

DEFORMATION POST-PROCESSING OF ADDITIVE MANUFACTURING COMPONENTS

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Abstract

Parts produced by additive manufacturing (AM) often require post processing to improve surface finish and mechanical properties. However, little attention has been given to including deformation in the post processing. Deformation post-processing can address some part size, manufacturing cost, and geometry limitations of 3D printing. Additionally, it could be used to create 3D surfaces using planar manufacturing processes (such as printed circuit board manufacturing). The challenge of deformation post-processing is the design of the correct fabrication state to produce the desired final state and the accurate deformation of the parts to the desired final state. This paper demonstrates the geometric capability, potential applications, and methods for accurately and repeatedly deforming the initial geometry to the desired configuration using features in the parts.

Introduction

Additive manufacturing (AM) relies on computer control of material bonding/deposition rather than part-specific tooling to define the geometry of the manufactured component. Typically, parts are built up layer by layer until they are complete. After the geometry is formed, the parts are post-processed to achieve the final geometry and properties. The post-processing methods vary with the AM process, but can include removal of support material, infiltration of pores, surface finishing, annealing, and cleaning (Gibson et al., 2010).

The AM approach provides substantial freedom in the geometries that are created and eliminates the time requirements of manufacturing specialized tooling. Additionally, some of these processes are capable of integrating multiple materials to create multifunctional components (Wicker and MacDonald 2012, Dollar and Howe 2006, Kataria and Rosen 2001, Malone, 2004). However, the processes themselves are typically much slower than traditional manufacturing methods. Additionally, despite substantial progress, the materials available for AM are more limited than for traditional processes.

This paper considers the use of deformation in the post processing of AM components to address some of these challenges. In deformation post-processing a part would be printed in one configuration and then during post-processing deformed into its final configuration. If this approach were applied to printing thin shells (such as what could be produced from sheet metal processing), the printing time and use of support material could be dramatically reduced. As an added benefit, more of the key features could be aligned where printing accuracy and surface finish is often highest. (Xu et al., 1999; Flores et al., 2003; Ollison and Berisso, 2010)

Deformation post-processing could also be integrated with traditional planar manufacturing processes to create 3D geometries. Thus, high speed, mature planar cutting and printing processes could be used to rapidly create 3D structures. This would be of particular value in fabricating multifunctional structures incorporating electronics from available printed circuit board technologies.

The keys to enabling this alternative approach are:

- 1) Avoid material Failure: Many materials of interest are relatively brittle and so the deformation must be achieved with minimal component strain to avoid failure.
- 2) Simplify the Deformation process: In the spirit of AM, it is important that the use of specialized deformation tooling be minimized. Preferably, the deformation response will be built into the component itself. Of course, the deformation process must be accurate as well in order for the final part geometry to be acceptable.
- 3) Simplify the part design process: In order to be applied to a variety of parts, it must be easy to integrate the required printing features into the components to achieve the desired outcomes.

In order to demonstrate the technical feasibility of these methods, this paper will utilize the temperature variation in mechanical properties to avoid material failures. The deformation process will be simplified by reference to both material properties and compliant mechanism design. These concepts are demonstrated for creating 90 degree bends. Additionally, a benchmark multifunctional part will be shown.

Deformation Strategies

If the desired post-processing deformation cannot be achieved by custom tooling, then alternative approaches are required. In this work, we consider controlled deformation through localized variation in the material properties and localized variation in the stiffness. Combining these two approaches permits accurate deformation of AM components. These approaches are discussed independently and then examples are presented. All 3D Printed components were produced using a Dimension sst-768 out of ABS.

Spatial Variation in Material Properties

While some AM processes are capable of printing variable material, the majority can only deposit a single structural material per part. Additionally, since post processing deformation is a one-time process, the ideal joint material would be flexible for deformation and then stiff during the use phase. The easiest route to achieving this property variation in polymeric AM materials is through heating (Nikzad et al., 2011). This is especially effective in polymer materials where heating above the glass transition temperature significantly reduces the material stiffness and increases the strain to failure.

The ideal hinge joint would have no torsional stiffness with infinite axial stiffness with just one axial degree of freedom. Typically, compliant mechanisms are designed for elastic motion and so this problem is addressed by making a beam very thin in the transverse direction. As bending stiffness varies with the cube of the beam thickness while axial stiffness varies linearly with thickness, this is a feasible approach. However, there are obvious compromises in the strength of the resulting element in use.

This concept can be integrated with the material properties of polymers to achieve a similar affect and permit temporary torsional flexibility while maintaining adequate axial stiffness. This can be accomplished by non-uniform heating of the part. The hottest regions will experience a dramatic decrease in their modulus while the cooler regions are relatively unaffected. The easiest way to accomplish this would be to apply heat to the exterior of the part such that the Biot number ($Bi = hs/k$) is large. Under these conditions, there will be a substantial (though temporary) gradient in the temperature through the part thickness. Since the thickness of the bending joints is much less than the component body, the joints heat through much quicker than the body. This softens the joints and allows the joints to easily undergo deformation while maintaining a much higher stiffness in the component body. Due to the low thermal conductivities of polymers, this condition is more easily achieved than in metals and the processing window will be larger.

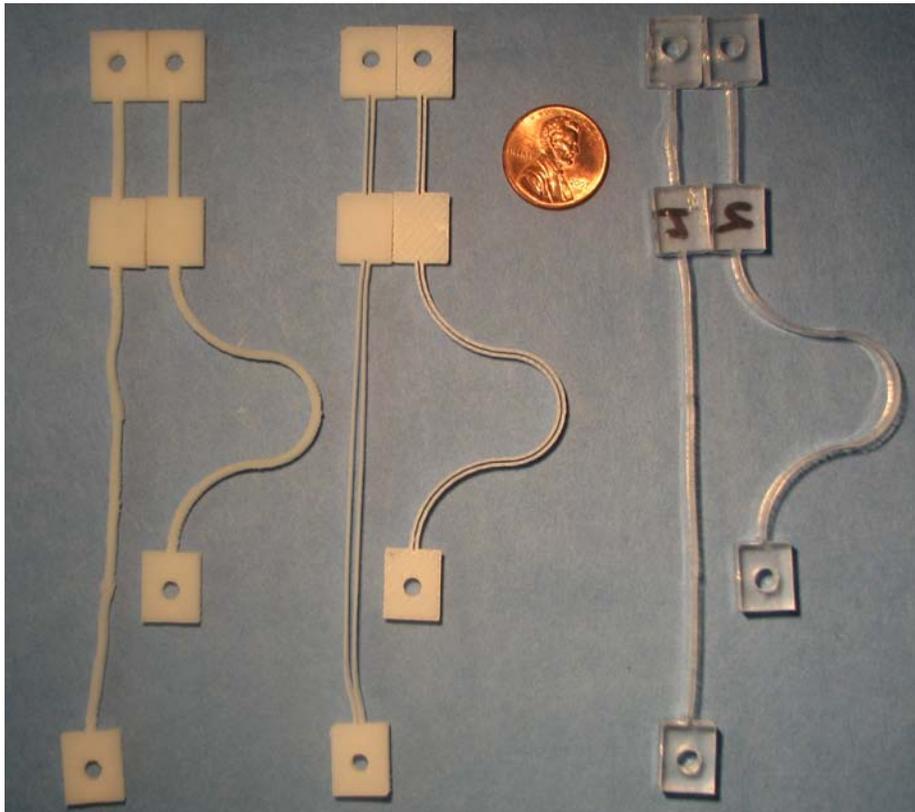


Figure 1 Demonstration of thermal bending without tensile strain for three different parts. Pairs compare a heated and unheated part of each type. From left to right, ABS plastic produced by FDM with the curve vertical, ABS plastic made by FDM printed in the position shown, and laser-cut acrylic.

To demonstrate the feasibility of bending a part without causing significant axial strain, a small test specimen illustrated in Figure 1 was created from both ABS plastic (FDM) and acrylic (laser cut). The ABS part was printed in two different build orientations. The planar print produced two thin strips of polymer with a gap between while the vertical build produced a filled structure.

A weight of 18 g was attached to one end of the specimen while the other was held in a furnace set to 200 C. When the curved segment was observed to straighten, the sample was removed from the furnace and quenched under running water. The change in the length of the straight segments was within the measurement errors for two part types and modest (1.5%) for the third while the final length of the curved segment was very close to the length of the centerline of the original arc despite a large change in the gap between the rigid blocks and accompanying change in curvature of the thin segment. This demonstrates the potential for bending deformation without significant axial strain.

Table 1 Measured strains in test components from heating under tensile load (Strain is the change in length before vs. after the test. Given the difficulties of measuring arc lengths, the nominal arc length was used to calculate strain. Gap change is the percentage change from the initial to final spacing between the solid blocks.

Material	Straight Segment	Curved Segment	
	Strain	Gap Change	Strain
ABS (Planar Print)	<0.1%	61%	0.9%
ABS (Vertical Print)	1.5%	64%	3.1%
Acrylic	<0.1%	59%	2.0%

By integrating the transient heating with a compliant mechanism, the local thinning of the flexing regions will heat through more quickly increasing the contrast in stiffness between the thick and thin regions.

Spatial Variation in Local Stiffness

Given that the printed material has fairly uniform material properties, variation in local stiffness is achieved by carefully designing the geometry. The key to this approach is designing geometry that is thin and can bend significantly without fracture. Often the effects that are desired require nonlinear deformation theory, and these effects are most aptly designed using *compliant mechanisms*.

COMPLIANT MECHANISMS

A mechanism is a device that transforms or transmits motion or energy; a compliant mechanism is a mechanism that achieves some or all of its motion through the deflection of flexible members (Howell, 2001). There are various techniques that have been proposed for the design of compliant mechanisms, including topology optimization (Sigmund, 1997), building block (Gallego and Herder, 2009)), and the pseudo-rigid-body model (PRBM) (Howell, 2001; Feng, 2010; Su, 2009). For the work done here, we used the PRBM approach because it lends itself to intuitive design approaches by way of analogy to existing rigid-body mechanisms. This is particularly advantageous when an existing mechanism has the motion desired, the motion of a scissor jack or a collapsible ironing-board.

The PRBM approach identifies compliant mechanism topologies that are physically analogous to mechanical linkages. For example, the large deflection motion of a cantilever beam is well-approximated (<0.5% relative error) by placing a pin joint 1/6 of the beam length from

the fixed end; the stiffness of the beam is simulated by placing a torsional spring at the pin joint. In rigid-body mechanisms, particular emphasis is placed on mechanisms with one or few degrees of freedom (i.e. controllable inputs). The reason is that motion prediction is simplest with only one (or few) input variables.

The notion of degree-of-freedom is only approximately valid for compliant mechanisms, in the sense that because of the potential energy associated with the flexible parts, the motion of a compliant mechanism is predictable (if occasionally unstable) even when the compliant mechanism has far fewer inputs than its rigid-body analog. The predictability of the compliant mechanism is based on the fact that its configuration minimizes the potential energy of the system consistent with the work done by the applied loads acting on it. For example, a paper clip has a known equilibrium configuration when it is unloaded (in the box), when it is loaded (by placing a sheaf of paper in it) it deflects to the position that minimizes its deformation energy consistent the loads the paper places upon it. The scope of designs available for compliant mechanisms is vast and includes spring design, origami, and many micro-electromechanical systems (MEMS) (Howell, 2001).

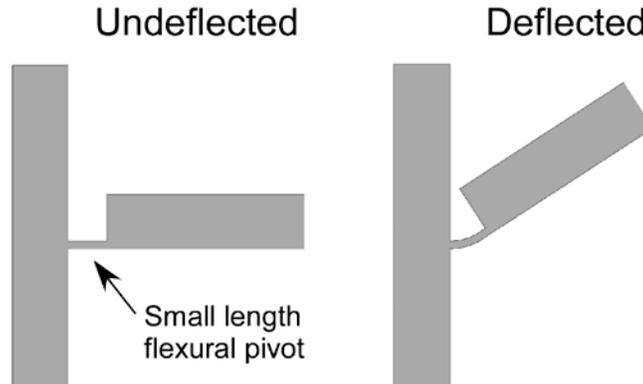


Figure 2 Illustration of a small length flexural pivot. In the Pseudo Rigid Body Model (PRBM), it is approximated by a pin joint placed at the center of the thin section.

SMALL-LENGTH FLEXURAL PIVOT

A commonly used compliant ‘joint’ is the small-length flexural pivot, in which a short, thin segment connects two larger thicker and more rigid segments as illustrated in Figure 1. When bent, the small length flexural pivot acts like a pin joint at the beam center with a torsional stiffness of EI/L , where E is Young’s Modulus, I is the 2nd moment of area, and L is the length of the compliant segment. The advantage of this joint is its simplicity, the disadvantage its weakness, i.e. it has neither significant bending stiffness nor strength and cannot be expected to resist significant loads.

COMPLEX JOINT

As a demonstration of the possibilities of deformation post-processing using spatial variations in local stiffness, we designed a joint which could serve the same function as a small-length flexural pivot, but that had significantly more stiffness and strength. In order to achieve this, we wanted a joint that was larger and capable of accommodating larger deformations. The compliant joint that we designed is a highly redundant parallel mechanism, similar in function to the mechanism used in a scissor jack (for lifting cars) or a pantograph mechanism. These

mechanisms use repeated parallelograms, and changes in their height and extent are accomplished by changing (shearing) the interior angles of the parallelograms. The joint is designed to accomplish a 90-degree bend with a high degree of strength and repeatability. In the bending of a uniform beam, half of the beam is in tension, half is in compression. In our joint design, we removed entirely the compression half of the beam by putting a 90 degree notch, this allowed for precise bending of the joint because there is a form-controlled mechanical stop. The parallelogram mechanism was placed on the tension side of the joint and allowed for the necessary elongation in that part of the joint.

Joint Demonstrations

Bending the small length flexural pivots can be as simple as locally heating the material at the bends. The local heating provides the local variation in material properties that is required. Figure 1 shows a series of parts in their progressive bending states. These bends were accomplished by locally heating the creases with a pocket butane torch. Several designs incorporated geometric features to increase the accuracy of the bent part. This approach is simple, but it relies on operator skill for accuracy and parts can easily be damaged by overheating or inaccurate bends. It is also difficult to apply if multiple joints need to be bent simultaneously. If heated through, the joint could be stretched such that the part is permanently deformed.

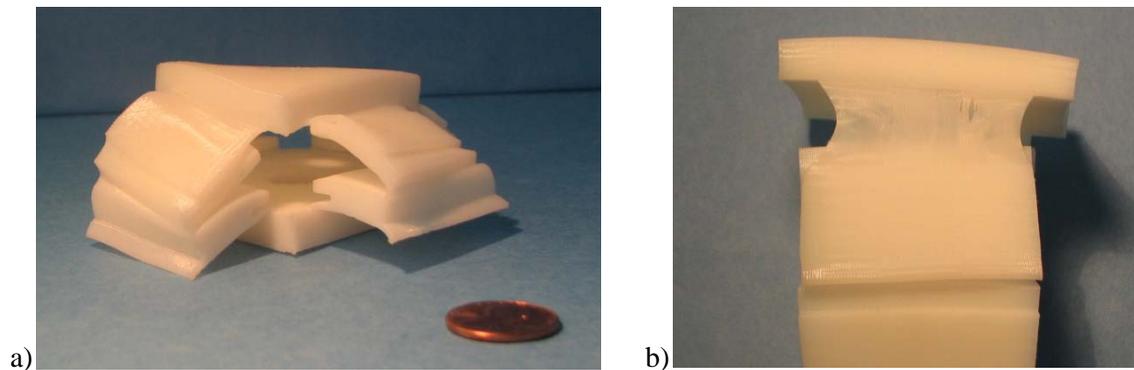


Figure 3 Deformation post processing failures. a) The part heated until all the sections were soft. b) The local joint was heated through until it stretched nearly to failure.

Figure 1 shows a block that was placed in an oven and heated slowly with and without an applied force. The applied force (Figure 1(b)) straightened the joints, but created a tension deformation while heating without an applied load eventually deformed all parts of the model as seen in Figure 1(a).

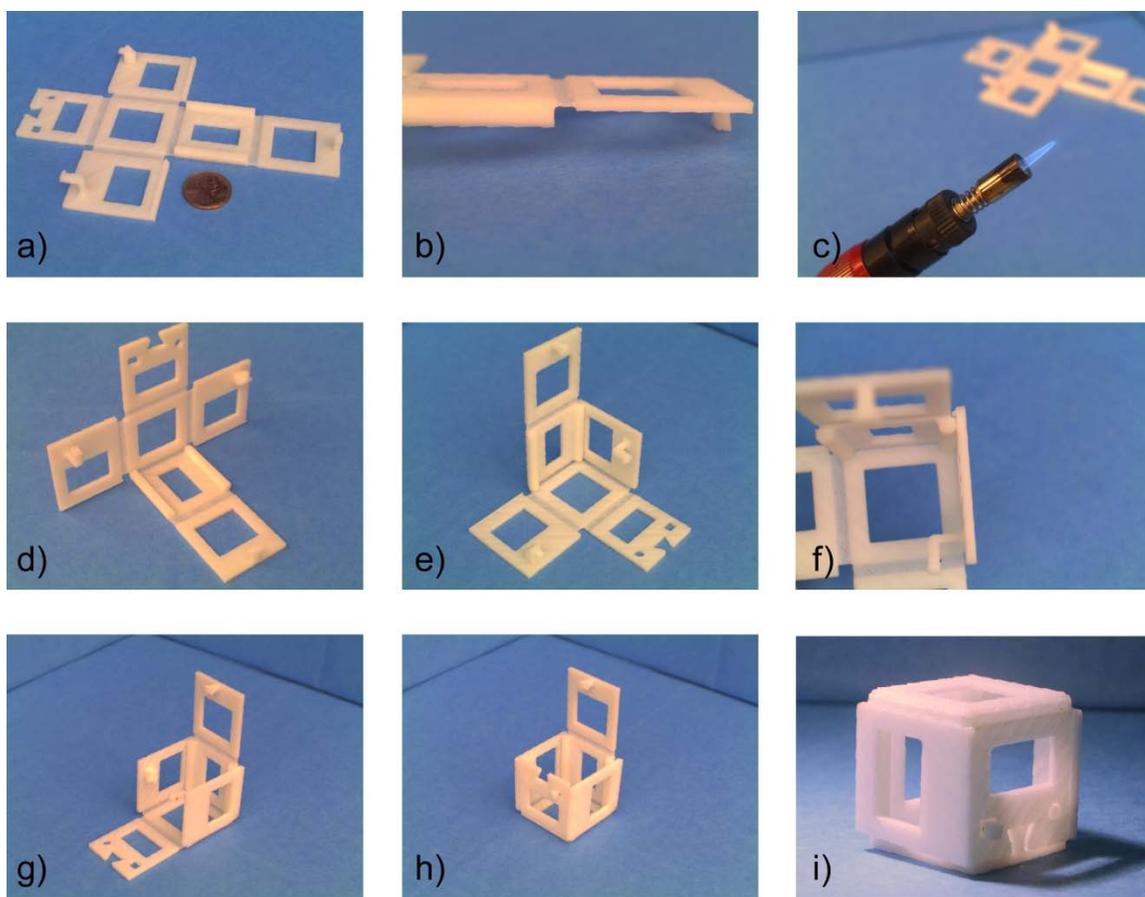


Figure 4 Process of folding a cube from an initial flat state into a full cube illustrating a variety of joint designs. a) As-printed state b) Close up of a bending segment c) torch used to locally heat the flexible segments d-i) documentation of the bend process.

Much better performance was obtained by using the complex joints illustrated in Figure 2. These joints were placed in a furnace preheated to 200 C and left for 15-20 s. They were removed from the furnace and bent into their final shape and held until they cooled. A water spray was used to speed the cooling process. These thin elements of these joints heat more quickly than the bulk material even when the entire object is placed in a hot furnace. Thus the joint deformed readily while the bulk material remained rigid and did not deform. Joint strength could be increased further by solvent welding the flat faces together after deformation.

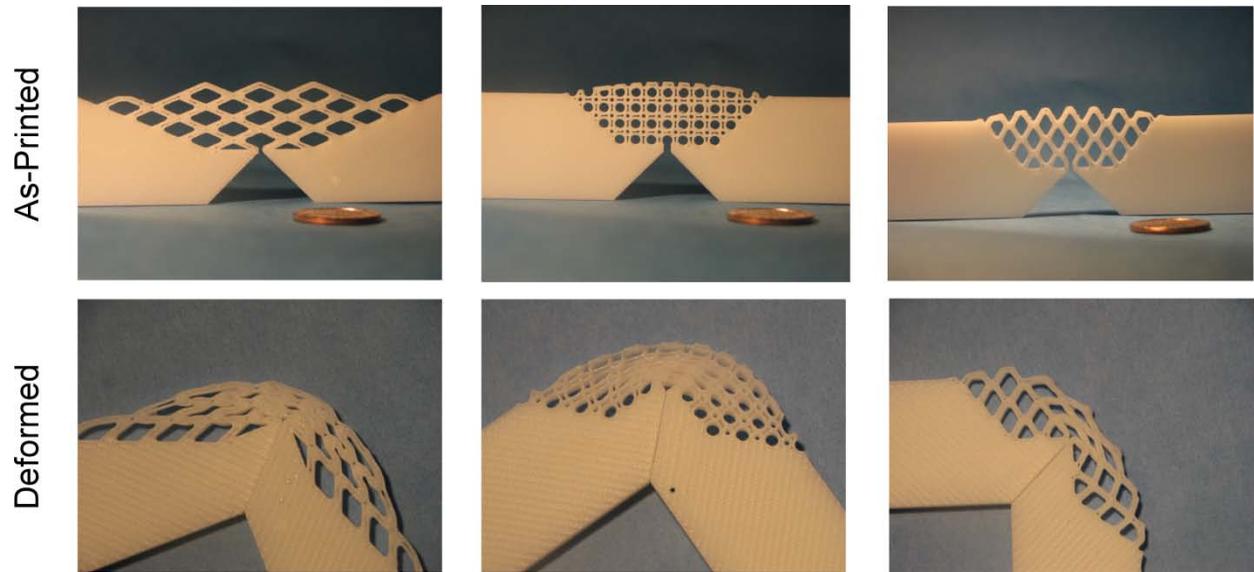


Figure 5 Three compliant joints designed for accurate 90 degree bends. The thin segments bend readily while the rest of the part remained rigid.

3D Antenna

Nassar and Weller (2013) demonstrated the printing of a 3D antenna using a combination of SLA structure and direct write conductors. They showed that the antenna gain decreased 2.5 dB relative to a printed circuit board antenna. While they expected that reliability might be increased by direct printing, the printing process is relatively difficult and the conductivity of the direct write conductors is reduced relative to bulk metals.

We applied deformation post-processing to make the antenna directly from a flat FDM component as illustrated in Figure 4(a). A copper tape was applied to both sides of the FDM-printed surface Figure 4(b). The tape was then cut using a CNC router and the excess removed (Figure 4(c-f)). The process was repeated for the other side and then the FDM part was deformed into its final shape. The deformation process was facilitated by the addition of open regions where the copper crosses the 90° bends. This dramatically reduces the strain required in the copper to perform the bends so that the bends were easily completed without deformation of the copper pattern.

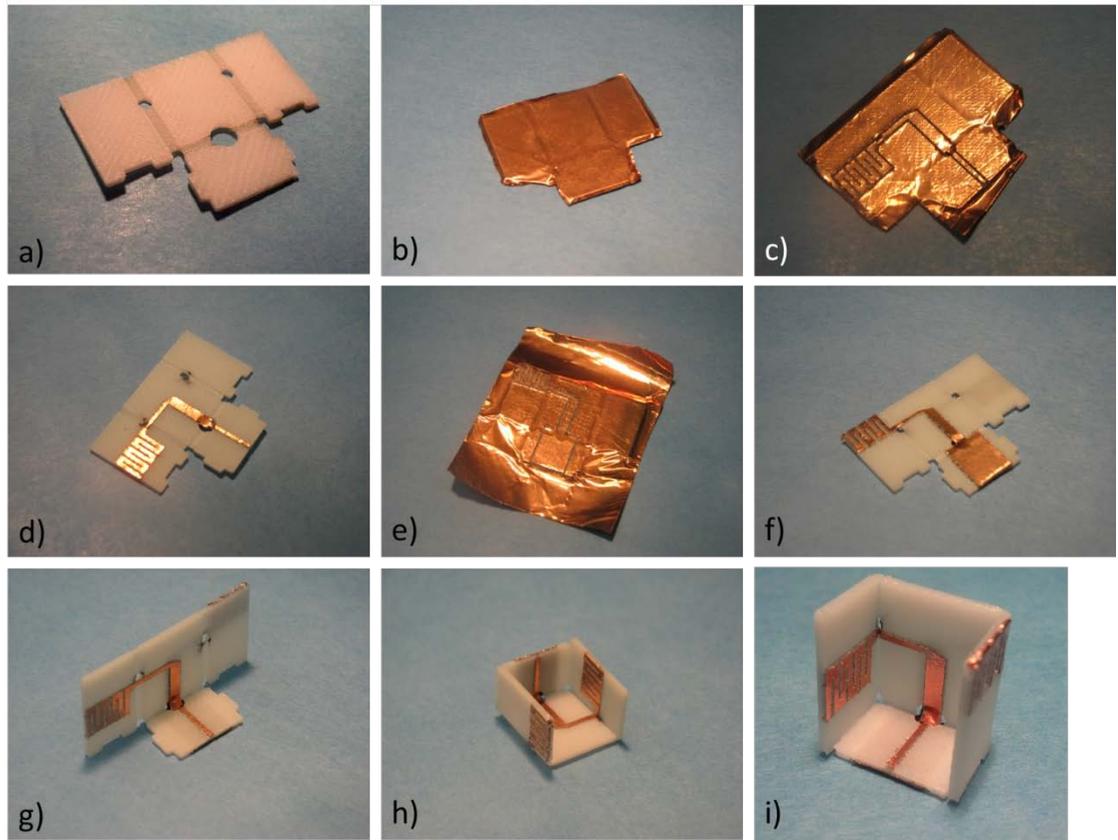


Figure 6 Process of making a 3D antenna by deformation post processing. a) Original FDM component b) Part covered by copper tape c) Conductor pattern cut into copper tape d) Part after removing excess copper g) Illustration of copper bent over material void h,i) Final antenna after patterning both copper elements and deforming to final shape.

Benefits of Deformation Post Processing

The two primary benefits of deformation post-processing of AM components are reduced printing cost and easier incorporation of multiple materials. Table 2 compares the predicted build times and material usage of printing in the flat condition compared to the final shape for both the (Figure 1) cube and the antenna (Figure 4). In this case, the difference in materials usage is not very significant because the open geometry minimizes the support material required. In the case of the antenna, the flat model actually uses more support material due to the need to support a wider base. However, the printing time is reduced in both cases (substantially in the case of the cube) due to the faster printing in X-Y axes compared to the Z axis.

Table 2 Comparison of printing time and costs for flat versus final geometry.

		Support Material (cm³)	Build Material (cm³)	Printin g Time (min)
Cube	Final Geometry	10.609	9.814	146
	Flat Geometry	7.465	10.266	79
	Change	-30%	+5%	-46%
Antenna	Final Geometry	0.664	1.078	12
	Flat Geometry	1.213	1.265	11
	Change	+83%	+17%	-8%

The 3D antenna demonstrated an easy technique for creating an antenna without the need for an expensive multi-material deposition system. While the specific method of depositing the copper (cover and trim) is not fully automated, there are many other alternative methods to create a circuit on a printed part. The antenna could have been fabricated by printing directly on the part with a conductive ink using a variety of commercial systems or by utilizing custom printed circuits board processes to pattern and etch the copper. The tight corners and orthogonal printing surfaces of the 3D antenna create a substantial manufacturing challenge. However, when printing in the flat position, the printing process is dramatically simplified. The subsequent bending is readily accomplished with simple tools.

Conclusions

We have proposed designing parts for post printing deformation as a path to reducing printing time, support material requirements, and simplify the incorporation of multiple materials. This approach has been demonstrated in the fabrication of several simple cubes and in the fabrication of a 3D antenna. These parts showed a consistent reduction of printing time relative to parts printed in their final shape even though these objects were open structures that required relatively little support material. This work could be extended to making complex shapes with continuous curvature variation.

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