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Structural response measurement of shape memory polymer components using digital image correlation method

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A R T I C L E I N F O

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A B S T R A C T

Shape memory polymer (SMP) can actively deform under a certain external stimuli and maintain the deformation after the stimuli is removed. When the corresponding stimulus is applied again, it can return to its initial state. Due to their high strength, low density and high rigidity, SMP and its composites are getting increasing attention. The study of their mechanical behavior is critical for the design of composite materials. However, due to the anisotropic and viscoelastic properties of SMP composite, it is difficult to carry out a comprehensive study of structural response of SMP and its composite structures through traditional experimental methods. In this paper, the full-field displacement and strain of disc, beam and ring structures based on SMP and its composites were investigated by digital speckle correlation method, which is important for the comprehensive study of mechanical behavior and fabrication of SMP composites.

1. Introduction

As widely used polymer in the field of smart materials and structures, SMP can sense the changes of environmental factors and actively respond. SMP can change their physical parameters (shape, volume or strain, etc.) under certain specific environmental conditions including heating, illumination, electromagnetic field, etc. When the environmental stimuli are removed or changed, this deformation state can be maintained. However, once these specific environmental stimuli are applied to SMP again, they will restore to their original shape [1–9].

SMP composites are attracting more and more attention from the field of aerospace and biomedicine for their specific properties, such as lightweight, shape memory effect, etc. [10]. Besides, the highly cross-linked molecular structure endows it with the advantages of high strength, high modulus, low creep rate, low relaxation rate, etc. Filling particles into SMP could result in a functional composite material which possesses high recoverable strain and large restoring force [8].

The study of basic thermo-mechanical properties of epoxy based SMP and its composite under various working conditions is very important for the designing of various structures. The nonlinear mechanical behavior of SMP has been studied comprehensively in various published research work [11–18]. Guo et al. studied the effect of strain rate and high temperature on the tensile parameters of epoxy-based SMP and proposed constitutive model to describe its mechanical behaviors [19]. Chaudhary et al analyzed the high strain rate behavior of toughened epoxy under compressive loading [20]. Makradi et al. investigated the stress-strain behavior of SMP under large deformation and strain-induced crystallization above the glass transition temperature and proposed a two-phase self-consistent model [21]. Qi et al. studied the finite deformation of thermo-mechanical behavior of thermo-responsive SMP [22]. Heuwers et al. found that stress applied on SMP always affects the shape recovery properties, which mean that specimens of thermo responsive SMP will return to their original shape even at low temperatures [23].

However, the current research on the mechanical behavior and structural response of SMP and its composite is limited and has not addressed the requirements of many potential applications. There are more spaces for detailed research in both theoretical models and experiments, which will be of great importance to understand the material, establish the constitutive model, and conduct design and optimization of the materials in practical applications. However, it is difficult to adopt traditional and conventional test methods to solve the problem or describe it clearly. Thus new experimental methods are required such as strain field measurements that combine electrical strain gauges and theoretical calculations together. The macroscopic properties of materials are closely related to the changes of microstructures. So finding experimental methods that can reflect the changes of microstructures and give correspond-

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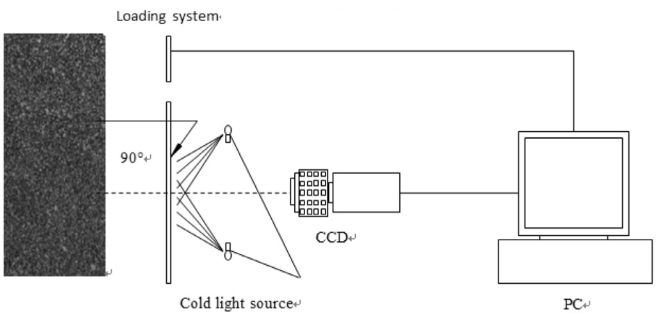

Fig. 1. 2D digital speckle correlation measure system.

ing quantitative analysis of mechanical parameters and properties is of theoretical and practical significance.

Optical measurement mechanics and corresponding experimental techniques provide effective supports for the aforementioned problems. Optical measurement mechanics are techniques that rely on the combination of basic principles of optics and basic theory of mechanics and obtain the mechanical quantities such as stress, strain and displacement from experimental results through mathematical tools. This method possesses characteristics of full field, non-contact, high-precision, etc. The earliest report about the digital speckle correlation method appeared in the early 1980s proposed by Yamaguchi [24]. The displacement and deformation fields of the specimen surface are measured by gray change of the two images before and after deformation. Many researchers have done a lot of work on the digital speckle correlation method. Utilizing this method, Peter etc. investigated the rigid body motion, Peters et al. studied the elastic-plastic problem and high temperature measurement problem [25], and Chevalier et al. explored the uniaxial and biaxial tensile mechanical behavior of rubber [26]. Digital speckle correlation method was also successfully used for the measurement of the crack tip strain field and micro-scale deformation, as well as measurement of mechanical behavior of various civil engineering materials and structures [27–31]. Besides, the digital image correlation method can also be used to measure the material parameters of SMP, which is also an effective method in the identification and inversion of material parameters. By this method, Dong et al. measured multiple thermo-mechanical parameters [32], coefficient of thermal expansion (CTE) [33], residual stress, etc.

In this work, the mechanical behavior of epoxy based SMP and carbon nanotube reinforced SMP composite were investigated using digital speckle correlation method. Through compression and three-point bending experiment, the influence of incorporating carbon nanotubes on the mechanical properties of SMP was investigated. And its characteristics are calculated from the deformation field. Two digital images of the measured surface of the disc, beam and ring structures before and after deformation are processed, of which the image before loading was called "pre-deformation image" while the images under loading are called "deformed image". By comparing gray-scale changes and tracking the position modification of each point, the overall displacement fields were obtained. And after some appropriate numerical difference calculation, the strain fields were obtained.

2. Compressive test of SMP disc

The digital speckle correlation measurement system used in the experiments was shown in Fig. 1. The optical axis of the CCD camera in the measurement system was approximately perpendicular to the epoxy specimen surface for high precision imaging. We assume that the specimen has only in-plane displacement, so the out-of-plane displacement during the loading process was neglected. CCD digital camera was used for real-time image acquisition. Each image was discretized into a 1280 × 1024 (pixels) gray scale matrix and saved into the computer and then calculated by the corresponding software. The black and white paints were sprayed on the surface of measured epoxy structure surface as artificial speckle to provide the characteristics for gray-scale matching.

Table 1
The maximum and minimum values of displacement and strain field distributions.

	Maximum value	Minimum value
U displacement field(pixel)	$\|-1\|$	0
V displacement field(pixel)	$\|-12\|$	$\|-2\|$
ε_{xx}	$\|-12\times10^{-3}\|$	$\|-4\times10^{-3}\|$
ε_{yy}	$\|-0.025\|$	0
ε_{xy}	$\|-0.01\|$	0

2.1. Compressive test of epoxy based SMP disc

Fig. 2 depicts a general thermo-mechanical cycle for SMP disc. As shown in Fig. 2(a), the whole process can be divided into four steps:

(1) Heat the SMP disc structure to a temperature above the transition temperature and give it a deformation of 2 mm;
(2) Cool the SMP disc to a temperature below the transition temperature while the constraint is kept to fix the shape;
(3) Keep the temperature below the transition temperature and remove the external load;
(4) Reheat the material to a temperature above the transition temperature without external load.

Three images in Fig. 2(b) demonstrated the condition of specimen before deformation, after deformation and after shape memory recovery. They respectively correspond to the moment of before step 1, end of step 1 and end of step 4. The analysis results under deformation condition (end of step 1, left figure) and after shape memory recovery (end of step 4, right figure) were shown in Fig. 2(c) and (d) respectively. When the specimen was in compression, the maximum shear strain ε_{xy} was 0.03 in Fig. 2(c), and the maximum strain ε_{yy} was $|-0.08|$ in Fig. 2(d). However, after shape memory recovery process in step 4, it can be observed that the color of most regions was approximate yellow except for some singular points. It meant that the frozen strain were nearly completely recovered, since the yellow color represented that the strain of this region approaches zero according to the colorbar in Fig. 2(c) and (d). The reason why there were some irregular areas was that the precision of the measure system was limited.

Firstly, the mechanical properties of epoxy based SMP were tested. Fig. 3 showed the disc structure used in the experiment. During the experiment, the epoxy-based SMP structure was subjected to a compressive load of 2400 N on a testing machine. The displacement of loading end was 1.26 mm. Selecting the whole region of the specimen surface as calculation area, the calculated results of displacement and strain distributions were shown in Fig. 4 (a–e) and Fig. 5 (a–e). Calculations showed that the contour lines are symmetric with respect to vertical and horizontal axis. Table 1 illustrated the maximum and minimum value of displacement and strain.

The variation of Y-direction strain field while increasing the load was illustrated in Fig. 6. The maximum strain increased always along with the vertical direction and extended to the center of the disc structure gradually. From the strain field distribution, it can be seen that the changes of strain field along the vertical direction. For example, there was an unconventional area in Fig. 6(b) which the maximum strain occurred in the center of the specimen under load of 1200 N rather than appeared in both ends. However, as load increase, the irregular contours were disappeared and the field distribution of strain turned into more symmetrical pattern. Variations of the maximum strain with the change of load were described in Table 2.