MECHANISMS FOR POST PROCESSING DEFORMATION WITHOUT PART-SPECIFIC TOOLING

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Abstract

Post processing deformation of additive manufactured components offers many advantages from reduced printing time and material usage to simplified multimaterial fabrication. For thermoplastic components, controlled deformations can be achieved by locally heating to temporarily soften the material. This paper investigates multiple methods of selectively heating and deforming desired locations to form the final component. The deformation location can be controlled by geometry (thickness), surface properties (reflectivity) or by local addition of a secondary material to control the heating. Demonstrations are provided for each of these deformation methods and then an example is provided to show how this approach could produce customized geometries from a standard feature.

INTRODUCTION

Additive Manufacturing (AM) builds components layer by layer where each layer is a thin cross section of the desired part. The connection of surfaces in 3D is broken and the continuity between the layers is then determined by the differences in cross sectional areas to the adjacent layers. In fused deposition modeling (FDM) these layers are created by extruding a molten material through a nozzle in a controlled manner [1]. This creates tremendous geometric freedom, but it also introduces directional variation in the material properties. Moreover, the build time and component cost depend on the build orientation.

Some AM components could benefit from printing in a more compact or even a flattened state to reduce printing time, improve strength in key directions, facilitate faster 2D processing methods and ease the incorporation of multiple materials [2]. Such methods could utilize the power of the matured 2D printing industry and the powerful folding capabilities of origami to add functionality to 3D surfaces at lower costs/faster speeds than can be achieved by direct AM of the 3D geometry. This can be compared to how 2D cardboard is folded into many shapes and sizes to become useful packaging solutions [3-5].

This paper describes options for deforming thermoplastic structures after printing without part-specific tooling to maintain the advantages of AM processes. The components can be deformed by utilizing thermal absorption characteristics to locally soften the material at desired deformation sites. Minor geometric and material variations are introduced to localize the deformation regions. We reference a prior demonstration of how this could be utilized to generate multifunctional components using low cost, mature, commercial processes. We then present some examples of simple deformations by multiple methods.

POST PROCESSING DEFORMATION

Post processing deformation (PPD) is a technique that was developed by combining the fields of additive manufacturing with an origami style of folding. This concept involves a deformation sequence which transforms a 2D part into 3D. PPD allows a part to be created in 2D then deformed into its desired 3D shape during post processing. This means that a 3D component could be produced from predominately 2D manufacturing processes. This has many advantages which will be discussed in the following paragraphs.

Crane et. al. [2] has demonstrated that by using post processing deformation (PPD) to create a hollow 3.6 cm cube the build time was reduced by 46% with a 30% decrease in required support material. A 3D printed antenna (Fig. 1) using PPD was able to be produced using inexpensive 2D equipment rather than 3D deposition. In many processes (including AM processes such as FDM), each of the layers are aligned parallel to the printing platform and stacked on top of each other. The strength of adhesion between layers is much less than the strength within a layer. PPD allows these high strength orientations to be aligned with the stress orientation, which can lead to an increase in tensile, fatigue, and flexural strength in critical directions and locations.

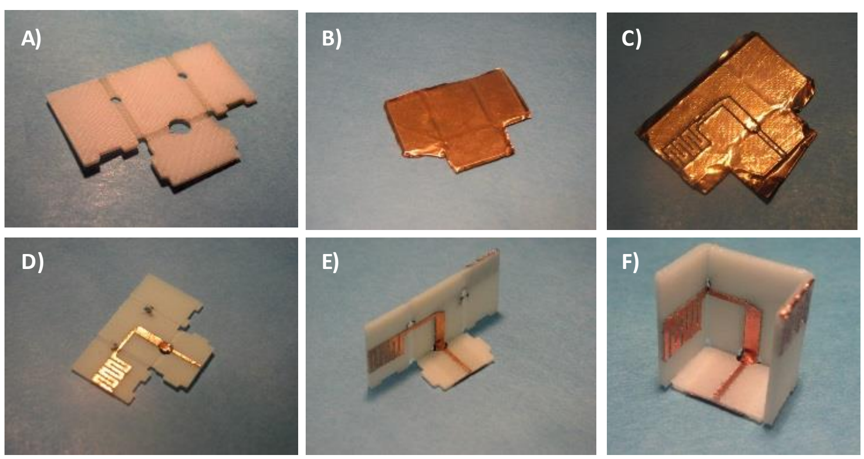


Figure 1 Formation of 3D printed Antenna. A) Part as printed B) Component coated with copper tape C) Electrical paths cut into copper D) Excess tape removed E) Deformation F) Final Component [2]

Another key advantage of PPD is the ease of incorporating multiple materials as in Figure 1. Material can be added between the final print and PPD so that the deposition locations can be oriented to maximize the ease of deposition and accessibility of the surfaces during secondary operations such as electronics printing. For example, material can be deposited on an easily accessible upward facing surface and then deformed into a final position. This would allow the material to be located on the underside of an overhang or the inside of a closed volume in the final state without the need for support material.

Figure 3 shows a pyramid formed by PPD before and after deformation. A small torch was used for localized heating of the joints. For the pyramid Figure 3 with a joint section 0.4mm thick only about a second of heating was required in order to become formable. It is a fast manual method of performing PPD suitable for prototyping and hobby applications. However, alternative methods of controlling the deformation would be preferred for industrial implementation.

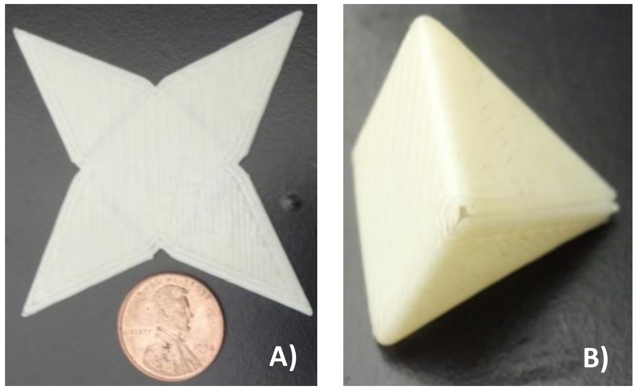


Figure 2 a) Part as printed in ABS with parallel horizontal layers b) After deformation performed with a pencil torch, layers are aligned into folded directions.

A practical process must be able to repeatably produce the desired geometry. The final geometry are a function of both the material properties of the part during deformation and the loads placed on the part. Typically, the relationship between loads and shape is complex. Most forming processes use a combination of force inputs and geometric constraints to control the formed geometry. For example, thermoforming uses air pressure to push the softened plastic against a mold surface that defines the final geometry.

However, predicting and controlling the deformed geometry can be simplified by eliminating the deformation in many regions of the part. In the simplest case, it can be constrained to deform along lines. This reduces the deformation to a folding process [6]. In folding, each fold is a joint in a spatial kinematic mechanism dramatically reducing the possible geometries that are formed and eases the prediction process. This limitation can be a large asset in increasing control and repeatability without requiring forming tools. Lang, R. [7] has shown that by sequencing just three simple fold types, complex 3D geometries can be created with remarkable complexity. This is the source of origami's great variety. Additionally, printed structures can incorporate other features to help control the deformation patterns.

In general, a folding process must provide for limiting deformation along specific paths. It is generally desirable to only make a small number of folds (often just one) at a time. For a thermoplastic, these folds could be made by selectively heating the fold lines. Folding sequence algorithms is a subdivision of computational geometry which has been actively studied since the late 1970's [7]. By modifying these algorithms to include the additional constraints added by heating sequencing the program can create an automated plastics deformation sequence. MIT recently used an automated folding sequence to create a self-assembling walking robot from a 2D structure [8]. The balance of this paper will consider methods by which the fold lines can be selectively heated including some methods that permit control over the heating sequence.

TARGETING DEFORMATION SITES WITH SELECTIVE HEATING METHODS

In order to control the deformation regions predictably, a contrast must be created between the stiffness/yield conditions in the regions to be deformed and the rest of the part. Selective heating methods are needed to create the contrast in properties and can also be useful to enable control over the sequence of deformations. This is particularly useful for thermoplastics as they undergo dramatic reductions in moduli over narrow temperature ranges [9-11].

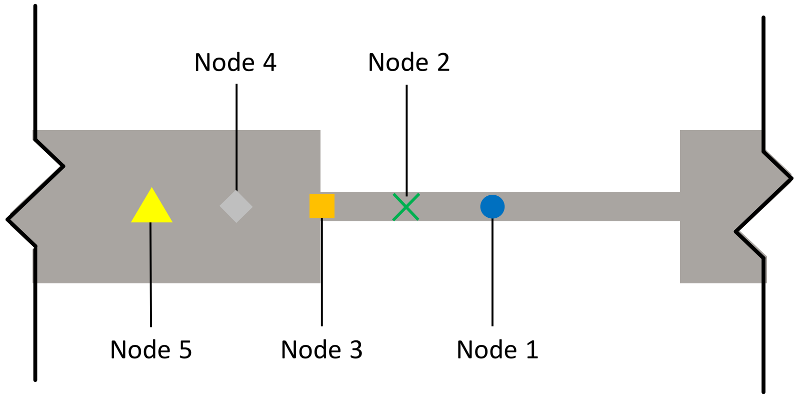
Methods exist for selectively heating specific locations by localizing the applied energy as with a laser. However, this equipment is often expensive. An alternative approach is to spatially control the absorption of energy or the required amount of absorbed energy to transform the region. This can be done by tailoring the geometry of the part or with the addition of a temporary material with the desired heating characteristics. These methods could be performed using either convection or radiation heating. The following sections evaluate the potential performance of several methods for achieving spatial variation in material properties.

GEOMETRICAL DESIGN FOR SELECTIVE HEATING

The simplest approach is to spatially vary component geometry to control the bending. Thin sections at joints decrease the bending stiffness and heating time relative to the bulk material. When heat is applied to the part, there will be a period of time in which the joint temperature is above the glass transition (T_g) while the part core remains below T_g.

With this method all the thin regions would be in their deformable state simultaneously. This would be an undesirable affect for sequence control. During deformation a small amount of internal stress will remain which results in a slight shape memory. If joints are reheated for additional processing, they will bend back towards their original geometry if not constrained.

A simulation was conducted to illustrate the feasibility of achieving the necessary property contrast with this method. The results seen in Figure 3 were obtained by simulating an Acrylonitrile Butadiene Styrene (ABS) component (T_0 = 23 C) part placed in a convection oven. The oven is assumed to be at 300°C with a convection heat transfer coefficient of 50 W/m^{2}K. After being in the oven for 20 seconds the part is removed and allowed to cool at room temperature with a convection heat transfer coefficient of 3 W/m^{2}K. The thickness of the joint is 0.4 mm with a length of 5 mm while the thickness of the part is 2 mm and its length can be considered semi-infinite.



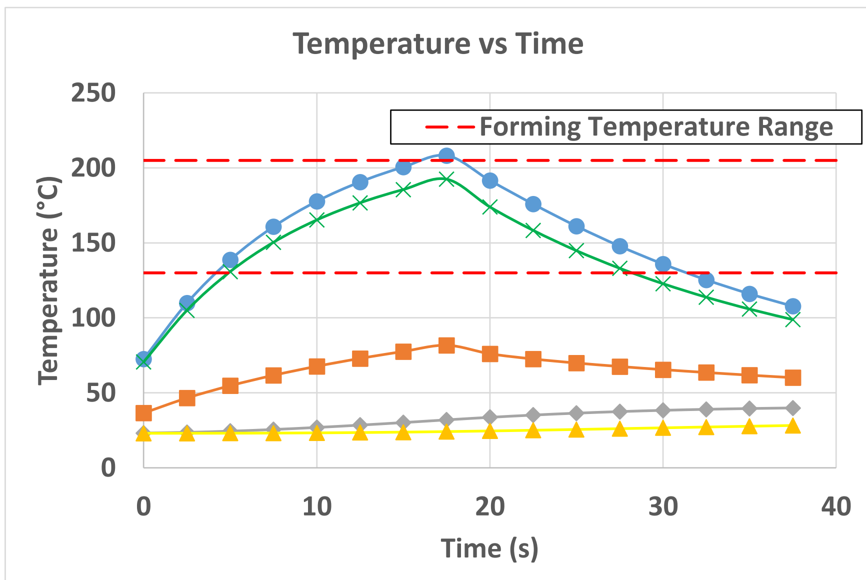


Figure 3 shows the FEA node locations and temperature profile of a joint subjected to convective heating at 300 °C for 20 seconds then cooled at room temperature for 20 seconds. This provides a forming time window of approximately 10 seconds.

The Finite Element Analysis (FEA) in Figure 3 demonstrates that the joint will be maintained above the glass transition temperature while the structure of the part will be well below that value. In amorphous plastics like ABS the glass transition temperature is when the plastic can be deformed without cracking. The forming of ABS is between 130°C and 205°C [10]. When heated above this range the plastic enters a viscous state and begins to sag, causing ripples as seen in Figure 4. If the part is removed from the oven when the peak temperature is at the upper limit, there will be approximately a ten second processing window to deform the joint. If the outer surface is permitted to exceed this limit, the core of the deformation region could still provide sufficient strength to limit the sagging but is heavily dependent on the thickness of the joint. On the other end of the processing window, simple bending processes could be completed with the core below the processing temperature due to the very small strains near the neutral axis. This may even be a favorable way of reducing/eliminating any net tensile deformation that might create undesired geometrical changes. Thus, the processing window could reasonably be increased by heating to higher temperatures or allowing further cooling before forming. However, there may be impacts on dimensional accuracy, material properties, and residual stresses that would need to be considered further.

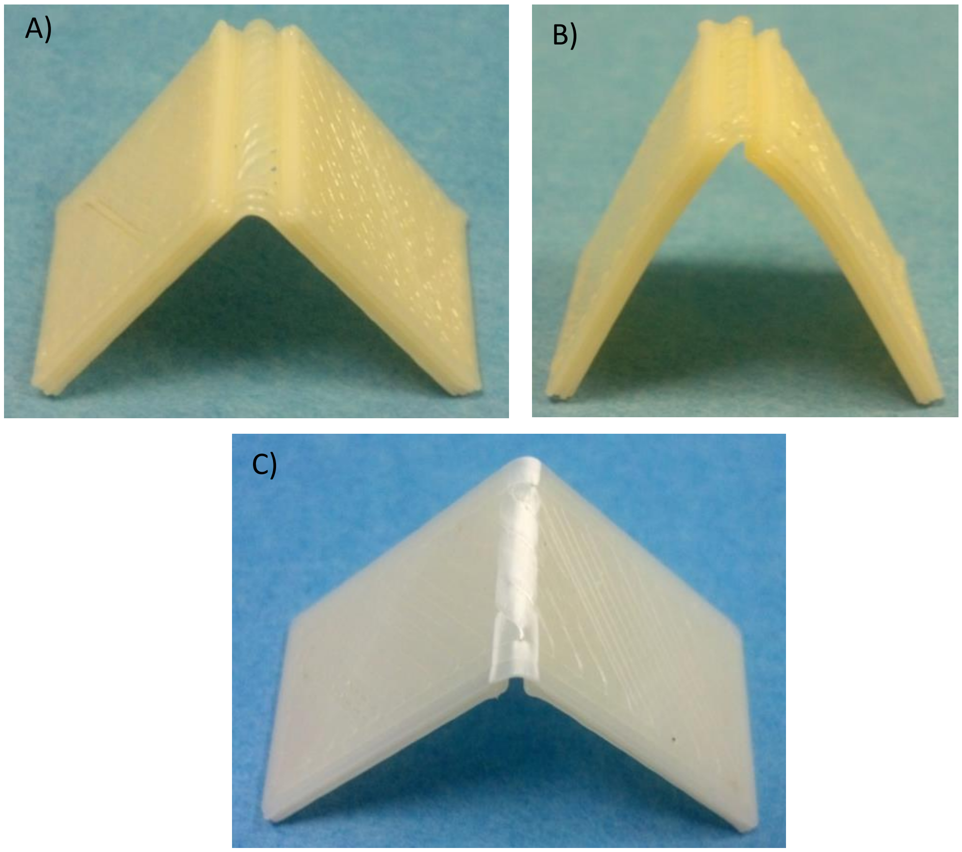


Figure 4 A) Joint formed inside of the thermal processing range exhibits a smooth 90° bend in joint section, B) Joint formed above the thermal processing range shows signs of discoloration with warped joint and structural sections, C) Joint formed below the thermal processing range exhibits internal cracking (white area).

A geometrical approach provides one method for placing an entire part under heating conditions which will selectively heating desired locations to the forming temperature. While the part's geometry must be specifically tailored to allow this, this is easily accomplished and the heating equipment requirements are very simple. Unfortunately, all deformation regions are heated simultaneously. This could be avoided by controlling the locations of energy absorption as discussed below.

SELECTIVE INFRARED HEATING

By taking advantage of the radiation absorption properties of materials, radiative heat absorption in the visible and infrared wavelengths can be tuned over a wide range by applying simple reflective coatings. For example, a reflective copper coating could reduce heat absorption by 90% [12]. By patterning the reflective and absorption regions in multiple steps, a defined deformation sequence could be achieved. This method provides the advantage of being able to selectively heat specific joints. Unlike the previous heating method infrared heating can provide sequential control of joint deformations if the reflective coatings can be modified or removed between deformation steps.

An FEA analysis was conducted to test the feasibility of this idea. The desired effect would be to have the infrared heat absorbed by the plastic in a specific area while a copper coating will reflect away heat in the other areas. Figure 5 displays the results of the analysis which demonstrates how a reflective coating can be used to selectively heat a semi-infinite ABS part. The modeled part was 2mm thick with an incidental radiation temperature from a 500°C ambient with a view factor of one, and emissivity of 0.1 for the 0.07mm thick reflective layer and 0.9 for the exposed plastic surfaces. The radiation heating condition is applied for 17.5 seconds after which the part is allowed to cool at room temperature with a convection heat transfer coefficient of 3 W/m^2K. Figure 5 illustrates the temperature profiles over time for key points around the joint.

Since the joint doesn't require that section to be thinner than the structure the thermal capacitance of the deformation region will retain heat for a longer period of time than when using geometrical thermal control. This leads to a longer processing time window than geometrical control by approximately 10 second with a total processing time of 20 seconds once removed from the infrared heaters. Additionally, the joint can have greater mechanical strength than when it is produced by a local thinning of the material.

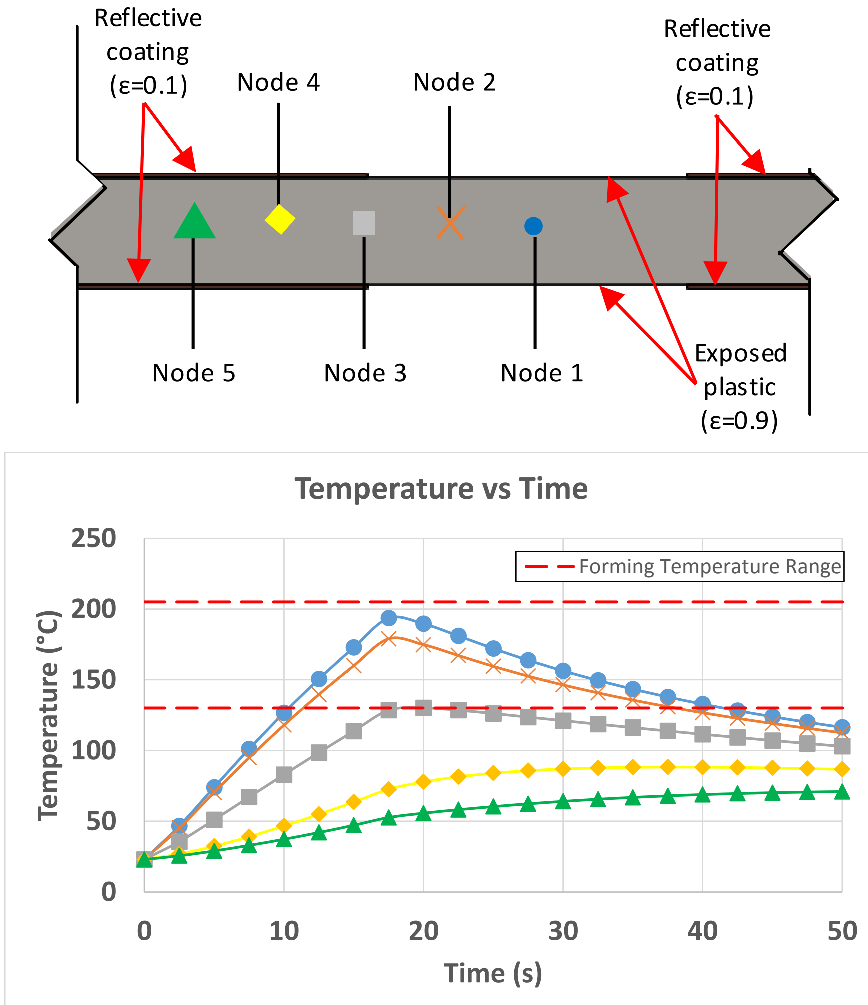


Figure 5 shows the FEA node locations and temperature profile for a joint heated on the top and bottom side by radiation for 17.5 seconds then allowed to cool at room temperature. Only the joints are exposed to the infrared radiation while a copper coating on the structure of the component reflects away unwanted radiation.

This method is not without its drawbacks. The reflective coating material must be applied, the part must undergo PPD, and then the coating must be removed. The reflective coating itself must also be shaped to the desired geometry. These items can make this a time consuming process. Since the part will be heated, it is possible that any adhesives used to affix the reflective coating may remain on the part. We present below a different method which can yield a quicker processing time while also providing a simple and clean material removal process.

SELECTIVE MICROWAVE HEATING

Microwaves are a particularly promising method of radiative heating. Most polymer materials used in additive manufacturing absorb little heat when exposed to microwaves. When small, local additions of a material with high absorptivity are added to the surface of the part, microwaves can be used to locally heat these specific locations. The microwave absorbing material then transfers its heat locally via conduction to the part. The amount of energy that a material converts into heat is measured by the material's loss tangent. The loss tangent is proportional to the amount of volumetric heating produced by a part when exposed to microwave irradiation. Water, oils, fats and sugars have high loss tangents resulting in high heat generation when exposed to microwaves. Polymers have a low loss tangent resulting in negligible heat generation.

Heating patterns could be formed by locally depositing the absorbing material. A liquid absorber would be easily patterned using inkjet printing or other direct write techniques. Conductive particles can also be integrated into the fluid to increase microwave energy absorption. The maximum temperature of a liquid absorber is limited to the boiling point of the fluid. While water boils below the processing temperature of most plastics, other liquids such as sugar solutions have higher boiling points suitable for plastic processing.

Honey was used as the substance for the localized microwave heating seen in Figure 5. Honey has a loss tangent roughly 50 times higher than ABS [13, 14]. When honey is deposited on the surface and microwaved the heat generated by the honey creates regions of high flexibility. Afterwards, the honey is readily removed by rinsing with water. Successive iterations of deposition and removal of the microwave absorbers can be used to control the deformation sequence. Honey has the advantage of staying semi-viscous at higher temperatures which leads to reduced spreading. In order to keep the honey from expanding out of the desired region it can be confined by the addition of a removable constraint such as a paper cutout. Honey has the advantage of having a boiling point around the temperature needed for deformation of thin regions. ABS joints up to 1mm thick were sufficiently heated to temperatures required for forming.

When using honey on a sheet to heat a pattern other than a joint, uniform heating becomes an issue. Inside microwave ovens there are zones of high microwave radiation and dead zones with very little radiation. This leads to non-uniform heating of the honey which can locally boil the honey on one side of the design while the other side remains much cooler (Figure 6B). If the honey is heated at a slower rate to allow more uniform heating then the heat absorbed by the honey is dispersed to the part and begins to heat undesirable locations (Figure 6C). Future work must be conducted to accurately heat a specific design locally but a more uniform method of microwave radiation must be used.

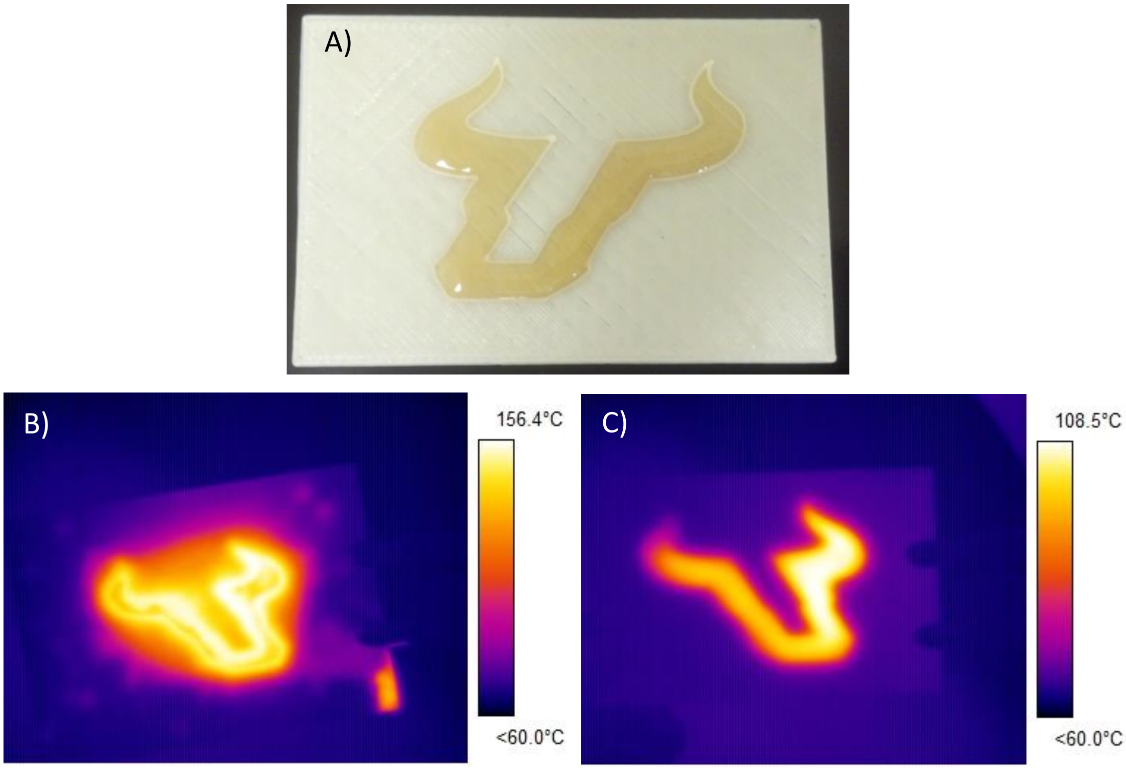


Figure 6 Microwave heating is used to selectively heat only the desired areas filled with honey. A) Part as printed, Thermal image of part from the bottom after microwaving for B) 45 seconds at 20% power and C) 30 seconds at 30% power in a 900W microwave oven.

One limitation of the honey is that the boiling point increases as the water evaporates off and at some point the sugars begin to react so that they are no longer easily removed. Other substances have also been shown to have suitable properties for selective microwave heating. In particular ethylene glycol and propylene glycol have boiling points in the processing range that would be ideal for use on ABS. They also form relatively nontoxic vapors upon heating and residues can be rinsed away with water.

DEFORMATION ANGLE CONTROL

In order to properly reproduce a 3D model from a 2D state, the final angle of the deformation must be precisely controlled. The accuracy and repeatability of the deformation angles are essential characteristics in preventing misalignment. In the case of simple bending deformation, this is possible by altering the geometry of the interfaces to interlock with each other. A locking joint can be either printed on the surface of the adjacent faces as in Figure 7 S or create a positive and negative shape to fit together like a puzzle piece as in Figure 8.

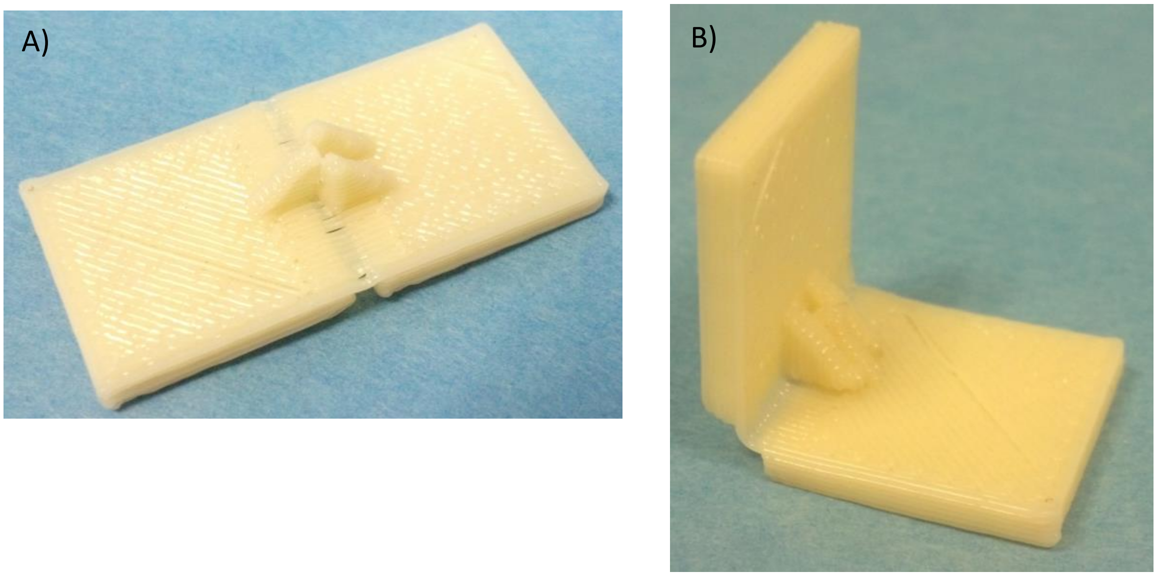


Figure 7 Surface mounted angle lock. A) Before deformation B) After deformation.

The lock joint seen in Figure 7 Shas been adopted and modified from Deng D. et. Al [15, 16]. The final folded shape is held in place by a friction contact. By modifying the shape of the mating triangles varying angles can be achieved. Once the flat edge of the triangle contacts the adjacent surface during deformation the final desired angle will have been achieved. This removes any human error from forming the correct angles and simplifies the deformation as the desired angle can be built into the part.

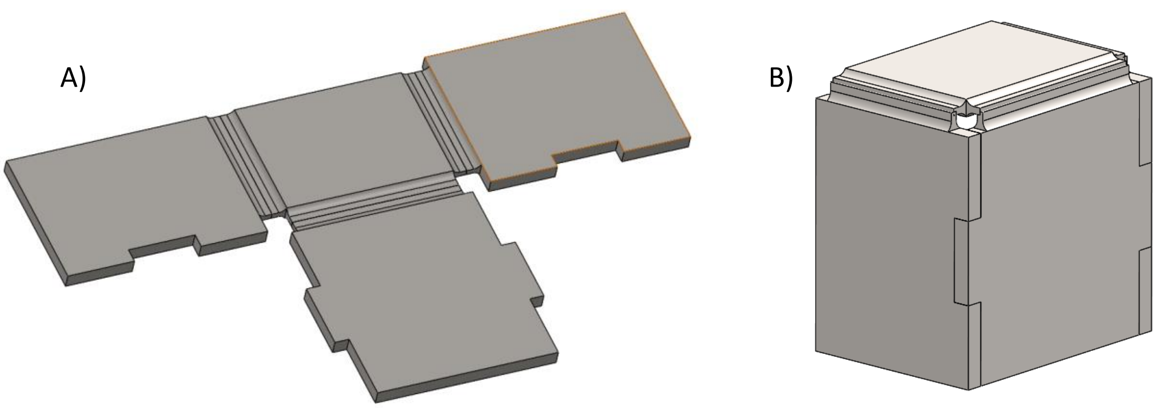


Figure 8 Friction interface angle lock. A) Before deformation B) After deformation.

The angle lock seen in Figure 8 is the design used to create the 3D antenna which is displayed in Figure 1. This design uses interlocking components that are held together by a friction contact. This style of the lock joint allows the desired angle to be built into the part without increasing the overall height of the part during printing.

CONCLUSIONS

Though AM opens the way for direct 3D manufacture, there are often penalties in properties, cost, and speed. There are potential advantages to printing a component in a flattened 2D state then deforming them into the desired 3D shape. These advantages include reduced printing time, reduced printing material, ease of incorporating multiple materials and increased mechanical properties. This work discusses methods for local heating of desired locations using convective and radiative heating as well as ways of controlling the final dimensions. Of particular interest, radiation absorbers can be used to selectively absorb radiative energy for localized heating. This was demonstrated using microwave energy with water and sugar solutions utilized as radiation absorbers. The boiling point of these materials provide a limit on the upper processing temperature that can be used to avoid overheating. In many cases, these absorbers can be removed by simple rinsing. These processes can become automated by a sequenced control of the deformations.

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