Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)
December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA

Controlled Shape Changing Components by Using 4D Printing Technology

Bijaya Bikram Samal, Anita Jena and Debadutta Mishra*
Department of Production Engineering
Veer Surendra Sai University of Technology, Burla-768018, India.

Abstract

Additive manufacturing (AM), commonly known as three-dimensional (3D) printing or rapid prototyping, has been introduced since the late 1980s. Although a considerable amount of progress has been made in this field, there is still a lot of research work to be done to overcome the various challenges remained. Recently, one of the actively researched areas lies in the additive manufacturing of smart materials and structures. Smart materials are those materials that can change their shape or properties under the influence of external stimuli. With the introduction of smart materials, the AM-fabricated components can alter their shape or properties over time (the 4th dimension) as a response to the applied external stimuli. Hence, this with the additional dimension, 4D printing is emerging as a novel technique to enable configuration switching in 3D printed items. Some of the approaches are namely self-assembly of elements, deformation mismatch, bi-stability, and the Shape memory effect (SME), etc. are identified as the generic approaches to achieve 4D printing. The research focuses on basic capabilities of the emerging 4D Printing technology using a combination of smart material and ABS/PLA to create models that will change their shapes on interaction with the environmental stimuli like water, temperature etc. without the use of robotics, motors or any other automation. This can be used to make different models and then they can self-assemble themselves without using any source of power.

Keywords: 4D Printing, Smart Materials, Shape Memory Alloys, 3D Printing with Smart Materials.

---

1. INTRODUCTION

3D printing is a process well known in manufacturing that utilizes the CAD geometry and sliced data to build a part layer by layer. In spite of a lot of advantages of 3D printed parts, there are some drawbacks like the built parts are static and do not change, though there is an exception of functional and moving parts like hinges, ball and socket joints, bearings etc. The built platform is also limited. Therefore, the concept of 4D printing evolved. Time is the 4th dimension combined with 3D printing. 4D printing provides an amazing chance to the objects to change and can cope up with responses provided by the environmental changes. 4D printing technology is in its basic research phase. A lot of projects and models have been made after the introduction of 4D printing in 2014 [1]. Current 4D printed models utilize smart materials like hydrogels, proteins, and shape memory polymers in thin sheets. These demonstrate impressive shape changing capabilities but have very low structural strength [2-4].

On the other hand, there is a smart material named shape memory alloy (SMA) which is defined by its ability to recover its programmed shape after providing a deformation to a certain limit when comes in contact with an appropriate stimulus like temperature. This material property is called as shape memory effect in alloys and the magnitude of shape change (with or without hysteresis) is proportional to the applied stimulus [5-6]. Since this type of material could sense the environmental changes and then take reactions accordingly in a predetermined sequence, they are considered as a promising alternative for the future components that can utilize its shape changing capabilities to achieve unprecedented practical applications [7].

In comparison with other smart materials that can be used for 4D printing application, it has high strain recovery, high melting point, low cost, excellent corrosion resistant, easy shape programming procedure and easy control of recovery temperature. These are also biocompatible and biodegradable and hence gained extensive research interests recently in various areas such as medical, civil, military etc.

This paper will provide design, analysis, simulation and the detail process plan is described for processing of a 3D printed part that will change its structure when coming in contact with the temperature. 3D printing technique is employed to create ABS sandwiched SMA with both spontaneous and sequential shape changing properties. The complete process includes the 3D printing from a CAD file that is being sliced using slicing software which specifies the details of the material configuration and its properties. This process is highly flexible in terms of design considerations and convenience of operation during the creation of a functional component. The SMA we used to be a nitinol sheet, whose shape recovery is thermally triggered.

Nitinol has been majorly used in the field of medical science for stents because of its unique property of changing its shape and super elasticity. Considering the detailed material and design specifications, it is found that the deformed component can successfully return back to the original shape in a predefined sequence, while the shape recovery [7] in the SMA component will be coming to halt either by the chamfered surface or it will deform till the programmed value. By using this process, we can directly embed SMA within the 3D printed part which acts as an actuator and that will provide a potential advantage for getting an accurate controlled shape recovery feature which will further enable the production of components having

---

*Author to whom correspondence should be made, Email: dmvssut@gmail.com

ISBN: 978-93-80689-28-9

unprecedented multifunctional features and high performance. This model will be having better structural strength than the previously made models which will be very helpful for using it in larger scale products.

2. NITINOL: THE SMART MATERIAL

Nitinol has very exceptional properties that are gleaned from a reversible solid-state phase transformation also called martensitic transformation, between two alternative martensitic crystal phases, requiring 60-130 MPa of engineering stress. Nitinol presumes an intermesh simple cubical structure known as the austenite at a high temperature. Nitinol impulsively transforms itself to a more intricate monoclinic crystal structure known as martensite at a low temperature [8]. There are certain transition temperatures which are associated to first austenite to martensite and then martensite to austenite transformations. Martensite begins to form when the alloy is cooled to the temperature called the start temperature of martensite and the alteration is completed which is known as the finish temperature of martensite. When the fusion is martensite then it is transferred to heating where formation of austenite starts at the start temperature of austenite and finishes at finish temperature of austenite. The name shape memory introduces to the fact that the shape of the high temperature austenite phase is remembered even after the fusion is critically deformed at a lower temperature**.**

3. MATERIAL CONSIDERATIONS:

We have considered the basic material as VeroWhitePlus as the printer we will be using is Stratasys Objet 30. VeroWhite plus is a very hard, durable, opaque, high resolution white material. It produces excellent surface and has a great fine feature details and smooth contour curves. It contains Acrylic monomer and Acrylate oligomer. Detail properties of the VeroWhitePlus is provided in Table 1.

Table 1. Physical properties of VeroWhitePlus [9].

Mechanical Properties	Test Method	Values
Tensile Strength	ASTM D638	58MPa
Elongation	ASTM D638	10%-25%
Young's Modulus	ASTM D638	2500MPa
Flexural Strength	ASTM D790	93MPa
Hardness		85D
Heat Deflection Temp	ASTM D648	48^{O}C

Nitinol sheet is used for embedding it in between to get a sandwiched structure [10]. Nitinol sheet is of light weight and it is a solid state alternative to conventional actuators. The material property of nitinol allows it to remember its shape and can be used to actuate when temperature is increased which uses passive source of energy and decreases the complexities in design using motors and other power consuming actuators. Nitinol sheet is the newest and most rousing product form for these unique shape memory properties. Nitinol sheet can easily processed by laser cutting, etching, stamping and EDM machining. Efficient processing and surface finishing establishes a smooth, light oxide surface. Many new medical innovations are now possible with the use of this very thin and versatile nitinol. Sheet is a 2D structure unlike wire and spring giving us many design options.

4. EXPERIMENTAL PROCEDURE

4.1. Concept

First the concept of self-folding cube is visualized and is further planned for designing and analysis processes.

4.2. Design of the product

During design of the component, it is most important to create the active origami structure [11] of the final product within the design and also consider all the aspects how the design will affect the functionality of the product. All the 3D models were made using SOLIDWORKS CAD software.

First the design of the base with cavities of 0.5mm thickness at center of gravity of each component was made as shown in Fig.1. There are 6 cuboids with 50mm x 50mm x 5mm. and the red colored space shows the cavity made for embedding the nitinol sheet.

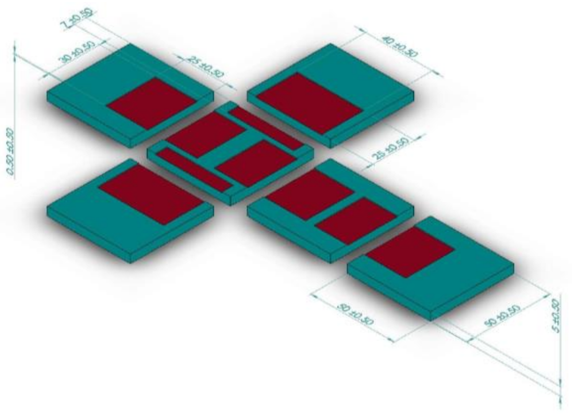


Fig 1. CAD model of base with cavities

Second the nitinol sheets are designed as per the dimensions given in Fig.2 and is assembled into the cavities made in the Fig.1.

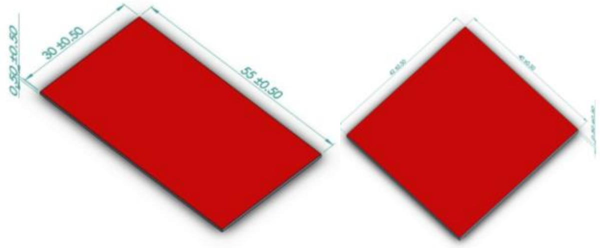


Fig 2. Nitinol sheets for assembly design

At last the design of the top part is made with the assembly of the previous models. A chamfer of angle 45^0 and chamfer length of 5mm is provided because the length in between the two component, where nitinol sheet is to be attached is 10mm and for a proper meshing of the chamfered corners which adds to its chamfer angles to make a right angle, required for a cube formation. For getting the correct design done, there is a gap of 5mm in between as shown in the Fig. 3.

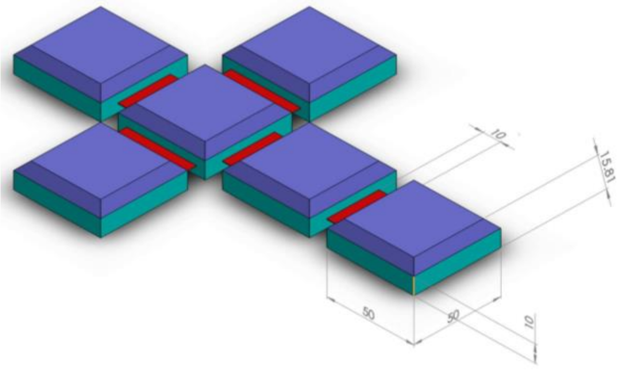
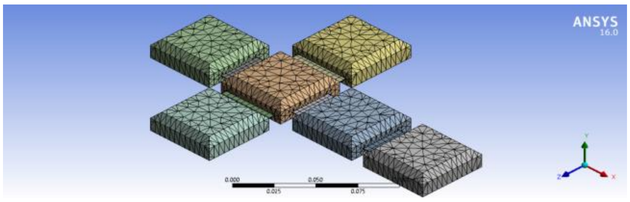


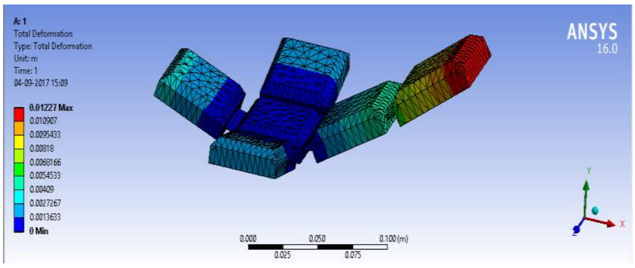
Fig 3. 3D CAD assembled model of the origami of the self-folding cube

4.3. Finite Element Analysis

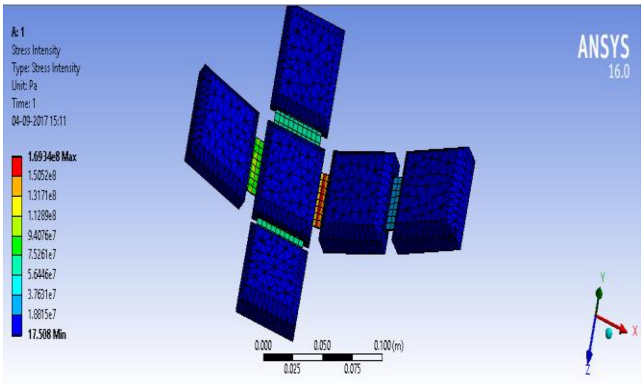
The design is very complex as two materials with different properties are being used. FEA analysis helps in predicting stress distribution in the component, possible failures after fabrication, finding out the point of maximum stress intensity and also finding out the maximum deformation under the load. The design data and the properties of nitinol and VeroWhitePlus are provided as input to ANSYS 16.0 software package. The model is then triangular meshed as it will be better because 3D printing requires STL format. Number of nodes are 38,499 and number of elements were found out to be 20,607 with minimum edge length of $5\text{x}10^{-4}$m. The maximum deformation and maximum stress intensity were found out when a pressure of 500 Pa is provided with proper fixed support at the middle cube position. The pressure provided was much more than the calculated value. The details of the simulation are shown in Fig 4.



a) Meshing of the geometry.



b) Maximum deformation found to be 0.01227 m



c) Maximum stress intensity found to be $1.6934\text{x}10^{8}$ Pa

Fig. 4. FEA analysis of the model

4.4. Programming of Nitinol sheet

Programming of nitinol is important because it should bend at an angle of 90^0 so that the actuation will give rise to a closed model of a cube. The following steps of processes are carried out to set its shape as per requirement.

4.4.1 Cutting of nitinol

The nitinol sheet that the manufacturer provided is of size 304mm x 304mm x 0.5mm. This is cut into three 55mm x 30mm sheets and two 44mm x 40mm sheets.

4.4.2 Bending of the sheet

Bending it at specific location as mentioned in the design data at an angle of 90^0.

4.4.3 Fixing the sheet in a fixture

The nitinol sheet is then clamped in a fixture, designed specifically for the part as shown in Fig 5.

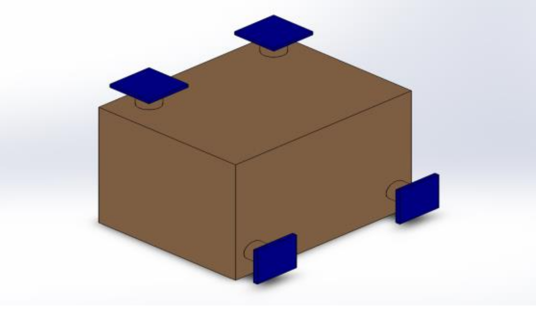


Fig.5. Fixture design

4.4.4 Heating the nitinol sheet

The nitinol sheet is then heated at a temperature of 500^0C for 10 minutes.

4.4.5 Quenching the sheet

Quenching of the sheet is done by dipping it into water at room temperature. Nitinol sheet has now remembered its shape.

4.4.6 Bending the quenched sheet

Bending the sheet again as it was before and now it is ready to be embedded into the model.

4.5. 3D Printing embedded with nitinol sheet

4.5.1 3D printing of the base

The design data is first sliced in a software and then it is transferred to the 3D printer to print. The 3D printer used is a Stratasys Objet 30 with VeroWhitePlus as the print material. The base is printed as per the design made in Fig.1 with cavities for attaching the nitinol sheet.

4.5.2 Pausing the printer

Once the base is made, the printing is stopped and then manually the nitinol sheet is being fixed into the cavities.

4.5.3 Resuming the printer

After embedding the sheet, the printing is resumed and as per the design parameters set, it completes the model as in Fig.3.

4.6. The final printed part

After the printing is completed, support materials are removed using high velocity water jets and the final 3D origami model of the cube is produced.

5. RESULTS AND DISCUSSIONS

After the whole process is completed, warm water of about 60^0-70^0 C is taken in a water bath and the 3D model is dipped inside it., the sheet bends at an angle of 90^0 precisely to form a cube from the origami that was 3D printed. This is due to the property of nitinol, as it was predefined to bend at an angle 90^0.The design considerations helped in the actuation as the chamfered edges provided for a perfect matting of each edge at exact right angles so that there will be no mismatch during the actuation. FEA analysis helps to ascertain the suitability and functionality with the use of shape memory alloy. The data from the FEA structural analysis helped in simulation of the whole process and also finding out the loopholes in this procedure like the strength of the whole printed part was still weak to be used as a component in any mechanical system. More research is needed in this noble field to make the system more optimized and improve its viability to be used in the real life situations.

6. CONCLUSION AND FUTURE SCOPE

In this article the detail procedures of controlled shape changing component in the form of a self-folding cube using SMA material is discussed and the detailed design and analysis of the component is done. This is just a beginning to understand the capabilities of 4D printing which will enable the design of a completely new system. This is an emerging technology having a lot of possible future applications like in environments and conditions where access for manual repair is limited, conditions which are hostile like space, it can be used to overcome the limitations of current flight technology by morphing aircrafts. This technology can be used in health care for advanced nanoscale stents and drug delivery system, electroactive components for artificial limbs, consumer goods with some multifunctional characteristics like transformative shoes, adaptive jackets, tire compound that can change according to different road conditions, pipping with variable diameter as per demand, robotics without heavy motors etc. This technology provides a lot of flexibility and customization to a product in a very short manufacturing lead time with the dynamic characteristics of changing its structure, functionality and adaptable to the environment that can be utilized to achieve maximum efficiency in any field of its usage. Future possible works in this field can be the use of shape memory polymer to 3D print different structures and use of nanotechnology with 4D printed parts that will further improve the material characteristics as well as provide better functionality.

References

[1] Tibbits S, 4D printing: multi-material shape change, *Architectural Design*, **84**(1), 2014.

[2] Qi G, Conner KD,Qi HJ,et al.,Active origami by 4D printing, *Smart Mater Struct*, **23**:094007, 2014.

[3] S. Naficy, R. Gately, R. Gorkin, H. Xin, G.M.Spinks, 4Dprinting of Reversible Shape Morphing Hydrogel Structures, *Macromolecular Materials and Engineering***,** **302**(I) :1600212, 2016.

[4] Mao, Y., Yu, K., Isakov, M. S., Wu, J., Dunn, M. L., & Jerry Qi, H, Sequential self-folding structures by 3D printed digital shape memory polymers, *Scientific Reports,* **5**: 13616, 2015.

[5] Bikas C. Maji, Madangopal Krishnan, Amit Verma, R. Basu, I. Samajdar, Ranjit K. Ray, Effect of pre-staining on the shape recovery of Fe-Mn-Si-Cr-Ni shape memory alloys, *Metallurgical and Materials Transactions A,* **46**(2):639-655, 2015.

[6] Y. Zhou *et al.*, From 3D to 4D printing: approaches and typical applications, *J. Mech. Sci. Technol.*,**29**(10): 4281–4288, 2015.

[7] K. Yu, A. Ritchie, Y. Mao, M. L. Dunn, and H. J. Qi, Controlled Sequential Shape Changing Components by 3D Printing of Shape Memory Polymer Multimaterials, *Procedia IUTAM*, **12**:193–203, 2015.

[8] Otsuka K, Ren X, Physical Metallurgy of Ti-Ni-based Shape Memory Alloys, *Progress in Materials Science*,**50** (5): 511–678, 2005.

[9] Stratasys: Polyjet Materials datasheet, VeroWhitePlus, Retrieved from: https://www.stratasysdirect.com/wp-content/themes/stratasysdirect/files/material-datasheets/polyjet/PolyJet_VeroWhitePlus_Material_Specifications.pdf

[10] Nikolas A. Meisel, Amelia M Ellicott and Christoper B Willams, A procedure for creating actuated joints via embedding shape memory alloy in polyjet 3D printing, *Journal of intelligent material systems and structures*, **1**-15, 2014.

[11] Lang R.J, The science of origami, *Physics World,* **20**(2), 30-31, 2007.