Design and manufacturing smart mandrels using shape memory polymer

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Abstract

A new kind of smart mandrels (shape memory polymer (SMP) mandrels) have been demonstrated to make up the drawbacks of traditionally mandrels (multi-pieces metal mandrel, water-soluble mandrel and elastomeric mandrel), such as time-consuming, high cost, and difficulty to remove. In the paper, the styrene-based SMP has been used to design and manufacture the bottle-shaped and air-duct shaped smart mandrel. Firstly, the glass transition temperature of SMP has been obtained by dynamic mechanical analysis (DMA) test, the peak value of the loss angle has been chosen as the glass transition temperature (63°C). Secondly, the bottle-shaped and air duct-shaped smart mandrels have been manufactured by the process of curing, forming, heating, inflating, cooling and removing. At the same time, the corresponding recovery processes of smart mandrels have been measured to show the good shape recovery ability of SMP mandrels. Finally, the filament winding is applied on the SMP bottled-shaped mandrel and the extraction is demonstrated. These results show that SMP can be selected as one of the ideal materials for the application field of smart mandrel.

Keywords: Shape memory polymer, Smart mandrel, Shape recovery process, Filament winding

Introduction

Shape memory polymer is a kind of new smart materials, which can keep one temporary shape and recover the original shape under some special external stimulus [Leng et al. (2011); Baghani et al. (2012); Liu et al. (2006)], such as temperature [Tobushi et al. (1997); Tan et al. (2013)], electricity current [Liu et al. (2009); Lv et al. (2010)], light [Lendlein et al. (2005)], magnetic filed [Conti et al. (2007)] and solution [Wang et al. (2012); Lv et al. (2008)], and so on. Nowadays, SMPs have cause a great deal of interest since the development of 1984, particular in the last few years. A typical thermomechanical cycle can be shown in Figure 1 [Lan et al. (2009)]:(1) Fabricating the original shape of SMP sample and heating it above the glass transition temperature; (2) Loading the sample to a temporary shape; (3) Keeping the deformation and cooling the temperature to the room temperature (lower than glass transition temperature); (4) Keeping the temperature and removing the external load; (5) Reheating the sample above the glass transition and recovering the original shape.

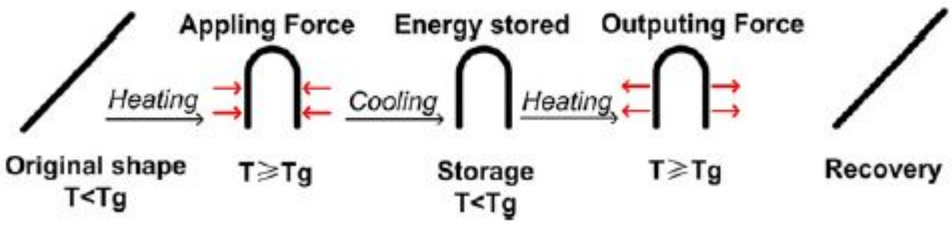

Figure 1. The schematic of a typical thermomechanical cycle of SMP sample [Lan et al. (2009)]

Compared with traditionally metal materials and shape memory alloy (SMA), SMP possess the unique advantages of low density, high elastic deformation, low energy consumption for shape programming, excellent manufacturability, and low cost [Baghani et al. (2012); Xie (2010); Meng and Li (2013)]. Today, SMP have been synthesized, fabricated, designed, investigated, developed and utilized in a wide range of application [Baghani et al. (2012)]. Such as aerospace [Sokolowski and Tan (2007)], medical research [Lendlein and Langer (2002)] and textiles industry [Hu et al. (2012)]. In this paper, the application of SMP for mandrel fabrication in aerospace field is investigated in detailed, mainly including bottled-shaped mandrel and air duct-shaped mandrel.

Traditionally, the fabrication methods for complex component-curved shape composite parts are mainly multi-piece metal mandrel, water-solution mandrel and inflation elastomeric mandrel [Everhart et al. (2005; 2006)]. However, there are some inherit disadvantages for every kinds of mandrels. Multi-piece metal mandrel must be disassembled one by one after curing the composite parts and reassembled before next use, the process is labor-consuming and the fabrication cost is high; water-solution mandrel must collect the waste and dispose it for next use, the process is time-consuming and the mandrel is fragile for use; inflation elastomeric mandrel is difficult to provide enough stiffness for uncured composites and the mandrel is easy to damage [Everhart et al. (2005; 2006)]. On the other hand, SMP mandrel can provide large deformation under high temperature and keep the shape until low temperature, when the temperature is lower than glass transition temperature, the materials can also meet the need of filament winding under small deflection, considering these factors, SMP can be expected to be used as new kinds of mandrel for the fabrication of complex component-curved shape composite parts in the future.

Based on the above-mentioned state, the mainly content can be organized as follows. In section 2, the polymer materials to fabricate the SMP mandrels are selected and the mechanical properties (such as storage modulus and loss angle) are measured by DMA; In section 3, the SMP bottle-shaped mandrel and air duct-shaped mandrel are fabricated by inflation method; In section 4, the shape recovery ability of SMP mandrels has been demonstrated under some special temperature, then, filament winding is carried out on the surface of bottle-shaped SMP mandrel and the extraction experiment is also shown; Finally, in section 5, the summary and conclusions are given to verify the feasibility of SMP mandrel for the future aerospace applications.

Materials

As shown in our prior paper, there are many kinds of SMP materials for application, mainly including styrene, epoxy, cyanate, and so on [Liu et al. (2014)]. In our work, the material for fabricated SMP mandrels is styrene-based SMP material due to the relatively large deformation ability and shape recovery ability. The general mechanical properties for styrene-based SMP can be measured by DMA device, the three-point testing is selected and the temperature range is designed from 298K(25°C) to 363K(90°C) with the heating and cooling rate 5K/min. The values of loss angle can be shown in Figure 2. The peak of loss angle (63°C) can be selected as the glass transition temperature in our work.

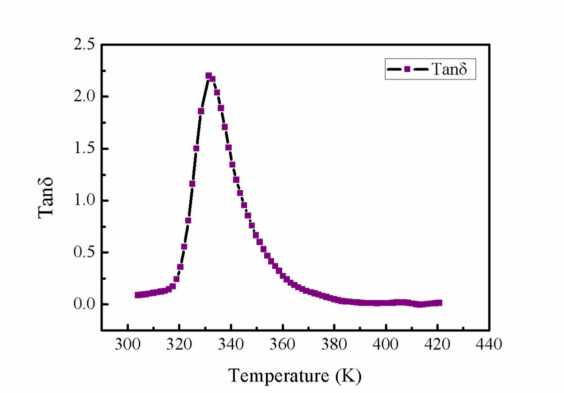

Figure 2. The DMA curve of styrene-based SMP

Fabrication of SMP mandrel

In this section, the bottle-shaped SMP and air duct-shaped mandrel are demonstrated by the fabrication technique of inflation method.

Fabrication of bottle-shaped SMP mandrel

The basic fabrication diagram of bottle-shaped SMP mandrel can be shown in Figure 3, mainly including curing, forming, heating, inflation, cooling and removing steps.

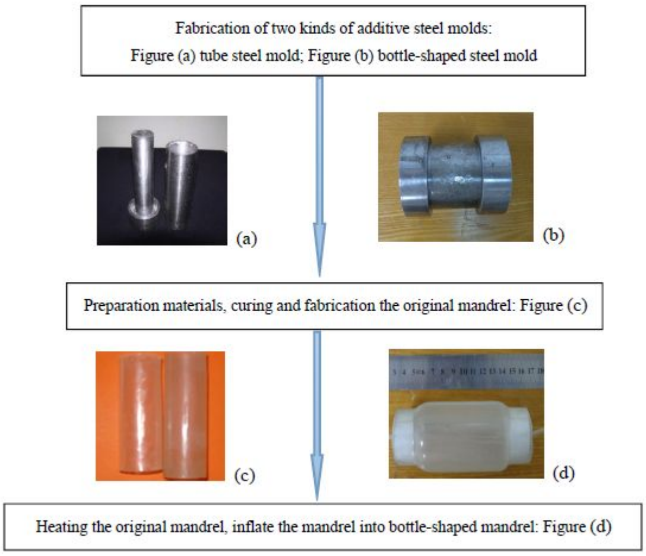

Figure 3. The design diagram of bottle-shaped SMP mandrel

As shown in Figure 3, the two kinds of additive molds for fabricating bottle-shaped mandrel are steel materials with high stiffness and low thermal expansion coefficient to make sure the accuracy of SMP mandrels. The original SMP mandrel is a tube with internal diameter 36mm, outer diameter 40mm and thickness 2mm, the length is 120mm; the final bottle-shaped mandrel with the maximum diameter 50mm at the middle part of the mandrel and 40mm at the two end of mandrel. The shape deformation can be defined by the change in the middle part of mandrel, so the maximum ratio is 25%. In addition ,the bottle-shaped mandrel with 50%, 75% and 100% can be fabricated with the same method.

Fabrication of air duct-shaped SMP mandrel

After the bottle-shaped SMP mandrel is fabricated, the air duct-shaped mandrel is also designed and fabricated to verify the feasibility of SMP mandrels. The geometry of air duct-shaped mandrel is that a rectangle section at one end with the length 48mm and width 36mm, the other end is circular section with a diameter 55mm, the middle part is gradually transformed from the rectangle section to circular section, the original shape of air duct-shaped mandrel is a tube due to the simple fabrication process, the final air duct shape can be obtained by inflating method, the final shape and original shape of air duct-shaped SMP mandrel can be shown in Figure 4.

Figure 4. The air duct-shaped SMP mandrel with final deformable state and original state

As shown in Figure 4, the original shape of air duct-shaped SMP mandrel is a tube, the final shape is a serpentine shape, the transition range is continuous and smooth with a large curvature. The diameter of tube produces obviously change after carrying out the internal pressure. The left end is a circular section and the right section is rectangle section. The experimental results show that the SMP materials can be easy to duplicate the cavity shape of additive steel mold with a small pressure, the SMP mandrel owns good shape fixity ability for temporary shape.

Experimental result and discuss

Shape recovery process of bottle-shaped mandrel

As a kinds of reusable smart mandrel, SMP mandrel can retain the temporary shape and recover original shape under some external stimulus, the good shape fixity ability can make sure the accuracy of mandrel production and the good shape recovery ability is a key factor for successful extraction from curing composite part. The shape recovery process of bottle-shaped mandrel under 90°C (above transition temperature 63°C) can be shown in Figure 5.

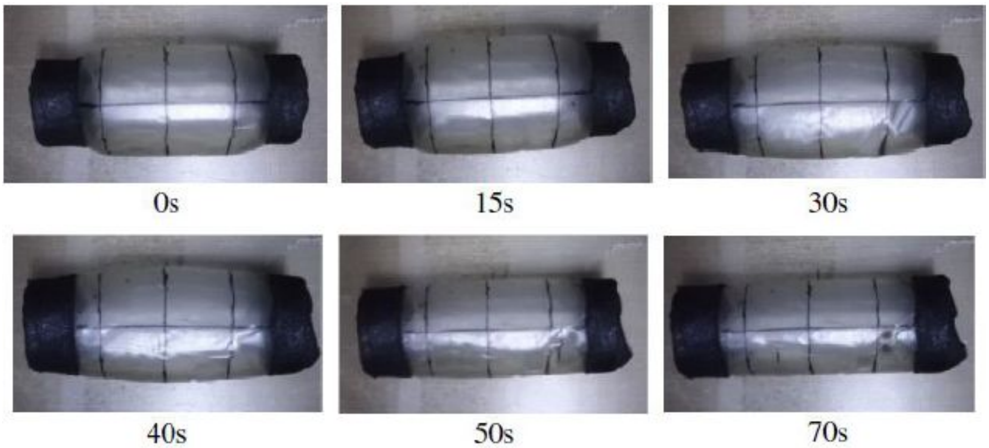

Figure 5. The shape recovery process of bottle-shaped smart mandrel
[Zhang et al. (2014)]

As shown in Figure 5, there are some perpendicular line on the surface of mandrel to locate the deformation. The shape recovery process mainly consists of three steps when placing the mandrel in the oven with temperature 90°C: step 1, the mandrel starts recovery after the mandrel putting into the oven, the rate is relative slow; step 2, The recovery rate markedly increases after 15s and gradually gets the peak; step3, the rate is declined to recover the original shape, when the time is 70s, the bottle-shaped mandrel nearly recovers the original shape. The total recovery rate curve is similar to Gauss function with a single peak. The recovery trend can be effective to alleviate the shock effect when SMP materials are used to fabricate the deployable space structures ,such as hinge, solar array, and so on.

As above-mentioned state, the shape fixity ability and shape recovery ability are two very important factors to the application of SMP. In our work, the shape fixity ability and recovery ability are obtained by measuring the maximum diameters change in the deforming process and recovering shape. The maximum diameters change are 25% and 50% in the paper, the definition can be shown as follows:

Shape fixity ratio R_f

$$R_f = \frac{D_L}{D_H} \times 100\% \tag{1}$$

Where D_H, D_L represent the diameter after high temperature deformation and the diameter after cooling to room temperature, respectively.

Shape fixity ratio R_r:

$$R_r = \frac{D_O}{D_R} \times 100\% \tag{2}$$

Where D_R, D_O represent the diameter after high temperature recovery and the diameter before deformation (original shape), respectively.

The shape fixity ratio and shape recovery ratio can be measured and computed as Table 1.

Table 1. Shape fixity ratio and shape recovery ratio of bottle-shaped mandrel

	Mandrel with 25% deformation			Mandrel with 50% deformation		
Measuring Location	Upper section	Middle section	Lower section	Upper section	Middle section	Lower section
D_H	40.00	50.00	40.00	40.00	60.00	40.00
D_L	39.85	49.72	39.81	39.92	59.67	39.66
R_f	99.63%	99.44%	99.53%	99.80%	99.45%	99.15%
D_O	38.49	38.59	38.57	38.90	38.81	38.85
D_R	38.62	38.71	38.87	38.95	38.91	38.97
R_r	99.66%	99.69%	99.22%	99.87%	99.74%	99.69%

Table 1 shows that the shape fixity ratio and shape recovery ratio are more than 99%, which verify the good shape fixity ability and shape recovery ability of SMP mandrel and provide deformation indexes for the application of SMP mandrel in the future.

Shape recovery process of air duct-shaped mandrel

Air duct-shaped mandrel is more complex component-curved shaped structure, in order to better show the good shape recovery ability and reusable ability, the shape recovery experiment is carried out under some special temperature. In our work, the shape recovery temperature is selected as 55°C and the shape recovery process can be shown in Figure 6.

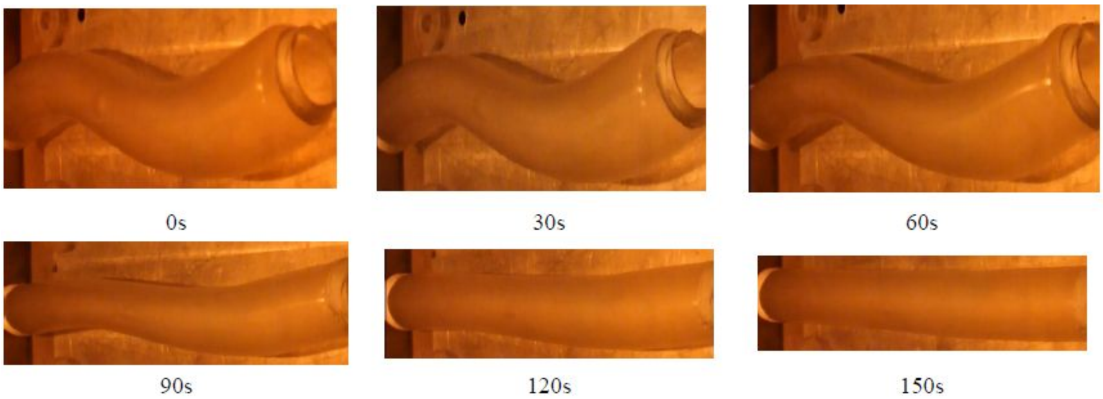

Figure 6. The shaper recovery process of air duct-shaped mandrel

As shown in Figure 6, due to the environment temperature (55°C) is relatively lower than glass transition temperature (63°C), the air duct-shaped mandrel can not obviously change during the first 30s; in the second 30s, the mandrel starts to provide some markedly recovery on the two end. Particular in the circular section, which undergoes the maximum deformation during the deforming process; in the third 30s, the rectangle section gradually transforms to circular section and the curvature of transition zone declines significantly; in the fourth 30s, the curvature zone continuously transform to circular section but the rate is slow; in the fifth 30s, the air duct-shaped mandrel nearly recover the original tube shape with a diameter 40mm. It is noted that the recovery process can take place in the around of transition temperature, when the temperature is less than glass transition temperature, the recovery time is increased obviously.

Extraction verification of bottle-shaped smart mandrel

It is well known that the SMP is in the rigid elastic state when the temperature is low, the deformation is stored and stiffness is commonly enough for filament winding and curing the fiber and matrix to obtain the final composite part. After that, the temperature is reheated above glass transition temperature and the mandrel comes into the soft rubber state with low stiffness, the storage deformation is released and the mandrel recovers the original tube shape to remove the mandrel from composite part. In our work, the glass fiber and carbon fiber are used to filament winding and verify the feasibility of SMP mandrels, the extraction process of bottle-shaped mandrel can be shown in Figure 7.

Firstly, the bottle-shaped smart mandrel is fabricated and cured on the room temperature environment, as shown in Figure7(a), then, the composite part is placed into the temperature chamber and heated up to 90°C to actuate the shape recovery of internal styrene-based SMP mandrel, when the SMP mandrel recovers the original tube state, opens the chamber and takes out the composite part with polymer liner, cools the temperature to room temperature and starts to remove the internal polymer mandrel, as shown in Figure 7(b); push out the polymer tube from one end to the other end, as shown in Figure 7(c); Finally, the polymer is removed from the composite part and leave the composite part without liner, as shown in Figure 7(d). It is noted that the interface between polymer mandrel and composite part is coated with release agent to avoid the bonding effect, In addition, the surface of polymer tube is smooth and without damage, which can save the manufacturing cycle and reduce the cost significantly.

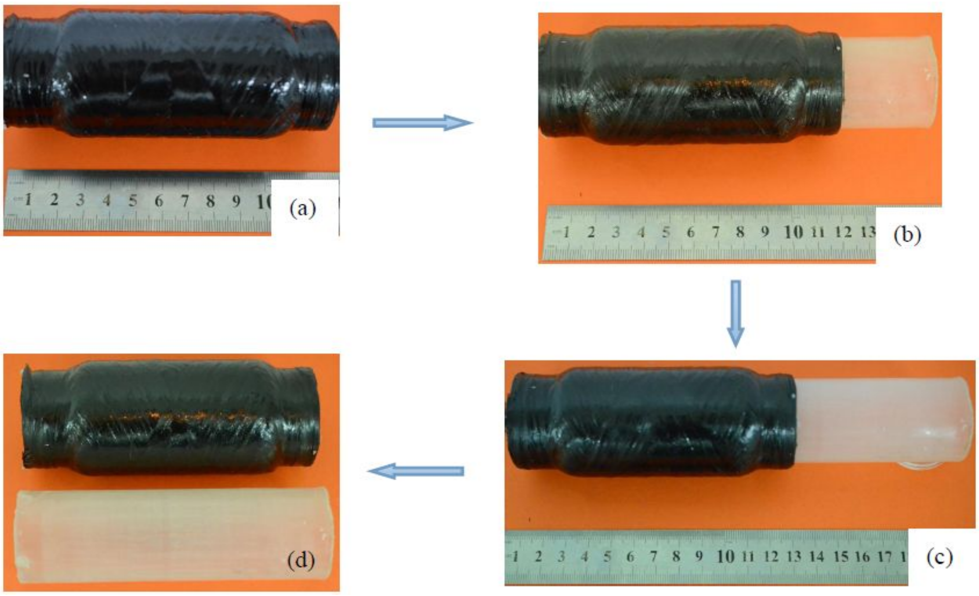

Figure 7. The extraction process of bottle-shaped mandrel with 25% deformation

Conclusions

The aim of this paper is design and manufacturing of bottle-shaped smart mandrel and air duct-shaped smart mandrel using shape memory polymer. The method is different from the traditional techniques and owns many unique advantages, such as low weight, short production cycle and low cost. The shape recovery testing has been carried out and some results can be shown as follows:

(1) Bottle-shaped SMP mandrel owns good shape fixity ability and shape recovery ability, which is large than 99% in the deformation process and recovery process. The advantage is obviously for SMP mandrel as a new kinds of mandrel manufacturing techniques for future applications;

(2) Bottle-shaped SMP mandrel and air duct-shaped mandrel can recover the original shape (tube) under some special temperature environment. It is noted that the air duct-shaped mandrel even recovers the original shape under the temperature lower than glass transition temperature;

(3) Bottle-shaped SMP mandrel can be easy to remove for composite part and keep the polymer mandrel without damage, the process is relatively easier than traditional mandrels, the results show the good feasibility of SMP mandrel for the fabrication of complex component-curved shape composite parts.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant No.11225211, No.11272106, No.11102052).

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