α/κ for the aluminum and SnBi are 8.19e5 cm and 1.07e7 cm, respectively. Indicating that a fixed length of SnBi will expand more than aluminum, since it will absorb more heat. If the materials reach the same temperature and are allowed to cool, the SnBi will shrink more. This problem is complicated by differences in geometry between the supports and build feature, and that the heat flows in three dimensions in the actual tests. We theorize that once the SnBi solidifies the support structure shrinks so that it is no longer in contact with the build specimen.

Both materials are poured into the supports in their molten states, then allowed to cool to room temperature, and then re-heated to reduced operating temperatures of the UC process. As the material changes the temperature, the volume subsequently increases and decreases. A thermal-mechanical analysis using the ABAQUS finite element package was used to perform a rudimentary test of this hypothesis.

Table 3: Thermal properties of aluminum, SnBi used in finite element simulation

Properties	Aluminum	SnBi
Thermal Conductivity	19 W °C/cm	160 W °C/cm
Coefficient of Thermal Expansion	2.32e-05 /°C	1.50e-05 /°C

In the analysis, convective heat loss is neglected, SnBi is a assigned an initial temperature of 450 °F, the initial molten temperature when poured into the trough, and it is modeled as totally filling the trough between the aluminum build specimen and support bracing, thus it occupies the same volume as the trough. A subsequent steady state analysis of cooling is performed at an ambient temperature of 68 °F. Next we model the reheating in the UC process by applying a 200 °F thermal boundary condition to the bottom of the base plate. Figure 11 shows the resulting geometry changes resulting from this analysis. The support is 34 μm smaller than the width of the trough. This is a substantial difference considering the peak-to-peak amplitude of the sonotrode during the tests was only 25 μm. The results obtained from this analysis are preliminary and cannot be taken as definitive. We use estimates of the thermal and mechanical properties of SnBi. The model neglects latent heat, potential non-linear expansion and contraction, and temperature dependent material properties. Furthermore, the SnBi undergoes a phase change when cooling from its molten state to solid state; changing its mass density. The density change should serve to amplify the change in volume.

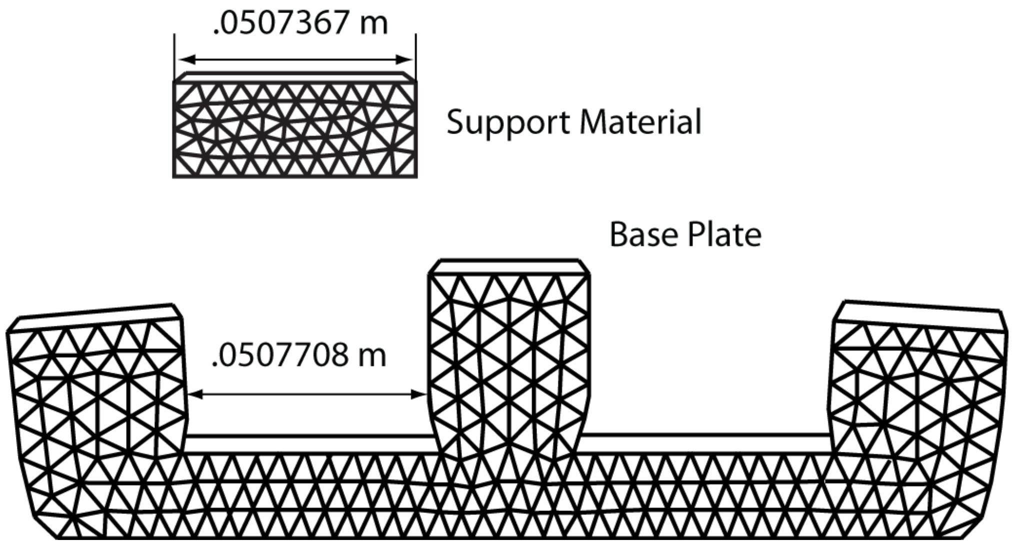

Figure 11: Deformation in heated SnBi support material and base plate from FEA model

CRACKING OF CANDY SUPPORT

Finally, the brittleness and resultant cracking of the candy suggested that, even in reheat during the UC process, the material was below its glass transition temperature. The glass transition temperature of the mixture of sugar, glucose and water used in this study is not readily available. Glass transition temperatures of similar substances range from 140 °F (60 °C) to 163 °F (73 °C) [11] which is above the operating temperature of 120 °F (95 °C) used in these experiments. Interestingly, the cracking does not affect candy's role in extending build height.

EFFECT OF GEOMETRY

The results of the study and the limited sample size make it difficult to determine the effects of the dimensions of the support material on the build limit. It is readily apparent that the support material does not have to equal the height of the build specimen for bonding to occur. The current set of experiments does not provide enough data points to predict the effect of width support material on build height. In the candy, we see smaller height support of 0.25 inches allowed the specimen to weld to 55 layers without any signs of failure compared to the support of height of 0.50 inches in which the specimen showed signs of cracking at 48 layers. The exact opposite was seen in SnBi with the crack formed when welding using a support of height of 0.25 inches. Finally, unaccounted for in this experiment is the effect of the dimension of support bracing which may play a prominent role in the support's effectiveness.

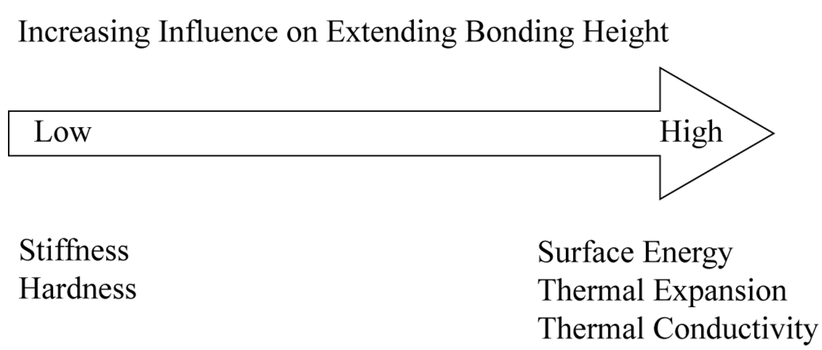

Figure 12: Summary support material properties on build height

RECOMMENDATIONS

Figure 12 summarizes the effect of support material properties on extending bond height. These results can be added to the original recommendations of Swank and Stucker [7] on the use of support materials. In using support material the surface adhesion and thermal expansion should be considered whenever possible. The surface energy of the molten support material and the build specimen should be as close as possible. The materials should have similar coefficients of thermal expansion when the support material is not completely enclosed. Finally, when using material with significantly differing coefficients of thermal expansion one may need to apply the support material in an enclosed channel.

FUTURE WORK

This work can lead to several avenues of future research. First, the results here can form the basis of an expanded support material study that considers the specimen and support material's, height, width and geometry, as well as back support height, and geometric configuration in extending build height using a design of experiments approach. Second, this study only considered two support materials. The experimentation should be repeated for the other materials such as those examined by Swank and Stucker [7]. This work illustrates that the design space of candidate support materials needs to be expanded to include the wetting and thermal properties of the materials.

ACKNOWLEDGEMENTS

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REFERENCES

1. George, J. and B. Stucker, *Fabrication of Lightweight Structural Panels through Ultrasonic Consolidation.* Virtual and Physical Prototyping, 2006. **1**(4): p. 227-241.
2. Robinson, C.J., et al., *Maximum Height to Width Ratio of Freestanding Structures Built Using Ultrasonic Consolidation.* Seventeeth Solid Freeform Fabrication Proceedings, 2006: p. 502-516.
3. Zhang, C. and L. Li, *A Study of Static and Dynamic Mechanical Behavior of Substrate in Ultrasonic Welding.* Seventeenth Solid Freeform Fabriaction Symposium, 2006: p. 502-506.
4. Zhang, C. and L. L, *Effect of Substrate Dimension on Dynamics of Ultrasonic Consolidation.* Ultrasonics, 2010: p. 811-823.
5. Gibert, J.M., E.M. Austin, and F. G., *Effect of Height to Width Ratio on the Dynamics of Ultrasonic Consolidation.* Rapid Prototyping Journal, 2010. **16**(5): p. 284-294.
6. Gibert, J.M., McCullough D., Fadel G., Martin G., Austin E. M., "Stick-Slip Dynamics in Ultrasonic Consolidation", *Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC 09) San Diego, CA* (August 30-September 2, 2009).
7. Swank, M.I. and B.E. Stucker, *Investigation of Support Materials for use in Ultrasonic Consolidation.* Solid Freeform Fabrication Symposium Proceedings, 2009: p. 231.
8. Gibert, J.M., *Dynamics of Ultrasonic Consolidation*, in *Mechanical Engineering*. 2009, Clemson University: Clemson.
9. Lee, J., et al., *Reactive Wetting between Molten Sn-Bi and Ni Substrate Ni substrate.* Journal of Electronic Materials 2003. **3**(32): p. 117-122.
10. Lindfors, K.R., *Surface Tension of Sugar Factory Products.* Industrial and Engineering Chemistry, 1924. **660**(3): p. 813-816.
11. Okomo, M., et al., *Glass transition temperature of amorphous solid formed from sucrose crrystal with different melting point.* Proceedings of the Research Society of Japan Sugar Refineries' Technologists, 2003. **51**: p. 7-12.