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3D PRINTING STRUCTURES THAT EXHIBIT TORSIONS

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ABSTRACT: Conventional 3D printing produces objects with the assumption that the shape does not change through time. However, most materials undergo morphological changes through time, though it could be unnoticeably small. 4D printing takes a different approach and embraces this change in time in a favorable manner. In other words, changes through time that is mostly regarded as a deficiency are used as an advantage. Despite the endless possibility, most 4D printing demonstrations were confined to bending motions. In this paper, we propose a new design that allows the object to twist its geometry through a controlled stimulus.

KEYWORDS: 3D Printing, 4D Printing, Twist component

INTRODUCTION

3D printing has the ability to additively build parts of arbitrary geometric. The unit of the build is called a voxel and in theory each voxel can be formed with different materials. For example, the polyjet technology by Stratasys can use up to 82 different materials for a single monolithic part. The ability to program the spatial material composition allowed the use of 3D printing to new applications. For example, in artificial organ applications researchers were able to build artificial structures composed of multiple materials that can provide the nutritions and the structural strength to grow living tissues. Note that this feature is unique to 3D printing and clearly distinguishes it from conventional manufacturing technologies that are often considered to be superior to 3D printing in terms of the quality and mass production. Other use of this spatial material variations happens in the field of structural engineering. For example by using smart materials that change their form through the external stimulations, 3D printing allows the construction of programmable shapes that undergoes structural changes known as 4D printing and coined by Skyler Tibbit. For example, a group of researchers led by Skyler Tibbit has produced 3D printed component that extends and bends through the time when soaked in water. The bending component they have invented is composed of double layers, where each layer is built from different materials that behave differently from the external. Specifically, one layer is formed with a material that rapidly absorbs water thereby expanding and the other layer is made with a material that is relatively less absorbing water. Due to the internal strain formed at the adjoining surface between the two layers the sandwich structure undergoes bending. Another example work can be found from the Qi Ge's group. They have used shape memory polymer (SMP) for the 4D printing. A double layer component was made where one layer was made with a single material and the other adjoining layer was made as a slab with embedded SMP fibers. The result is the existence of two layers each behaving differently to the external stimulations. The stimulations consist of the tensile strengths applied at the both ends and the thermomechanical programming steps. Thermomechanical programming steps involve cooling of the component with the tensile strengths applied at the both ends and subsequent cooling with the component under the tensile strengths. Removal of the tensile strengths will bend the double layer component and it will go back to the original shape when heated. Note these works specifically uses the bending of the component. On the contrary,

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we propose a new design that can incur twisting motion of the formed structure under controlled external stimulations. The design constitutes two circumferentially placed double layers that bend under the stimulation. The bending direction is purposely made opposite to each other so that they apply oppositely directed forces thereby turn the attached rigid structure in the counter-clockwise direction. We have also provided some preliminary experimental results that show the time variant bending and the resulting twisting angles under the external stimulations.

DESIGN AND FABRICATION

The aforementioned twisting component was designed in a commercially available design software called NX by the Siemens. The materials used for the active component layers were thermoplastic polymers: vero white and tango+ provided by the Stratasys. These two materials were used to form the active component that deforms under the external stimuli. Note that the vero white is quite inert when immersed in a medium composed of ethanol. On the contrary, tango+ exhibits significant expansion under ethanol.

Figure 1. Active component.

When these two materials are formed joined as a structure shown in Figure 1 and immersed in ethanol, only the portion formed using the tango+ will expand whereas the verso white stays the same. The result will be a significant bend as shown in Figure 1.

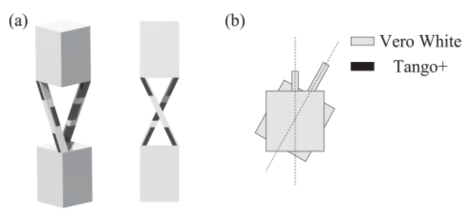

Figure 2. (a) The twisting component. (b) The twisting angle measured by the two protrusions on the two rigid parts.

We have invented a new design that utilizes the above mentioned bending structure for the purpose of exhibiting twisting motions. The design that we call as the twist component is shown in Figure 2(a). Twist component is composed of an unchanging rigid portions and the deforming active structures. The rigid portions exist for the purpose of assembling the twist component to another part or sub-assembly. It is made with a very stable vero white. The bending structure between two ending rigid parts is made as a double layer composed of vero white and tango+. These bending structures deform when immersed in an ethanol. As shown in Figure 2(a), the two double layers undergo different bending. First the left double layer undergoes bending in the red arrow direction. However, the double layer on the right undergoes bending in the blue arrow direction. These two bending structures bend in the opposite directions but because they are placed in the circumferential directions they simultaneously push the two rigid components in the same counter-clockwise direction. The two small protrusions, one longer than the other, at the two rigid ends are shown in Figure 2(b) exist for the purpose of measuring the twisting angles.

To manufacture the designed twisting component, we used multi-material polymer 3D printer (Objet 260 Connex, Stratasys, Edina, MN, USA). This 3D printer uses polyjet technology to form the voxels. As shown in Figure 3, the printing head moves in an XY plane and jets photocurable resins and supporter(GEL) resins simultaneously on the building platform and the ultraviolet light is subsequently illuminated to solidify the droplets. After one layer on the building platform is cured, the platform is lowered in the z-direction and the next layers are repeatedly formed until the final structure is formed. This printer is equipped with a printing block that holds multiple materials and a multiple inkjet head is paired to each material. Thereby it allows the printing different materials on a single layer.

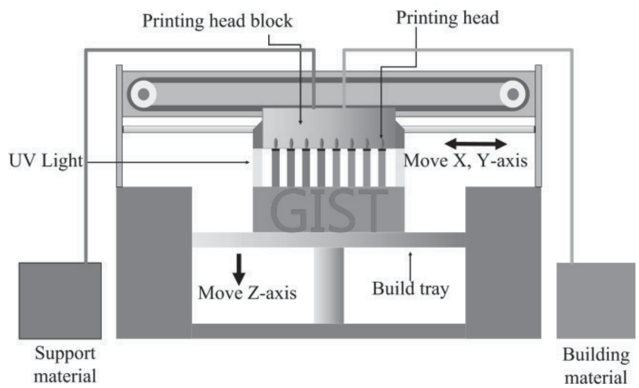

Figure 3. Polyjet printing principle

Using above mentioned device, we were able to fabricate a component composed of tango+ and vero white. Figure 2(a) shows the use of different materials in a sample 3D printing using different colors. Vero white is translucent rigid plastic like material and it is composed of isobornyl acrylate, acrylic monomer, urethane acrylate, epoxy acrylate, acrylic oligomer, and the photo initiator. The other used material tango+ is a translucent rubber material and it is composed of urethane acrylate oligomer, Exo-1,7,7-trimethylbicyclo [2.2.1] hept-2-yl acrylate, methacrylate oligomer, polyurethane resin, and the photo initiator.

The magnitude of the twist angle of the designed component is determined by the thickness of the vero white and tango+ double layers. The twisting effect is more prevalent when tango + layer is thicker than the vero white layer. Currently, we are only using ethanol as the sole stimuli but we envision water, heat, electric current can be also used to construct a new 4D printing component each likely to require a new design.

EXPERIMENT & RESULT

The experiment was performed at room temperature (18℃) with 100% ethanol 100%. It may be possible to change the temperature but raising the temperature poses extremely quick evaporation of the ethanol that is very volatile even at room temperature. We thus have only varied the dimensional variation of the double layers of the active component. As listed in Table 1 the thickness of the tango+ and vero white layers are shown as ratios. Using Table 1, one can easily find the corresponding layer thicknesses of the vero white and tango+ layers and their relative thickness ratios.

Table 1. Double layer dimension

	Case 1	Case2	Case3	Case4
Vero white (mm)	0.37	0.35	0.33	0.31
Tango+ (mm)	0.78	0.8	0.82	0.84
Ratio	0.474	0.437	0.402	0.369

At room temperature, a container full of ethanol was used to immerse the test specimen and the corresponding angular changes were recorded. When placing the component into the ethanol the upper cube body is fixed to the lid of the container so that the component does not move or rotate. The attaching was done on the upper cube to remove any possible weight bearing to the bending structure. For example, if the lower cube was fixed to the bottom of the container and the experiment was carried out in this setting, the bending structure will receive the weight of the upper cube in the course of the experiment. The weight will apply bending to the bending structure thereby the experimental result will include the effect of the body weight bending. This is obviously not desirable. Thus, we have fixed the upper cube to the lid so that no weight effect will influence the bending of the bending structure.

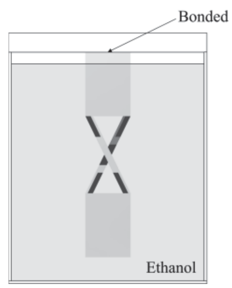

Figure 4. Experimental condition diagram

Figure 5 shows the projected top view of the twisting component undergoing rotation. We can verify that the component undergoes clock-wise rotation.

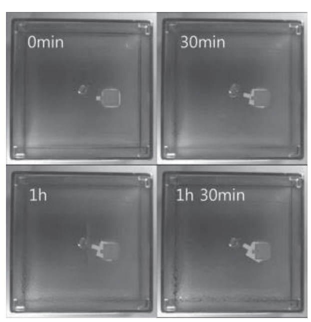

Figure 5. Time lapse shots of the twisting component immersed in ethanol;

Figure 6 shows the change in the rotational angle for each test case immersed in ethanol. As seen from the graph, if we exclude the test case 1, we can see that the magnitude of the rotation angle increases as the ratio of the tango+ is increased. Case 1 is composed of a highest ratio of tango+

but the resulting angle of rotation is smaller because of the unwanted bending that erased the effect of the rotation. In other words, the structure rotated more in the out-of-plane (XY) direction than the in-plane, twisting rotation thereby the measurement exhibits small twisting rotations. For this reason case 1 is removed for further discussions. When the ratio of tango+ is bigger, we were able to see faster rotations, but we can see that if we increase the lapsed time, the rotation angle in all cases, all converged to some identical values.

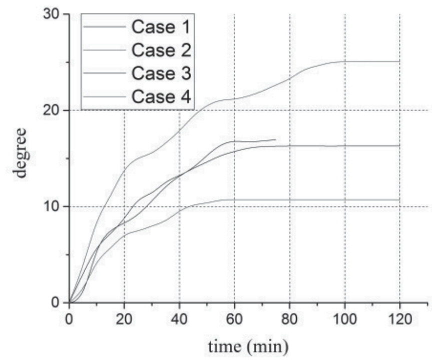

Figure 6. The rotational angles for four different cases

DISCUSSION AND LIMITATION

In addition to the out-of-plane bending motions for the case 1, case 1 also showed mechanical failure. As shown in Figure 5, the structure deteriorated at the time lapse of 120 minutes. We can explain this due to the fact that the bending structure reached the yield stress, thereby the structure was severed. This is due to the reason that the ratio of vero is smaller in the double layers. It is therefore important to have the two materials vero and tango at the appropriate ratios. In the proposed models, case 3, 4 showed very weak twisting effects. Case 2 performed best in terms of twisting among others.

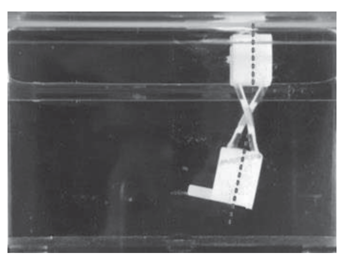

Figure 7. A case showing out-of-plane rotation being more prevalent than the in-plane rotation (twisting)

We have monitored the experiment using a top view and thus only the in-plane rotation was monitored. However, some structure wen out-of-plane rotations as seen from Figure 7, case 1. To fix this out-of-plane rotations, it would be necessary to place secondary constraining structures to the design so that on the in-plane rotations are allowed. It would also be possible to design a new bending structure that would only allow in-plane rotations. The current model also does not put a limit to the rotation angle. If a stopping angle is desired by the user, we can add additional stopping mechanism so that once designed rotation has been reached, the structure locks itself and prevents any further rotation to come to effect. We can also seek for new smart materials that can be triggered by different stimulations or one that can show high recovery angles. These will all increase the usability of 4D printing.

CONCLUSION

3D printing is now being extended by the introduction of time-variant structures that can be triggered by the external stimuli. Using new smart materials and novel component designs various active forms of motions can be made possible that include stretching and bending. This paper used two materials, a rubber-like photocurable resin (tango) that expands its volume when immersed in ethanol and rigid photocurable resin (vero) that is inert to the existence of ethanol. Combining these two materials with a new structure design, a double layer active component was invented that can be used to realize a twisting motion. We have verified the working of our design, by manufacturing and then placing them and monitoring the motion under ethanol. By experimenting with various ratios of the double layers we have shown that the twisting effect becomes stronger for the higher ratio of tango thickness. Previous researches have shown stretching, bending and folding structures. But as far as we know, there has been no work for twisting structures. The proposed novel design of twisting component can potentially add more freedom to dynamically changing 4D printing components. We plan to extend our work in accordance with the 4d printing simulator that is in a progress of development. These combined studies will enable a new designing platform that can simulate the kinematic motions of complex machines formed using 4D printing components. The designing platform will support early stages such as component design to the final assembly and simulations.

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