Thermomechanical analysis of porous SMP plate

R. Tao[1], *Q. S. Yang[1]

Beijing University of Technology, China
Department of Engineering Mechanics, Beijing University of Technology
Beijing 100124, PR China

*Corresponding author: qsyang@bjut.edu.cn

Abstract

Shape memory polymers (SMPs) are a kind of intelligent material with response to the external temperature stimulus. It can recover from a deformed state (temporary shape) to its initial state (permanent shape). In this work, the thermo-mechanical behavior and shape memory effect of a SMP-based porous plate is modeled by the finite element method using a 3D constitutive equation. The whole process of shape memory of porous SMP plate includes loading at high temperature, decreasing temperature with constant load, unloading at low temperature and recovering the initial shape by increasing temperature. The results demonstrate the thermo-mechanical deformation of SMP structure.

Keywords: Smart material and structure, Shape memory polymers, Constitutive model, Porous plate, Shape memory effect

1 Introduction

As an intelligent macromolecule material, applications of shape memory polymers (SMPs) have evoked great interest since the 1980s. Because of their light weight, good durability, large deformation and shape recovery, SMPs provide several advantages over shape memory alloys and ceramics, such as low density, high shape-fixed strain, easy operation, tailorable critical transition temperature and part of them bio-compatible. Therefore, it has great potential application in the textile, biomedical materials, defence and Military and so on [Behl, Zotzmann and Lendlein (2010); Leng, Lan, Liu and Du (2011); Hu, Meng, Li and Ibekwe (2012); Mather, Luo and Rousseau (2009)]. Since the first shape-memory polynorbornene successful development in the world, in the past two decades various SMP materials have been developed out [Lendlein A and Kelch S (2002); Takahashi et al. (1996); Yang et al. (2003)].

It has the ability to retain the deformed shape when subjected to external heat, moisture, electrical and magnetic stimulation factors can be restored to the original shape, which has a memory function to the initial shape. Thus, the storage and release of strain [Meng and Hu (2009); Nelson (2008); Lendlein and Kelch (2002)] can be achieved. Thermally isotropic SMP is the most basic and common of such materials. Achievement of storage and release of strain is due to the occurrence of glass transition of SMPs, as the temperature changes [Takahashi, Hayashi and Hayashi (1998)]. The thermomechanical cycle process in the SMPs involves the following four steps: loading at high temperature, cooling under constant load, unloading at low temperature and heating under free load. The elastic, viscoelastic and thermal deformation, and shape memory effect are displayed in this process. The above mentioned high and low temperatures denote temperatures above the end and below the beginning of glass transition of SMPs. To obtain relatively high mechanical properties, several researches have worked on SMP composites reinforced by variety of fibers and particles [Yang, Huang, Le, Leng and Mai (2012)]. These composite materials with shape memory that use of continuous fibers as reinforcement and use of thermosetting SMP as matrix have a very large potential application. In recent years, they have been widely appreciated in the space expanded structure [Keller and Lake (2003); Gall and Lake (2003)]. In the study of the constitutive models of thermotropic SMPs, which the representative study are as follows. e.g. [Tobushi, Hashimoto, Hayashi and Yamada (1997)] developed a thermomechanical constitutive model by modifying a standard linear viscoelastic model [Tobushi et al. (1997)]. The model involved a slip element due to internal friction and took account of thermal expansion. Therefore, a SMP linear constitutive model of thermodynamic properties is established. Considered the large deformation characteristics of

SMP, Tobushi et al. further proposed a nonlinear constitutive model based on the above work [Tobushi, Okumura, Hayashi and Ito (2001)]. These models are macroscopic and experienced but thermodynamic internal mechanism of SMP materials has not been considered. Liu et al. proposed a three-dimensional, small strain, linear elastic, and rate-independent SMP thermodynamics constitutive equations [Liu et al. (1997)]. The model can roughly predict the change trend and recovery of shape memory of SMP materials on different constraints. But this model does not consider the impact of the SMP viscoelastic. Zhou, Liu and Leng formulated a 3D thermomechanical constitutive equation of SMPs [Zhou, Liu and Leng (2009)]. However, applications of these constitutive equations are limited due to the lack of experimental data for material parameters. Another type of constitutive model of SMPs is the micromechanics-based method, such as the phase transition and the mixture theory. Liu, Gall, Dunn, Greenberg and Diani (2006) proposed a 3D linear elastic constitutive model for small deformation that considers the molecular mechanism of the shape memory. Chen and Lagoudas established a thermomechanical constitutive model for large 3D deformation of SMPs. A review of advances of constitutive relations of SMPs was given by Zhang and Yang very recently.

However, these constitutive equations of SMPs are so complicated and contain so many material parameters that it is difficult to apply them in practical engineering. The lack of experimental data for material parameters restricts the finite element implementation of the constitutive models. It is necessary to develop applicable constitutive equations with physical definitions and the finite element procedure for complicated deformation of SMPs. Actually, the available 3D finite element program and numerical investigations are very limited in existing literature.

In this paper, by considering the elastic, viscoelastic and thermal deformation of isotropic SMPs, we propose a three-dimensional form of a thermomechanical constitutive equation for isotropic thermal actuated SMPs, with defined physical significance. A finite element procedure based on the present constitutive model is implemented by using user material subroutine (UMAT) of ABAQUS, and some numerical examples are provided to illustrate the 3D deformation and shape memory effect of SMPs.

2 Thermomechanical constitutive model of SMPs

SMP thermodynamic constitutive equation plays an important role to the commercial aerospace industry adopting SMPs into their structures. In recent years, the research of the constitutive equation has been a hotspot and has made a lot of achievements. However, due to the complexity of the mechanism of SMP itself, research is continuing.

Tobushi et al. proposed a one-dimensional linear constitutive model for SMPs of polyurethane series [Tobushi et al. (1996)]. Shi et al. gave a three-dimensional constitutive equation of SMP in a rate form [Shi et al. (2013)].

$$\dot{\varepsilon}_{ij}+\frac{5\nu-1}{3(1-2\nu)}\delta_{ij}\dot{\varepsilon}_{kk} \tag{1}$$

$$=\begin{cases}\dfrac{(1+\nu)\dot{\sigma}_{ij}}{E}+\dfrac{\sigma_{ij}}{\mu}-\dfrac{\varepsilon_{ij}}{\lambda}-\dfrac{1}{3}\left(\dfrac{E}{\mu(1-2\nu)}-\dfrac{1}{\lambda}\right)\delta_{ij}\varepsilon_{kk}+\alpha\dot{T}\delta_{ij}, & \\ \qquad\qquad \text{as } \bar{\varepsilon}^{c}(t)<\varepsilon^{l}(T) & \\ \dfrac{(1+\nu)\dot{\sigma}_{ij}}{E}+\dfrac{\sigma_{ij}}{\bar{\mu}}-\dfrac{\varepsilon_{ij}-\bar{\varepsilon}^{s}(T,C)\delta_{ij}}{\bar{\lambda}}-\dfrac{1}{3}\left(\dfrac{E}{\bar{\mu}(1-2\nu)}-\dfrac{1}{\bar{\lambda}}\right)\delta_{ij}\varepsilon_{kk}+\alpha\dot{T}\delta_{ij}, & \\ \qquad\qquad \text{as } \bar{\varepsilon}^{c}(t)\geq\varepsilon^{l}(T),\ \dot{\bar{\varepsilon}}^{c}(t)>0 & \\ \dfrac{(1+\nu)\dot{\sigma}_{ij}}{E}+\dfrac{\sigma_{ij}}{\mu}-\dfrac{\varepsilon_{ij}-\varepsilon^{s}(t_1,T)\delta_{ij}}{\lambda}-\dfrac{1}{3}\left(\dfrac{E}{\mu(1-2\nu)}-\dfrac{1}{\lambda}\right)\delta_{ij}\varepsilon_{kk}+\alpha\dot{T}\delta_{ij}, & \\ \qquad\qquad \text{as } \dot{\bar{\varepsilon}}^{c}(t)\leq 0 & \end{cases}$$

where E is Young's modulus and α is coefficient of thermal expansion. μ and λ are viscosity coefficient and retardation time, respectively, depending on the temperature. $\varepsilon^s(t,T)$ is creep residual strain, unrecovered part of the creep strain, while $\varepsilon-\varepsilon^s$ is retardation strain. It is noted that as the temperature is above the glass transition region, i.e. $T > T_h = T_g + T_w$, where T_g is the glass transition temperature and T_w is temperature amplitude of the glass transition region, the creep strain can be recovered completely, which means the $\varepsilon^s(t,T)$ does not appear. Within the glass transition temperature region, i. e. $T_h = T_g + T_w > T > T_l = T_g - T_w$, there is a critical value of creep strain at which part of the creep strain becomes irrecoverable while for the case below glass transition temperature, the creep residual strain is a constant. The constitutive equations, with the temperature-dependent parameters, can reflect the thermo-mechanical behavior of different types of SMP materials.

Within the range of glass transition of SMP, material parameters are strongly temperature-dependent, which can be expressed

$$X = X_g \exp\left[K\left(\frac{T_g}{T} - 1\right)\right] \quad (2)$$

where T_g is the glass transition temperature, X denotes one of the material parameters E、μ、λ、C and ε_l. K is a coefficient corresponding to parameter X.

3 Introduction of model

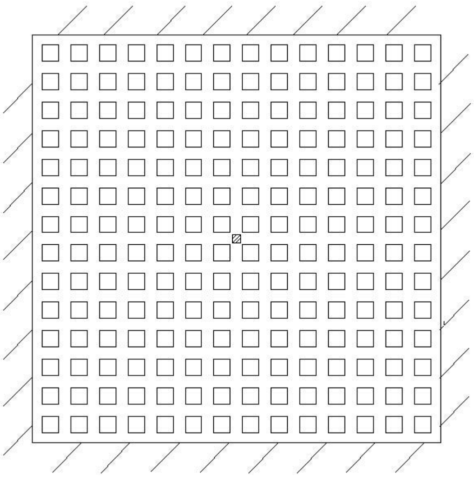

Figure 1. The simplified model of porous SMP plate

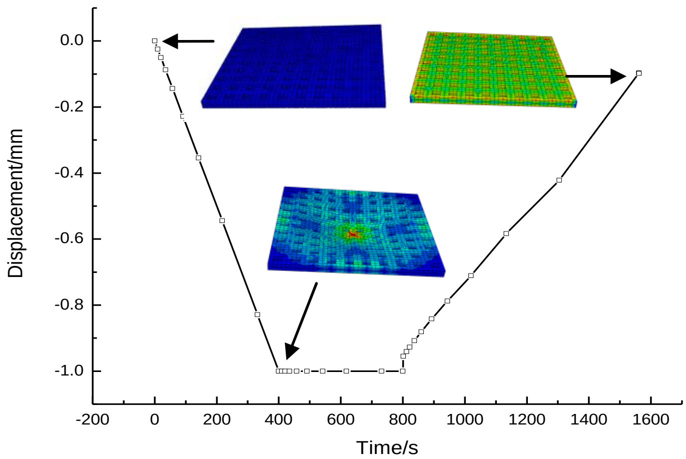

Figure 2. Displacement–time diagram showing the thermomechanical behavior of SMP

In order to realize analysis of thermo-mechanical behavior of the porous SMP plate, a simplified model is established. As shown in Fig.1, the model size is 100*100*5mm, the through holes of 5 * 5mm square uniformly distributed on the planar plate. Boundary conditions are set as follows: four sides in the edge are fixed and a specific displacement is imposed in the central region of the surface of the plate.

4 Numerical results and discussion

4.1 Experiment model and its shape-memory process

In this work, the UMAT program of SMP three - dimensional constitutive equation was developed, with the help of user material subroutine interface provided by the ABAQUS platform. Based on the correctness of the program, a series of numerical simulation of porous SMP plate were carried out. The entire process of numerical simulation has four steps. In the first step, a loading rate 1.5mm/min at 343k is applied displacement into 1mm. In the second step, temperature is reduced from 343K to 313K at the rate of 4.5k/min and the model remains loaded 1mm until the cooling process completed. In the third step, the model keeps the temperature 313k state and relieved the displacement, completing the unloading process at the low constant temperature. In the fourth step, temperature is rises from 313K to 343K at the rate of 4k/min without external load. The recovery process is completed with the heating. The time-displacement curve of whole thermodynamic cycle and deformation process of structure were shown in Fig. 2. Despite the presence of a small residual stress, the final residual strain is very small, so it can be considered to achieve a reasonable recovery effect.

4.2 Effect on the recovery of the different applied displacement

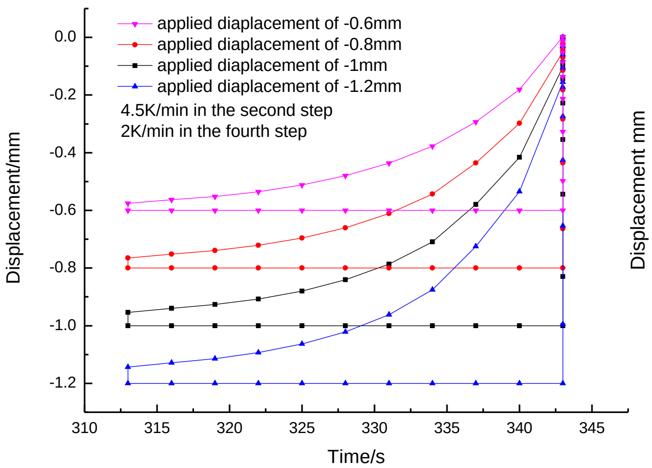

Figure 3. Temperature-displacement curves in different displacement load

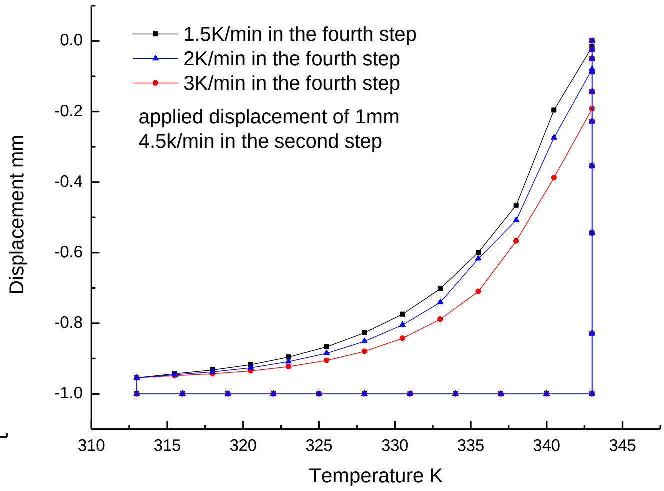

Figure 4. Temperature-displacement curves in different heating rate

Due to the viscoelastic properties and the temperature dependence of the SMP material, different applied displacement has a direct impact on the final curve. The effects that different applied displacement loads on the central region of porous SMP plate are studied. The four throughout the thermodynamic cycle are contrasted. In four experiments, the heating rate and cooling rate maintain constantly. The different displacement is applied on the model. First, all displacement is 0 before being applied displacement in four groups. Again, the loaded specimen is maintained while reducing the temperature of specimen. Then, part of the strain is restored during unloading. Finally, the results of recovery are different because of different applied displacement. As shown in Fig. 3 different applied displacement has great influence on the final residual strain. Residual strain becomes smaller with displacement load reduced from1.2mm to 0.6mm.,

4.3 Effect on the recovery of the different heating rate

As the temperature-dependent material properties of SMP, different heating rate for the restoration of the loaded displacement has impact. Keeping constant applied displacement, the heating rate impact the recovery of residual strain. As shown in Fig. 4, the characteristic of the recovery process varies from fast to slow and the turning point follows the glass transition temperature. It is the main reason viscosity coefficient and delay time and other parameters are reduced at high temperature. With heating rate reduced from 3k/min to 1.5k/min, residual strain is decreasing. Whether full recovery of residual strain or not is directly affected by different heating rates. When the heating rate is less than 1.5k/min, the residual strain nearly completely recovered. It is mainly reason that the SMP is a viscoelastic material.

4.4 Effect on the recovery of the different thickness

In the structural design of the porous plate, it is inevitable to choose a reasonable thickness and the hole opening ratio based on recovery rate of residual strain and mechanical performance's requirements therefore study of influence of this parameter is important. As shown in Fig. 5, the thickness of plate were set to 2mm, 3mm, 4mm, 5mm, 6mm when the hole opening ratio , heating and cooling rate are constant. The greater the thickness of the porous SMP plate, the smaller the strain in thickness direction. The strain needed to restore is reduced in this case. Therefore, different thicknesses of porous SMP plate have a significant impact for the final residual strain in the stage of heating and recovery.

4.5 Effects of structural parameters on the recovery process

The structure should select the appropriate the hole opening rate in order to save costs. Whether different hole opening ratio will affect result of recovery or not. Thickness of model is 3mm and heating, and cooling rates held constant. The applied displacement of 5mm is imposed on the center region of porous SMP plate. The hole opening ratio of the porous plate were set to 0, 7.84%, 17.64%, 31.36%, and 49%. With the increase of the hole opening ratio, the mass of the porous SMP plate is reduced. As shown in Fig. 6, the effect of different hole opening ratio for results of recovery is small.

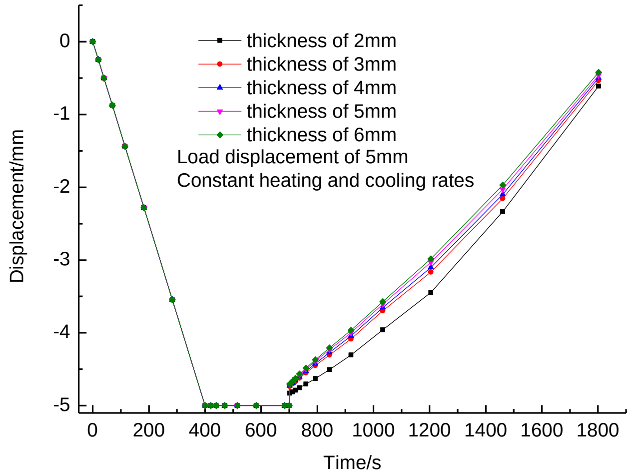

Figure 5. Time-displacement curves in different thickness

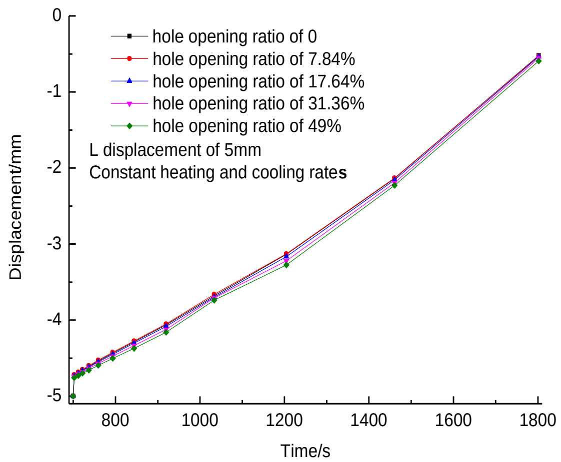

Figure 6. Time-displacement curves in different hole opening ratio

5 Conclusions

Based on the correctness of the SMP three-dimensional constitutive equation, a series of numerical simulation were carried out. The results show that the present 3D thermo-mechanical constitutive model can be used effectively to describe the complicated mechanical behavior of SMP. Experiments show that property of SMP material has strong temperature dependence. So the reasonable control of temperature is essential for the control of the mechanical behavior of SMP.

Whether full recovery of residual strain or not is directly affected on the thickness of the porous plates. However, the effect of hole opening ratio is small. The porous SMP plate has excellent thermo-mechanical property and the structure can be designed according to the needed.

References

Behl, M., Zotzmann, J. and Lendlein, A. (2010) Shape-Memory Polymers and Shape-Changing Polymers, *Adv. Polym. Sci***226**, 1-40.

Liu, B. F., Dui, G. S. and Zhu, Y. P. (2011) A Constitutive Model for Porous Shape Memory Alloys Considering the Effect of Hydrostatic Stress. *CMES: Computer Modeling in Engineering & Sciences* **78**, 247-276.

Hu, J. L. Meng, H. P., Li, G. Q. and Ibekwe, S. I. (2012) A review of stimuliresponsive polymers for smart textile applications. *Smart Mater. Struct* **21**, 053001.

Mather, P. T., Luo, X. F. and Rousseau, I. A. (2009) Shape Memory Polymer Research. *Annu. Rev. Mater. Res* **39**, 445-471.

Lendlein A, Kelch S. (2002) Shape-memory polymers. *Angew.Chem.Int.Ed* **41**,2034-2057.

Takahashi T, Hayashi N, Hayashi S. (1996) Structure and properties of shape memory polyurethane block copolymers. *J.Appl.Polym.Sci* **60**,1061-1069.

Yang J H, Chun B C, Chung Y C et al. Comparison of thermal/mechanical properties and shape memory effect of polyurethane block-copolymers with planar or bent shape of hard segment. *Polymer* **44**, 3251-3258.

Yang, B., Huang, W. M.; Li, C. and Chor, J. H. (2005) Effects of moisture on the glass transition temperature of polyurethane shape memory polymer filled with nano-carbon powder. *Eur. Polym. J* **41**, 1123-1128.

Keller P N, Lake M S, Codell D et al. (2003) Development of elastic memory composite stiffeners for a flexible precision reflector. *AIAA Journal*, 2003-1977.

Gall K R, Lake M S.(2003)Development of a shoekless thermally aetuated release nut using elastic memory composite material .*AIAAJournal*, 2003-1582.

Tobushi, H., Hashimoto, T. Hayashi, S. and Yamada, E. (1997) Thermomechanical constitutive modeling in shape memory polymer of polyurethane series. Intel. *Mater. Syst. Struct* **8**, 711-718.

Tobushi, H., Okumura, K.; Hayashi, S. and Ito, N. (2001) Thermomechanical constitutive model of shape memory polymer. *Mech. Mater* **33**, 545-554.

Liu, Y. P., Gall K, Dunn M L et al. (2006) Thermomechanics of shape memory polymers: Uniaxial experiments and constitutive modeling. *Int.J.plastieity* **22(2)**, 279-313.

Zhou, B. Liu, Y. J. and Leng, J. S. (2009) Finite Element Analysis on ThermoMechanical Behavior of Styrene-Based Shape Memory Polymers. *Acta Polym. Sin* **6**, 525-529.

Shi G H, Yang Q S, He X Q, Kim M L.(2013) A three-dimensional constitutive equation and finite element method implementation for shape memory polymers. CMES: Computer Modeling in Engineering & Sciences. **90(5)**, 339-358.