Analyzing the 3D Printed Material Tango Plus FLX930 for Using in Self-Folding Structure

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***Abstract*— Self-folding is the ability of the structure to fold and/or unfold without human intervention or any application of external manipulation. It is known that the structure of folding object consists of two essential parts. These parts are the faces and the creases.**

In this paper, it is assumed that the faces could be built by using solid materials, and the crease lines can be built using soft material which provides a high bent ability. Furthermore, these two materials should be combined built without using any connections between them. Fortunately, the 3D printer provides this capability. It can print two types of different materials at the same time for the same structure. Therefore, a 3D printer is chosen to fabricate a folding structure using two types of material. These types are the Vero for solid faces and Tango plus FLX930 for the soft creases lines. The soft material at hinge part (creases lines) subjected to the load directly when the structure folds. It should have a clear view of the mechanical properties of this material. Therefore, several mechanical tests for Tango FLX930 material are operated to calculate its mechanical properties and find the force that required to fold it.

Keywords— Self-Folding Structure; 3D printer; Tango Plus.

I. INTRODUCTION

The self-folding structure gives the opportunity to manufacture many types of robots as a plane sheet. This sheet can fold itself during the task operation. The folding robots are inspired from the “origami” which is the Japanese’s word that means the art of folding papers. In the last few years, some researchers consider the origami robots and self-folding sheet to be potential solutions for the applications that require a morphing structure [1], [2]. The ambition of these researchers is to reach the design of robot with a high degree of freedom which is simple manufacturing and inexpensive. In addition, it can be self-folding, and self-assembly and it can be used to operate a minimally invasion task in surgery or search and rescue mission because it is folded from a 2D sheet into a 3D structure.

However, there are no real applications of folding robots in search and rescue field except the two papers by Lee that present a prototype of rescue robots using origami wheels. Lee designed two robots with deformable wheels using the origami magic ball pattern to fabricate the wheels [3],[4]. The two robots using a folding structure to fabricate a simple part of the robot, but the unique characteristics of folding open the future to many unexpected designs that can be adopted in many robotic fields.

The two major categories of folding material depending on the folding process which are the manual folding and self-folding robots. These two categories depend on the same steps to fabricate the folding robots which are: (1) planner and design the pattern, (2) select materials and fabrication procedure, and (3) choose the actuators that operate the motion or locomotion in manual folding robots or operate the self-folding and locomotion in the self-folding robots. The researchers focus on how to fabricate simple, cheap and fast fabrication robots by using a folding approach. While in self-folding, the researchers focus on morphing the 2D sheet into 3D structure at the operation task or how can build reconfiguration robots by using folding approach.

Some researchers build a printable robot using paper and folding it manually [5], [6]. Other researchers developed a self-folding hinges by using multilayer laminate which consist of shape memory polymer SMP, paper or plastic sheet, and resistive circuits [7]. They used an outer layer of SMP from two sides. This self- folding technique shows the capability of creating complex geometries. They fabricated a printed inchworm robot [8] by using this self-folding approach. Recently, they developed a crawling robot that folds itself by using five layers. These layers are two outer SMP layers, two paper layers and the middle layer of the copper-polyimide [2].

This paper focuses on the material that could build a folding structure. It is assumed that the folding structure could be easily fabricated using the 3D printer. The 3D printer can print a sheet with solid faces and soft material for the hinges. Therefore, it is chosen the Vero material to be the solid faces and Tango Plus FLX930 to be the soft material. For that reason, the Tango Plus FLX930 should be analyzed to calculate its mechanical behavior such as tensile, bending, and fatigue.

II. ORIGAMI AND FOLDING STRUCTURE

All folding structures are inspired from origami which is the art of paper folding. The essential difference is that the folding structure could be made from any material, while the paper is the major material for origami structure. However, all the structural design of any folder structure can be obtained by using the principals of origami design pattern.

The creases are the singularity part in folding structure and should build from soft material. The *creases* are the locations of localized folds of the sheet. Every crease can be folded either convex (*mountain*) or concave (*valley*). The *vertices* are the endpoints of the crease lines. The *faces* are the closed areas that bounded by the creases and it should be built from hard material. All the creases with its mountain and valley assignments make up the *crease pattern*. These concepts are shown in Fig. 1. The Vero is chosen for solid faces and Tango plus FLX930 is chosen for the soft creases lines to fabricate the folding structure using 3D printer.

The Tessellation origami is the appropriate type of origami shape to produce the folding robot because this type has a high flexibility and can be reconfigurable after folding. These two properties are very important to the functionality of robots. Furthermore, the crease patterns of this type consist a similar element that can repeat forever to form structures on any scale. This property makes it easy to put actuation procedure for one element and repeat it for all other elements. The best examples of Tessellation origami are origami magic ball. The major features which provide by this design is that, the magic ball can contract and expand in all directions See Fig. 2.

One element of magic ball structure was printed by using 3D printer see Fig. 3. The element has a square shape with 20 mm length and 1mm thickness. The creases lines have width of 2mm which are made from Tango Plus FLX 930. The strain in the creases is analyzed before these dimensions are chosen.

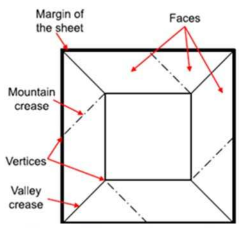

Fig. 1. Crease pattern illustrating various origami concepts.

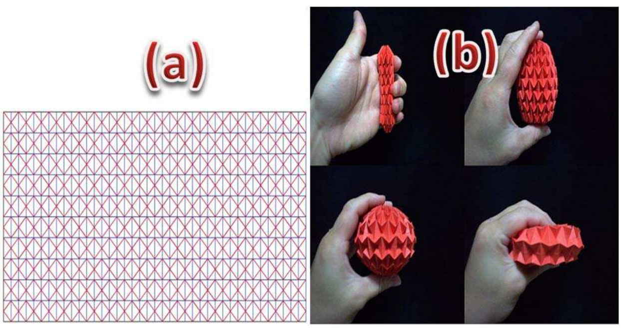

Fig. 2. (a) Crease patterns of Magic Ball, (b) Origami Magic Ball after folding [9].

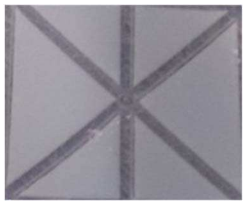

Fig. 3. One element from the magic ball pattern Manufacturing by 3D printer

III. STRAIN IN THE CREASES

All the deformation for any origami structures occurs on the crease line. Whatever it is a mountain or valley crease. We should have a clear description of this area to achieve a correct design. When the crease line is analyzed for any material (not just paper), it should be assumed that the crease line work as a hinge connected other solid material. This hinge has two effective dimensions which are the width b and the thickness t. Every crease has a radius of curvature R and folding angle θi when it is bent. From these parameters, the strain ε at any point on the edge can be calculated as:

$$\varepsilon = \frac{\Delta l}{l} = \frac{r\theta_i - b}{b} \qquad (1)$$

Where r is the variable radius and its value: $(R \leq r \leq R + t)$ and *l* is the length.

By assuming that the maximum fold occurs when the two inner sides of a hinge attached, see Fig. 4. In this special case, the radius assumed to be equal to the thickness and the maximum strain on the outer surface of the hinge can be calculated as:

$$\varepsilon_{max} = \frac{t \times \pi}{b} \qquad (2)$$

It can be seen from equation (2) that the maximum strain on the creases tip directly proportional to the thickness and inversely proportional to the width. For example, if there is a square hinge (i.e. b=t) the maximum strain is π. Therefore, the mechanical tests should be operated for the Tango Plus FLX930 material to ensure that the maximum strain does not exceed by tension, bending and fatigue.

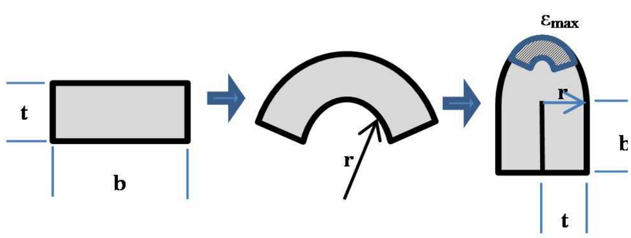

Fig. 4. Simple sketch of a hinge with width b, and thickness t . Starting from flat shape until it is completely fold.

IV. Mechanical Tests and Results

Mechanical properties can demonstrate the behavior of the materials and give the answer of the question for using this material for fabrication crease lines in folding robots or not. Our case requires several mechanical tests such as tensile test, bending test and fatigue test for the Tango Plus flx930 material. These three tests can show the results for the tensile strength limit, fatigue limit and the forces require to fold different thickness sheets into many folding angles.

A. Tensile Test

Although, the tensile test is a traditional mechanical test and there are many standards which show the modulus of elasticity and the tensile strength of different materials, there is lack information about tensile strength for elastomer materials especially for the materials using 3D printer.

Moreover, it is very hard to calculate the modulus of elasticity for elastomer materials analytically, because of many issues such as large deformation response, and non-linearity of the stress-strain curve [10]. Therefore, every new elastomer material should have a particular tensile test to indicate their properties. Although, some elastomer properties depend on time due to the hysteresis effect, this test can give us suitable induction for these properties.

The tensile test was operated three times for three specimens which have the same shape. The specimen has a cylindrical shape with effective length and area (37.7mm, 39.92 mm2) respectively. All specimens were printed on an Object-1000 3D printer in "digital material" mode. The final specimen shape can be seen in the Fig. 5.

The test velocity was set at 60 mm/min. After that, the test was operated which took almost two minutes for every specimen. The stress-strain curve can be calculated from the data of load-displacement which was collected from the tensile test machine. It can be determined by using traditional equations of stress σ and strain which are:

$$\sigma = \frac{F}{A_e} \tag{3}$$

$$\varepsilon = \frac{\Delta L}{L_e} \tag{4}$$

Where, A_e and L_e are the effective area and length.

The stress-strain curve can be seen in the Fig. 6. This figure shows the stress-strain curve for the three specimens, and it is clear that the tensile strength of the first specimen equal to 0.68 Mpa and the maximum elongation is 260%. For all specimens, the tensile strength range is between 0.63-0.68 Mpa and the maximum elongation range is between 250-260% and that is nearly the standard that given for this material.

Fig. 5. The tensile test specimen made from Tango Plus flx930.

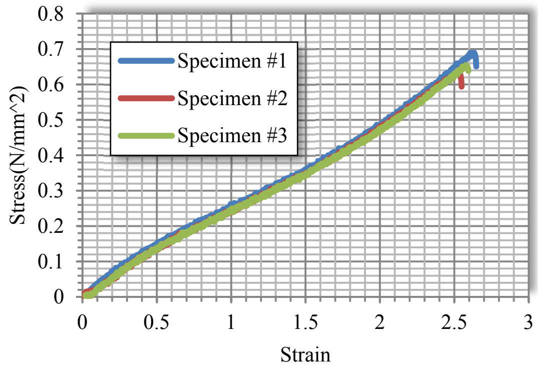

Fig. 6. The stress-strain curve for Tango Plus flx930.

B. Bending Test

The important useful information, which is required from the material behavior, is the amount of force that could fold the sheet made from this material. Therefore, this test can find the amount of force which required folding different thickness beams into a range of folding angles.

Flat specimens are used for this test which have a beam shape. The dimensions of these specimens are 40mm length and 10mm width with three different thicknesses which are 3mm, 5mm, and 7mm. In addition, two types of specimens are used for the 5mm thickness; the first one is completely flat, and the other one has a notch on both sides in the middle with 1mm radius, see Fig. 7. The reason for using these specimens is to find the relation between the thickness and the folding force. Furthermore, these specimens can show the effect of the notch on the folding force. The machine, which was used for this test, is the tensile machine with the graspers of three-point bending test. These graspers used to calculate the material resistant to bending damage. We change the middle rod of this grasper, which is 6mm thick, with the smaller wire, which is 1mm in diameter, to make the folding angle sharp and to reach a smaller radius of curvature for the folding specimen. The test machine requires the speed of test and the final displacement to stop. For our situation, we used the speed of test 60 mm/min and the final displacement 20mm.

When the folding angles are calculated, it is found that there are drooping in load after the angles 105°, 120°, 125° and 135° for the thickness 3mm, 5mm with a notch, 5mm and 7mm respectively. This drooping in load due to the slipping of specimens from grasper rod sides when reaching these angles.

Therefore, the relationship between the folding angles and loads is drawn as it is seen in the Fig. 8, and canceled the slipping zone.

It can be seen from the Fig. 8 that the load increase when the thickness increase, but in the same behavior and that is clear from the slopes of the curves. Furthermore, it can be seen that the result for the specimen 3 (5mm thickness with notch) does not decrease the load a lot. Although, it has a 3mm thickness between the notches, its load does not reach the load of specimen 1 (3mm thickness).

C. Fatigue test

The fatigue life limited is very active parameter when the material is used in an operation that have a dynamic load. In origami structure, the material in the hinge subjected to repeated load which is produced by folding and unfolding process. Therefore, the fatigue limit for the Tango Plus FLX930 should be calculated by using the fatigue test. Especially, when there is lack information for the fatigue life of the 3D printed materials. The fatigue test was operated for three specimens with three different elongation magnitude (30%, 60% and 100%). The specimens were designed according to the ASTM standard ASTM D4482-11, 2011. The final specimen shape that printed on an object-1000 3D printer can be seen in the Fig. 9.

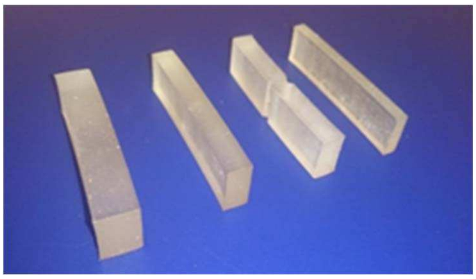

Fig. 7. The bending test specimens made from Tango Plus flx930.

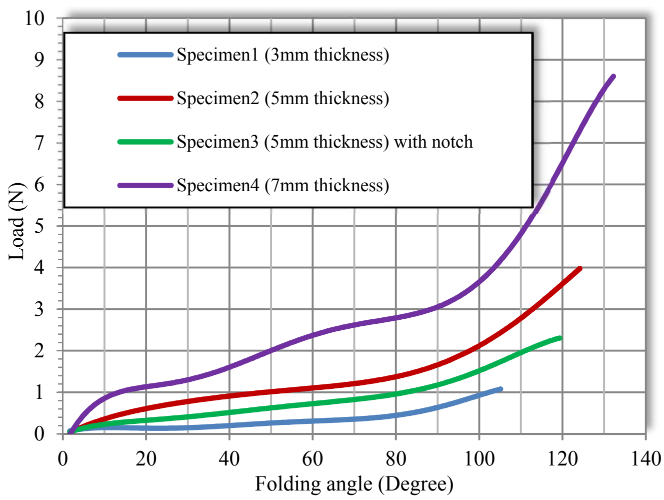

Fig. 8. The folding angles -loads curves for different thickness specimens.

Fig. 9. The fatigue test specimen made from Tango Plus flx930.

The test was operated three times for three specimens with different elongation (i.e., the elongation is the maximum extension input to the machine). The loading and relaxation cycle was taken from the ASTM standard. This standard specified a testing frequency of 1.7 Hz. The results taken from fatigue machine are (6992 cycles, 3640 cycles and 1861 cycles) for the strains (0.32, 0.6, and 1) respectively. From these results it can obtain the equation of fatigue life:

$$N = \left(\frac{\varepsilon_a}{\varepsilon_o}\right)^k \tag{5}$$

Where N is the fatigue life in a number of cycles, ε_a is the actual strain and ε_o & k are the constants of the equation. In our case, we can calculate the constants as (ε_o=732 and k= -1.14). Therefore, the equation of fatigue life for the Tango Plus FLX930 will be:

$$N = \left(\frac{\varepsilon_a}{732}\right)^{-1.14} \tag{6}$$

Furthermore, it can obtain the ε-N curve from the results which represent the strain vs fatigue life for the Tango Plus FLX930. See Fig. 10.

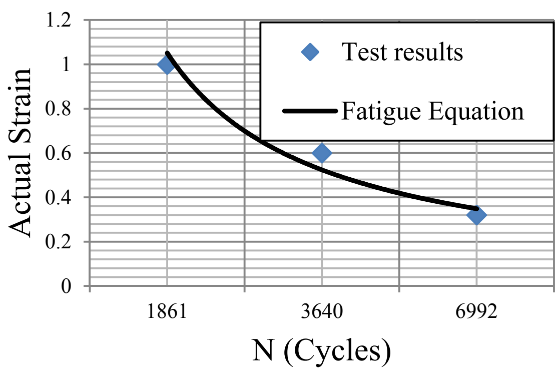

Fig. 10. ε-N curve for the Tango Plus FLX930.

V. CONCLUSIONS

In this paper, it is assumed that the folding structure can be printed on the 3D printer using the Vero material for surfaces and Tango Plus FLX930 for the hinges. The strain and stress can be determined in these hinges by assuming them as a beam and using mechanical principles equations. However, the mechanical properties of the material at that hinge must be calculated by mechanical tests.

The mechanical tests for Tango plus improve that this material can be used as a hinge for the folding structure. Furthermore, it has a high range of elongations that can give the folding structure more flexibility. The fatigue limit is calculated, and it is shown that this material can be used in high dynamic load with the strain limit 0.226. In addition, the bending test gives the data that could used to calculate the force required for folding this material into different folding angles.

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