CHARACTERIZATIONS OF THREE-DIMENSIONAL DEPLOYMENT BEHAVIOR OF SHAPE MEMORY POLYMER COMPOSITE ANTENNAS

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ABSTRACT

Deployable antennas have good transportability due to their small volume when folded. A launching vehicle is launched with a folded antenna, after which the antenna can conduct its mission after unfolded in space. Existing deployable antennas have some drawbacks such as heavy weight and small deformability. Shape memory polymers (SMPs), smart materials which have ability to recover their original shape from deformed shape by external stimulus such as heating, can be used to overcome these disadvantages. Deployable antennas made up of SMPs have advantages including light weight, large deformability, good processability, and self-transformation capability without any power device. However, they have not enough mechanical properties for aerospace application, promoting various researches to enhance their mechanical property, e.g., by introducing fillers into SMPs.

In this research, multi-walled carbon nanotubes (MWCNTs) were used to improve the mechanical properties of SMP. The mechanical, thermal and shape memory properties of CNT/SMP composites were characterized. Compared to the neat SMP, the mechanical properties of the CNT/SMP composites, in particular strength and stiffness were improved. In order to investigate the feasibility of the CNT/SMP composites in aerospace, a miniature of circular reflector was fabricated. The deployment test of the reflector was conducted in a heating chamber. The deployment behaviour of the reflector was characterized using a 3D shape descriptor which is a computational tool used to analyse the 3D shape information. As a result of the deployment test, the folding efficiency and the shape memory performance was evaluated focusing on the effect of CNTs on the shape memory polymers.

1 INTRODUCTION

Shape memory polymers (SMPs) are smart materials which have ability to recover their original shape (permanent shape) from the deformed shape (temporary shape) by external stimulus such as heating. There have been lots of researches that make deployable antennas using SMPs in aerospace application [1-2]. Deployable antennas have good transportability due to their small volume when folded. A launching vehicle is launched with a folded antenna, after which the antenna can conduct its mission after unfolded in space. However, Existing deployable antennas have some drawbacks such as heavy weight and small deformability. SMPs can overcome these disadvantages because they have advantages of light weight, large deformability, good processability, and low cost [3]. In addition, deployable antennas made up of SMPs can transform its shape by their own inherent recovery force, so they do not need additional power devices. However, they have poor mechanical properties for aerospace application, promoting various researchers to try to enhance the mechanical properties of SMPs by incorporating fillers into SMP matrix.

In this research, multi-walled carbon nanotubes (MWCNTs) were used to improve the mechanical properties of SMP. The mechanical, thermal and shape memory properties of shape memory polymer composites (SMPCs) were characterized. In order to investigate the feasibility of the SMPC in aerospace, a miniature of circular antenna was fabricated. The deployment test of the antenna was conducted in a heating chamber. The deployment behaviour of the antenna was characterized using a 3D shape descriptor. Shape descriptors are computational tools used to analyse the 3D shape information [4]. Existing characterization methods of shape memory behavior cannot describe the three-dimensional deployment behavior of SMPC antenna. Therefore, the 3D shape descriptors were proposed to explain three dimensional shape changes during deployment test. As a result of the deployment test, the folding efficiency and the shape memory performance was evaluated focusing on the effect of MWCNTs on the shape memory polymers.

2 EXPERIMENT

2.1 Materials and fabrication of SMPC

Epoxy resin (Epofix®, Struers) and a curing agent (Jeffamine D-230®, Huntsman) were used to fabricate SMP matrix. MWCNT (MR99, Carbon Nano-material Tech. Co., LTD, carbon purity ~99%) was used as received. The outer diameter of the MWCNT was 20 nm and the length of it was 5μm.

SMPC was prepared following the method shown in Figure 1. Firstly, epoxy resin and MWCNTs were mixed and stirred mechanically. For dispersing MWCNTs in SMP matrix, two different methods were used; bath sonication and tip sonication. The mixture was sonicated and the curing agent was added to the mixture. Then it was sonicated one more time. To remove the bubbles in the mixture, it was degassed for 90 minutes. After degassing, the mixture was poured on a hot mold and cured at 130 ℃ for 120 minutes. The weight ratio of MWCNTs were 0.5, 1, 1.5, 2 wt%.

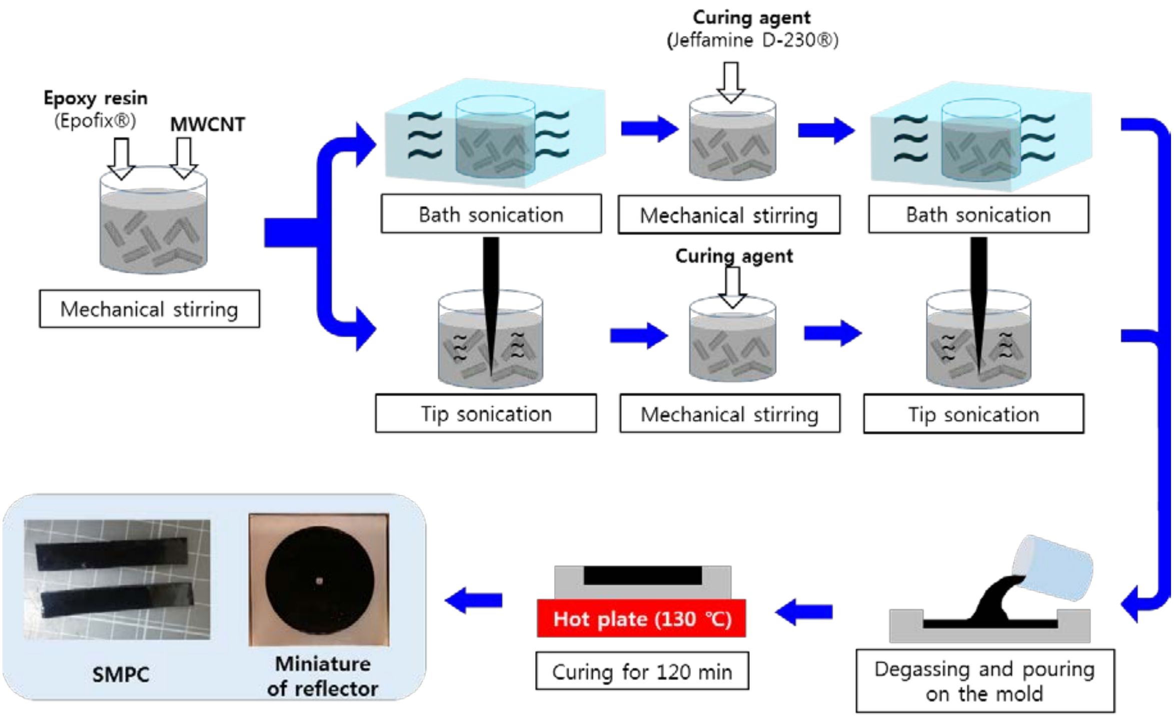

Figure 1: Fabrication method of SMPC

2.2 Characterization of SMPC

To see the dispersion of MWCNTs in SMP matrix, the fracture surface of SMPCs were observed via FE-SEM (JSM-7600F). The transition temperatures of SMPCs were measured using differential scanning calorimetry (DSC, 200 F3 Maia) and dynamic mechanical analysis (DMA, Q800). The tensile properties above and below the transition temperatures were measured using universal testing machine (UTM) combined with heating chamber (Figure 2 (a)). The test followed ASTM D638 (type I, IV). Rectangular shaped specimens (10 mm x 50 mm x 1 mm) were used to do thermomechanical test using UTM. Through the test, shape memory properties including shape fixity ratio and shape recovery ratio were calculated according to equation 1, 2, and Figure 2 (b).

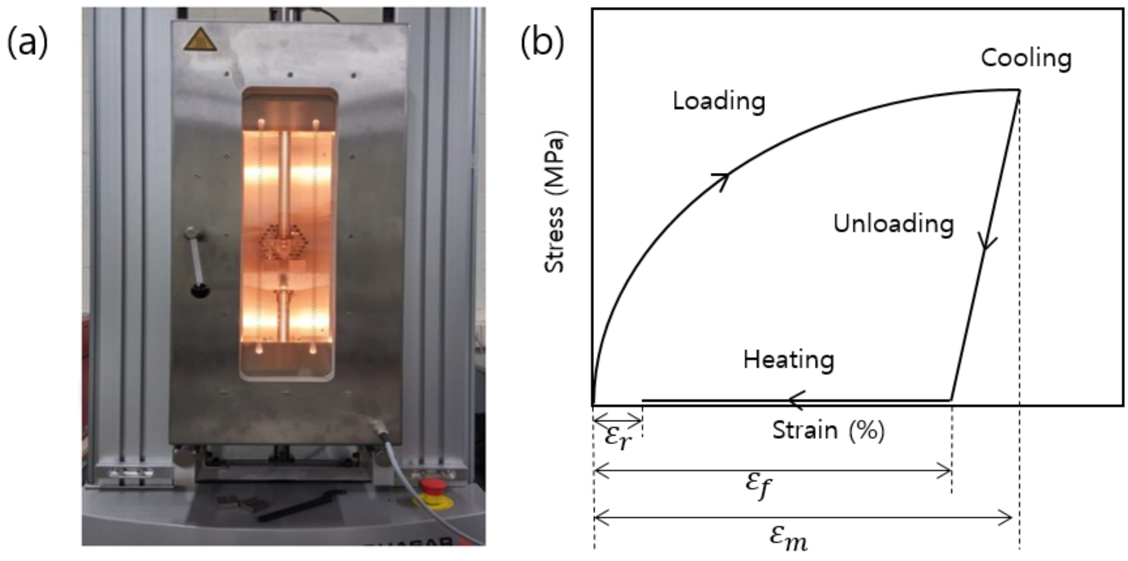

Figure 2: (a) Universal testing machine (UTM), (b) typical result of thermomechanical test (ε_m = maximum strain, ε_f = strain after unloading, ε_r = strain after recovery)

Shape fixity ratio, $$R_f = \frac{\varepsilon_f}{\varepsilon_m} \tag{1}$$

Shape recovery ratio, $$R_r = \frac{\varepsilon_m - \varepsilon_r}{\varepsilon_m} \tag{2}$$

Each symbol (ε_m, ε_f, ε_r) represents the maximum strain, strain after unloading, and strain after recovery.

2.3 Characterization of three-dimensional deployment behavior of SMPC antenna

For the deployment test, a miniature of circular SMPC antenna whose diameter is 16.5 mm and thickness is 1 mm was fabricated. The deployment test followed the process shown in Figure 3. The antenna was folded above the transition temperature (T_{trans} + 20 ℃). In the folding process (Figure 3 (a)), a self-produced folding equipment was used. Then it was fixed to temporary shape by cooling process. The SMPC antenna maintained its shape without the folding apparatus below the transition temperature (T_{trans} – 20 ℃). After the folding process, the antenna recovered its original shape as the temperature was increased up to T_{trans} + 20 ℃ (Figure 3 (b)).

In order to characterize the shape changes during deployment test, three-dimensional compactness was used. There have been some characterization methods of one-dimensional behavior of SMP. For example, tensile elongation change or angle change of folding SMP was used to explain the shape memory behavior one-dimensionally [5]. However, existing characterization methods could not describe the three-dimensional deployment behavior of SMPC antenna. In this research, 3D compactness was used to describe the deployment behavior.

3D compactness is a kind of shape descriptor. Shape descriptors are one of computational tools which can describe the shape information of an image. It is usually represented in numerical value and the value describe the specific characteristic of 2D or 3D shape [4]. In this research, 3D compactness which was proposed by Martinez-Ortiz was used [4]. The definition of it is shown in equation 3.

$$Compactness,\ C = \frac{3^{5/3}}{5(4\pi)^{2/3}} \times \frac{\mu_{0,0,0}(S)^{5/3}}{\mu_{2,0,0}(S) + \mu_{0,2,0}(S) + \mu_{0,0,2}(S)} \tag{3}$$

μ(S) is a central moment of a given shape S [6].

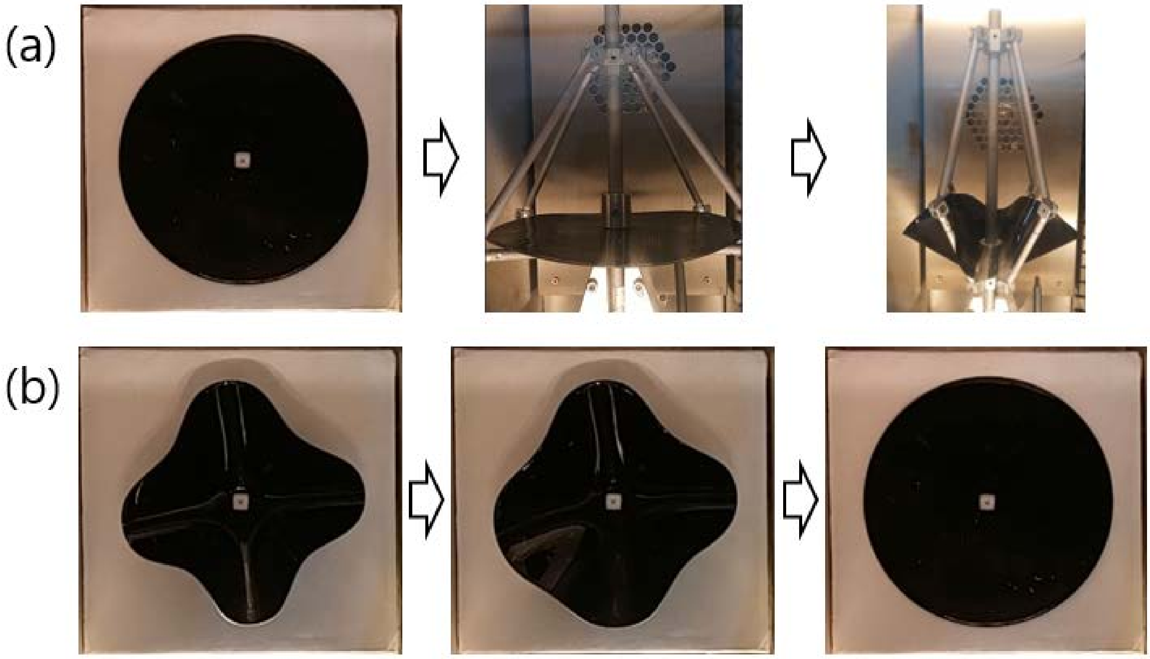

Figure 3: Deployment test of SMPC antenna. (a) folding process (b) deploying process

To calculate the 3D compactness, it is need to obtain the 3D image data from the deployment test. An Optical 3D scanner (ATOS Core 500, Figure 4) was used to scanning the three-dimensional shape of the SMPC antenna. Using the 3D scanning data, the 3D compactness value was calculated from each shape. From the 3D compactness value, three-dimensional shape memory properties including fixity ratio and recovery ratio were calculated.

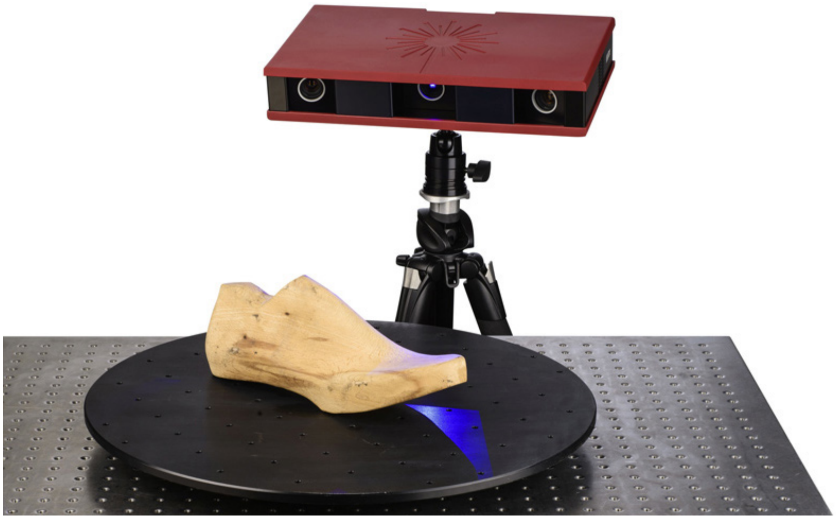

Figure 4: Optical 3D scanner (ATOS Core 500, GOM) [7]

3 RESULT & DISCUSSION

The SEM images of fracture surface of SMPCs were shown in Figure 5. SMPC-T was fabricated using tip sonication method and SMPC-B was fabricated using bath sonication. The MWCNTs in SMPC-T were well-dispersed in the matrix (Figure 5 (a)). The MWCNTs were separated individually. Otherwise, the MWCNTs in SMPC-B were agglomerated together compared to that of SMPC-T. It showed that the tip sonication method is better than bath sonication to disperse MWCNTs in SMP matrix.

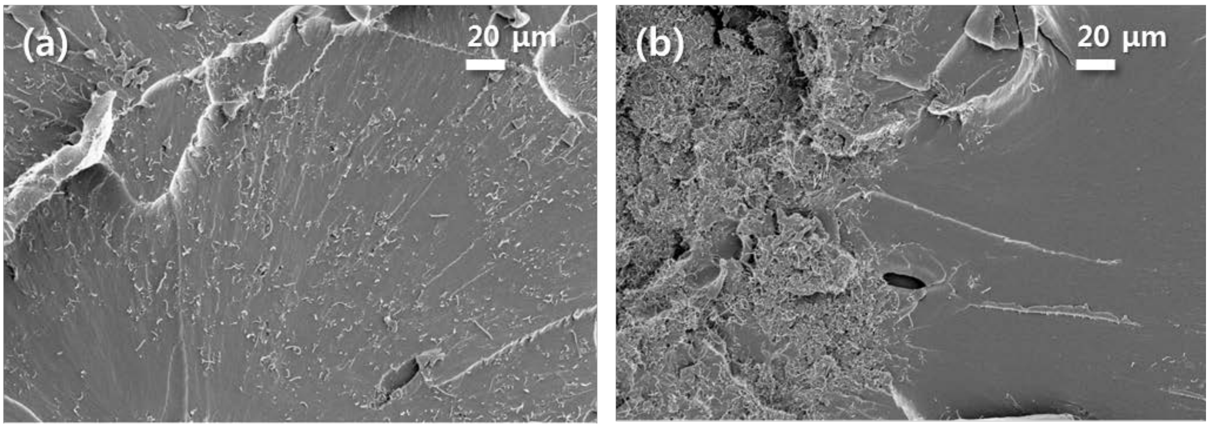

Figure 5: SEM images of fracture surface of SMPCs. (a) SMPC-T (b) SMPC-B

According to the DSC and DMA results, the transition temperature of the SMPC was increased compared to that of neat SMP. The transition temperatures of SMPCs were about 75℃. Table 1 showed the results of thermomechanical tests. As MWCNTs were added in SMP matrix, the fixity ratio was increased and the recovery ratio was decreased. It is because the MWCNTs interacted with the netpoints of SMP matrix, which prevents the chain slippage of the polymer chains.

Specimen	R_f	R_r
SMP	74 %	91 %
SMPC-B (0.5wt%)	91 %	85 %

SMPC-B (1.0wt%)	86 %	83 %

Table 1: Shape memory properties of SMP and SMPCs

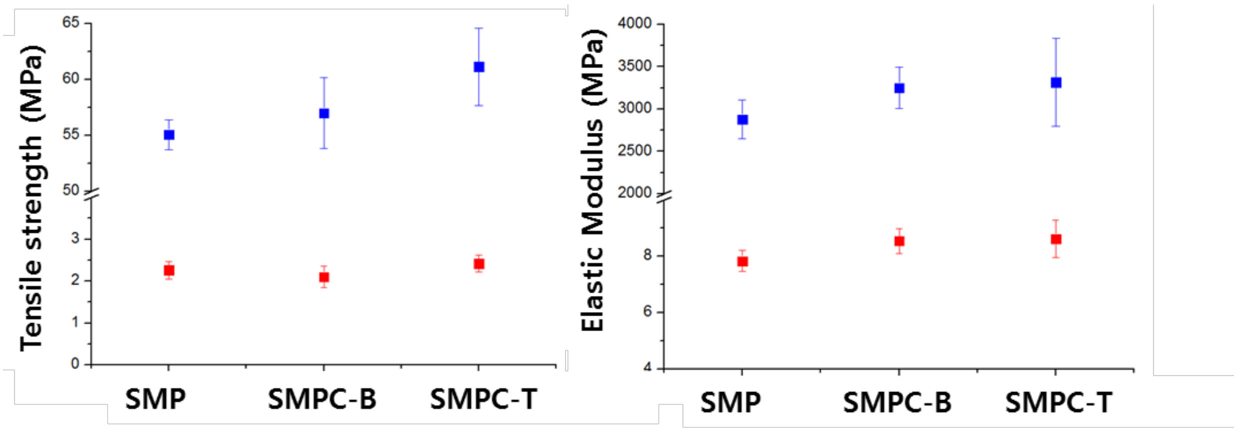

Figure 6: Tensile strength and Elastic modulus of SMP and SMPC (blue: below T_{trans}, red: above T_{trans})

strength and elastic modulus of SMPCs were increased. Especially, the SMPCs made by tip sonication showed better mechanical properties than bath sonication method. It is consistent results with the SEM images.

Finally, the deployment test of SMPC antenna was conducted, and the deployment behavior was characterized using 3D scanning data and a 3D shape descriptor, compactness. The detailed results will be presented in the conference.

4 CONCLUSIONS

For application in aerospace deployable antenna, the MWCNT-reinforced SMP was fabricated to have better mechanical properties. The transition temperature and the mechanical properties of SMPCs were increased compared to that of pure SMP.

A miniature of SMPC antenna was fabricated and it was deployed in a heating chamber. The deployment behavior of the antenna was observed by optical 3D scanner. Then the 3D information was characterized using 3D shape descriptor, compactness. The 3D shape descriptor could explain the 3D shape changes more efficiently.

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