Constitutive model for epoxy shape memory polymer with regulable phase transition temperature

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ABSTRACT

The epoxy shape memory polymer (SMP) with adjustable phase transition temperature is a kind of high-performance shape memory polymer, which can change its phase transition temperature and improve its mechanical properties through the process of photo curing. An epoxy SMP constitutive model combining phase transition and viscoelasticity is established by discretizing the epoxy SMP into several glass phase units and rubbery phase units in this paper. The model includes the viscoelastic constitutive equations of glass phase units and rubber phase units, the parameter expression during shape memory process, and material parameter equation during photocuring process. And the stress relaxation behavior of epoxy SMP at different temperatures and the change of material parameters during the photo-curing process are simulated numerically, and the simulation results perform consistency with the experimental data. The model can not only relate shape memory effect and phase transformation in physics but also better characterize the viscoelastic properties of SMP and predict the shape memory response of SMP.

Introduction

Shape memory polymer (SMP) is a kind of smart material, which can revert to the original shape from the deformed shape with the effect of outside stimulus like light [1], heat [2],
electromagnetic field [3], specific ion [4] and so on. Compared with general materials and composite materials [5], SMP has excellent deformation ability, biodegradability, biocompatibility, and well manufacturing performance, so that it has wide application prospect in biomedicine [6] and aerospace [7] and electronic devices [8]. The thermally responsive SMP is one of the research hotspots because it is easy to trigger shape memory process and easy to be controlled of the deformation.

In order to further expand the application areas of shape memory polymer and provide reference for structural design, synthetic and preparation, performance optimization, material selection, and processing, many constitutive models has been proposed in the past decades. Tobushi et al. [9] introduced a slip element into the linear viscoelastic model to describe the irrecoverable strain caused by internal friction, and first established a continuous thermodynamic model of shape memory polymer. Nguyen et. al. [10] established a thermodynamic viscoelastic constitutive model of amorphous SMP by incorporating nonlinear Adam-Gibbs relaxation model and modified Eyring viscous flow model into the continuum finite deformation thermoviscoelastic framework. Diani et. al. [11] established a three dimensional SMP finite strain thermoviscoelastic constitutive model based on the study of viscoelastic behavior of cross-linked SMP networks. Zhou et al. [12] established the three dimensions constitutive equation on the basis of the tensile experiment of styrene SMP, and carried out finite element numerical simulation analysis with the development function of finite element analysis software. Zhou et al. [13] established a macroscopic three dimensional constitutive model of SMP on the basis of solid mechanics and thermoviscoelastic theory. Balogun and Mo [14] established a three-dimensional isotropic constitutive model of SMP and conducted numerical simulation in the form of time dispersion. Guo et al. [15] established a thermodynamics viscoelastic constitutive model of shape memory polymer that can describe the behavior of typical thermodynamic cycle tests. Based on the phase transition theory of Liu et al. [16], Chen et al. [17] defined the frozen phase function to describe the freezing process of shape memory polymer and established a three dimensional nonlinear constitutive model of large deformation.

In recent years, in order to establish more reasonable and accurate constitutive models of SMP, a new type of mixed constitutive models of SMP are established by referring to solid phase transition theory and viscoelastic theory. Guo et al. [18] proposed a new constitutive model to explain the relationship between the phase transitions of SMP in the shape memory process and to study the thermodynamic behavior of shape memory polymers based on viscoelastic theory and phase transition theory. Guo et al. [19] established a three dimensional constitutive model that can accurately characterize the mechanical properties and shape recovery behavior of SMP based on the viscoelasticity theory and phase transition theory. In 2017, based on deformation gradient multiplication decomposition method, Li et al. [20] established a viscoelastic model to describe phase transition and viscoelasticity of SMP. On the basis of above work, Li et al. [21] further developed a shape memory polymer constitutive model combining phase transition and viscoelasticity. Zheng et al. [22] established the viscoelastic-plastic constitutive model of shape memory polymer based on the phase transition theory and solid mechanics theory. And then Zheng et al. [23] investigated the size effect and shape memory effect of the shape memory polymer micro beam, which combined the shape memory polymer constitutive model and modified couple stress theory.
There are still many challenges in the practical application and commercial production of SMP. Therefore, it is of great significance to develop high-performance shape memory polymers [24–28] and study their mechanical properties. Zheng [29] et. al. developed a two-component epoxy amine shape memory polymer system, which has excellent shape memory performance. Wang [30] et. al. used the epoxy shape memory polymer developed in literature [29] to conduct the experiment and studied the thermodynamic performance. Chen et. al. [31] synthesized a kind of shape memory epoxy with unsaturated double bond. The local modulus variation range of this material can be expanded and the phase transition temperature can be adjusted in the range of 40–70°C through the process of photo curing. Liu et al. [32] introduced the research progress of hydrogels and Huang et al. [33] presented some research gaps and new research directions for hydrogels and SMPs constitutive modes to provide the direction for the research of soft materials.

The constitutive model that can not only reflect the micro mechanism of shape memory, but also describe the thermodynamic characteristics of SMP will be established in this paper. The reasonable micro structure diagram and the SMP rheological presentation are proposed to interpret the micro mechanism of SMP during shape memory process. Based on the viscoelastic theory and phase transition theory, SMP is discretized into a number of glassy phase units and rubbery phase units, and their constitutive equations are established. In view of the mutual transformation behavior of glassy phase unit and rubbery phase unit in the process of temperature change, the parametric equations of epoxy SMP in the process of shape memory are proposed by introducing a volume fraction function. A model of SMP material parameters in the process of photo curing is established, because the photo curing process of SMP can not only regulate the glassy conversion temperature, but also expand the range of material parameters during the shape memory process. The numerical simulation for the viscoelastic behavior, material parameter during photo curing process, and mechanical behavior during shape memory process are conducted, which will give reference for the design of the high-performance SMP.

**Constitutive equations of SMP**

**1.1. Rheological representation**

In order to reflect the viscoelastic properties and the phase transition process of epoxy SMP, the proposed constitutive model is supposed to be composed of the rubbery phase element, glassy phase element and thermal element. As shown in (Figure 1), the thermal element, rubbery phase element and glassy phase element are in series to be generated as a whole, which is able to combine the phase transition process and viscoelastic properties. The mechanical properties of epoxy SMP vary during shape memory process, which can be explained by the transition between rubbery phase and glassy phase. The rubbery phase units transform to glassy phase units with the decreasing of the temperature and the glassy phase units transform to rubbery phase units with the rising of the temperature. According to the experimental results in literature [30], epoxy SMP present obvious stress relaxation and creep features with low temperature but they merely present feeble stress relaxation features with high temperature. Therefore, the rubbery
1.2. Viscoelastic constitutive equation

The viscoelastic equation for the glassy phase is deduced as

$$\varepsilon_{gi} = \frac{\sigma}{E_{gi}} + \int \frac{\sigma}{\eta_{gi}} dt + \frac{\sigma}{E_{gi}} \left( 1 - e^{-t/\tau_{gi}} \right)$$

which can be detailed as

$$\varepsilon_{gi} = \frac{\sigma}{E_{gi}} \left( \frac{E_{gi1} + E_{gi2}}{E_{gi2}} - \frac{E_{gi1}}{E_{gi2}} e^{-t/\tau_{gi}} \right) + \int \frac{\sigma}{\eta_{gi}} dt$$

where $E_{gi1}, E_{gi2}, \eta_{gi1}, \eta_{gi2}, \tau_{gi}$ are the elastic modulus, viscosity coefficients and relaxation time of glassy phase units in (Figure 1). The index $i$ means one of all the glassy phase units.

According to the theory of viscoelasticity, we can find that the rheological representation of glassy phase units consists of three parts, which are the spring model, the Kelvin model and the dashpot model. The total strain of glassy phase units includes elastic strain and viscous strain. As a whole, the elastic strain is produced by the spring model and the Kelvin model, considering the creep properties of Kelvin model, we can describe the elastic strain as

$$\varepsilon_{gi}^e = \frac{\sigma}{E_{gi}} \left( 1 - e^{-t/\tau_{gi}} \right)$$

where $E_{gi}$ is the elastic modulus of glassy phase units. The viscous strain is produced by the dashpot model, we can describe the elastic strain as

$$\varepsilon_{gi}^\nu = \int \frac{\sigma}{\eta_{gi}} dt$$

where $\eta_{gi}$ is the viscosity coefficient of glassy phase units. Thus, the total strain of glassy phase units, Eq. (2), can be simplified as
\[\varepsilon_{gi} = \varepsilon_{gj}^e + \varepsilon_{gj}^v = \frac{\sigma}{E_g} \left(1 - e^{-t/\tau_g}\right) + \int_0^t \frac{\sigma}{\eta_g} \, dt \quad (5)\]

The total strain of glassy phase is the sum of total strain of glassy phase units. When all the units of SMP are the glass phase units, we assume that the number of units is \(n\), we can describe the strain of glassy phase as

\[\varepsilon_g = \sum_{i=1}^{n} \varepsilon_{gi} = \frac{\sigma}{E_g} \left(1 - e^{-t/\tau_g}\right) + \int_0^t \frac{\sigma}{\eta_g} \, dt \quad (6)\]

where \(E_g\) is the elastic modulus of glassy phase, \(\tau_g\) the relaxation time of glassy phase, and \(\eta_g\) the viscosity coefficient of glassy phase.

Deducing the viscoelastic equation of the rubbery phase element according to (Figure 1), the strain of random rubbery phase unit is expressed as

\[\varepsilon_{ij} = \frac{\sigma}{E_{ij}} + \frac{\sigma}{E_{rj}} \left(1 - e^{-t/\tau_{ij}}\right) \quad (7)\]

namely,

\[\varepsilon_{rj} = \frac{\sigma}{E_{ij}} \left(\frac{E_{ij}}{E_{rj}} + \frac{E_{ij}}{E_{rj}} e^{-t/\tau_{ij}}\right) \quad (8)\]

where \(E_{r1}, E_{r2}\) are the elastic modulus of rubbery phase units and \(\tau_{ij}\) the relaxation time of rubbery phase units in (Figure 1). the index \(j\) means one of all the rubbery phase units.

According to the theory of viscoelasticity, we can find that the rheological representation of rubbery phase units consists of three parts, which are the spring model, the Kelvin model. The total strain of rubbery phase units includes elastic strain. The elastic strain is produced by the spring model and the Kelvin model, considering the creep properties of Kelvin model, we can describe total strain of rubbery phase units, Eq. (9), as

\[\varepsilon_{ij} = \frac{\sigma}{E_{ij}} \left(1 - e^{-t/\tau_{ij}}\right) \quad (9)\]

where \(E_{ri}\) is the elastic modulus of rubbery phase units and \(\tau_{ij}\) the relaxation time of rubbery phase units. When all the units of SMP are the rubbery phase units, we assume that the number of units is \(m\), the strain of the rubbery phase for epoxy SMP can be expressed as

\[\varepsilon_r = \sum_{j=1}^{m} \varepsilon_{ij} = \frac{\sigma}{E_r} \left(1 - e^{-t/\tau_r}\right) \quad (10)\]

where \(E_r\) is the elastic modulus of rubbery phase and \(\tau_r\) the relaxation time of rubbery phase.

The glassy phase and rubbery phase of the same specimen are under the same loading condition, so the strain can be expressed as

\[\varepsilon = f_1 \varepsilon_g + f_2 \varepsilon_r + \varepsilon_f \quad (11)\]
where $\varepsilon_g$, $\varepsilon_r$ are the strain of glassy phase and rubbery phase, respectively, and $f_1, f_2$ are the volume fractions of the glassy phase and rubbery phase in SMP, respectively. Based on the experiment data, the expression of $f_1$ and $f_2$ can be obtained as:

$$f_1 = \frac{1}{2} \left[ 1 + \sin \frac{\pi(T_g - T)}{20} \right]$$  \hspace{1cm} (12)

$$f_2 = 1 - \frac{1}{2} \left[ 1 + \sin \frac{\pi(T_g - T)}{20} \right]$$  \hspace{1cm} (13)

and

$$\varepsilon_T = a\Delta T$$  \hspace{1cm} (14)

is the thermal strain, where $a$ is the coefficient of thermal expansion.

Inserting the glassy phase strain expression, Eq. (6), rubbery phase strain expression, Eq. (10), and thermal strain expression, Eq. (14), into the total strain expression, Eq. (11), the detailed strain expression is obtained as

$$\varepsilon = f_1 \left[ \frac{\sigma}{E_g} (1 - e^{-t/\tau_g}) \right] + \left[ \frac{\alpha}{\eta_g} \right] dt + f_2 \left[ \frac{\sigma}{E_r} (1 - e^{-t/\tau_r}) \right] + a\Delta T$$  \hspace{1cm} (15)

Taking the derivative with respect to time and considering the viscosity of shape memory polymer we can obtain

$$\dot{\varepsilon} = \dot{\sigma} \left[ \frac{f_1}{E_g} (2 - e^{-\frac{t}{\tau_g}}) + \frac{f_2}{E_r} (2 - e^{-\frac{t}{\tau_r}}) \right] - \sigma \left( \frac{f_1}{\eta_g} + \frac{f_1}{E_g\tau_g} e^{-\frac{t}{\tau_g}} + \frac{f_2}{E_r\tau_r} e^{-\frac{t}{\tau_r}} \right) - f_1 \frac{\varepsilon}{\tau_g} + a\dot{T}$$  \hspace{1cm} (16)

where $E_g$ is the glassy phase elastic modulus, $E_r$ the rubbery phase elastic modulus, $\eta_g$ the glassy phase viscosity coefficient, $\tau_g$ the glassy phase relaxation time and $\tau$, the rubbery phase relaxation time.

**Material parameters equations of SMP**

**2.1. Phase transition mechanism**

(Figure 2) represents both the shape variation and phase transition during the shape memory process, which include the loading process with high temperature, cooling process, unloading process with low temperature, and shape recovery process. Epoxy SMP is in rubbery phase during the loading process with high temperature, and loading on the SMP will lead to rubbery phase deformation, $d$ $r$, as shown in (Figure 2). The rubbery phase units gradually transform into glassy phase units during the process of holding the deformation as constant and cooling the SMP that is named as cooling process. The cooling process results in the transition from rubbery phase deformation, $d$ $r$, to glassy phase deformation, $d$ $g$, and elastic deformation, $d$ $e$. The elastic deformation will disappear after the unloading process and the glassy phase deformation is locked, which results in the permanent shape of the SMP. Finally, the glassy phase units gradually transform to rubbery phase units with the rising of temperature during the shape recovery process, and the SMP reverts to the original shape. The relevant chemical structure of the SMP is described in detail in the literature [29].
2.2. Material parameter equation

The mechanical properties change with the variation of the temperature, which performs as the variation of the material parameters such as the elastic modulus and relaxation time. Therefore, establishing proper material parameter equations is the basis of illustrating the shape memory effect. According to the experimental data in literature [31], the material parameter equation is proposed as

\[
E = E_r + \frac{(E_g - E_r)p}{1 + e^{(T_g/2-T)h_1}} + \frac{(E_g - E_r)(1 - p)}{1 + e^{(T_g-T)h_2}}
\] (17)

where \(E_r\) is the elastic modulus of the rubbery phase at high temperature, \(E_g\) the elastic modulus of the glassy phase at low temperature, \(T_g\) the phase transition temperature, \(T\) the instantaneous temperature, \(p\) and \(h_1\) the corrected parameters. Similarly, the relaxation time is expressed as

\[
\tau = \tau_r + \frac{(\tau_g - \tau_r)p}{1 + e^{(T_g/2-T)h_1}} + \frac{(\tau_g - \tau_r)(1 - p)}{1 + e^{(T_g-T)h_2}}
\] (18)

where \(\tau_r\) and \(\tau_g\) are the relaxation time of the rubbery phase at high temperature and relaxation time of the glassy phase at low temperature, respectively. The viscosity coefficient is expressed as

\[
\eta = \eta_r + \frac{(\eta_g - \eta_r)p}{1 + e^{(T_g/2-T)h_1}} + \frac{(\eta_g - \eta_r)(1 - p)}{1 + e^{(T_g-T)h_2}}
\] (19)

where \(\eta_r\) and \(\eta_g\) are the viscosity coefficient of the rubbery phase at high temperature and viscosity coefficient of the glassy phase at low temperature, respectively.

The cross-linked network of SMP will change when exposed to ultraviolet, which due to the free radical polymerization or cationic polymerization. The material parameters vary
with the variation of the expose time, and the expression of the glassy transition temperature is obtained as

\[
T_g = \begin{cases} 
T_0 + At_e & t_e \leq t_p \\
T_0 + At_p & t_e > t_p 
\end{cases}
\]  
(20)

where \( T_0 \) is the glassy transition temperature without curing, \( t_e \) the exposed time, \( t_p \) the curing end time and \( A \) the curing rate obtained from the numerical fitting of the experiment data. Similarly, the elastic modulus during the curing process is expressed as

\[
E = E_0 + (E_n - E_0) \left(1 - \frac{1}{1 + \exp \left((t_e - (t_p - t_s))/t_s \right)}\right)
\]  
(21)

where \( E_0 \) is the elastic modulus without curing, \( E_n \) the elastic modulus after curing, \( t_s \) the curing relaxation time.

**Numerical examples**

We numerically simulate the stress relaxation behavior employing the material parameters of epoxy SMP in literature [30], and compare the numerical simulation results with the experimental data in literature [30]. The material parameters have been presented in (Table 1). At 20°C, the values of the relevant parameters are \( E_g \), \( T_g \) and \( \eta_g \). At 60°C, the values of the relevant parameters are \( E_n \), \( \tau_r \) and \( \eta_r \).

The comparison results between the numerical simulation and experimental data have been presented in (Figure 3), where the loading temperatures are held at 20°C, 40°C, and 60°C, respectively. The epoxy SMP are gradually loaded during the loading process firstly and then keep the load constant to obtain the stress relaxation data. It can be observed in (Figure 3) that the stress rises with loading time firstly and then occurs at different levels of decreasing, which results from the combination of the loading process and the viscoelastic properties of epoxy SMP.

It is obvious by comparing (Figure 3(a-c)) that the stress decreasing ranges rising with the reducing of loading temperature, which illustrates that the stress relaxation behavior is more obvious with lower loading temperature. Epoxy SMP is in the state of glassy phase under low loading temperature and presents obvious viscous features. And epoxy SMP presents nearly elastic features in the state of rubbery phase with high temperature. The phenomenon is in accordance with the rheological representation for the proposed constitutive model exhibited in (Figure 1).

In this section, the SMP material parameters after curing are computed to verify the veracity of the proposed parameter equations. The parameters in (Table 2) are requisite for modeling the SMP material parameters, which are available to be obtained through experimenting.

**Table 1.** Material parameters for simulating viscoelastic properties of epoxy SMP.

| T(°C) | \( T_g(°C) \) | \( E(\text{Mpa}) \) | \( \tau(\text{s}) \) | \( \eta(\text{Gpa·s}) \) | \( a \) |
|-------|---------------|----------------|----------------|----------------|------|
| 20    | 48            | 1120.9         | 85             | 116            | \( 4.5 \times 10^{-5} \) |
| 40    | 48            | 45.85          | 28             | 14             | \( 4.5 \times 10^{-5} \) |
| 60    | 48            | 2.36           | 10             | 2.03           | \( 2.76 \times 10^{-5} \) |
Figure 3. Curves of stress versus loading time under different temperature (a) Curves of stress versus loading time when the temperature is 20°C (b) Curves of stress versus loading time when the temperature is 40°C (c) Curves of stress versus loading time when the temperature is 60°C.

Table 2. Parameters for modeling SMP material parameters.

| $T_g$(°C) | $E_r$(MPa) | $E_g$(MPa) | $\Delta E$(MPa) | $t_p$(s) | $t_e$(s) | $A$ | $h_1$ | $p$ |
|-----------|------------|------------|-----------------|----------|---------|-----|-------|-----|
| 43        | 0.5        | 1200       | 7.5             | 150      | 32      | 0.19| −0.2  | 0.9 |
(Figure. 4) plots the curves of temperature versus elastic modulus, which are obtained from the numerical simulation and experiment data [17], respectively. It can be observed from comparing the numerical results and experiment data that the established parameter equation for the epoxy SMP has great performance in predicting the variation of the material parameters with the change of temperature.

(Figure.5) plots the curves of exposure time versus the phase transition temperature and the glassy phase elastic modulus, which are obtained from the numerical simulation and experimental data [31]. It can be observed from Figure 5(a) that the phase transition temperature rise with the increasing of the exposure time firstly, and then tend to be stable. This due to that the double bond polymerization finished after a period. It can be observed from Figure 5(b) that the glassy phase elastic modulus rise with the increasing of the exposure time nonlinearly and then gradually tend to be stable. It can be seen from (Figure 5) that the prediction results of the model established in this paper are in good agreement with the experimental results, and the model can well predict the variation of phase transition temperature and glassy phase elastic modulus with the changing of exposure time.

(Figure 6) plots the curves of temperature versus elastic modulus, which are obtained from the numerical simulation and experimental data [31], under different curing time of 60s, 120s, 240s, respectively. It is clear that the elastic modulus decrease with the increasing of the temperature and rise with the increasing of the exposure time. It can be observed that the variation amplitude of the elastic modulus with different temperatures increase with the rising of the exposure time, which indicates that the cured epoxy shape memory polymer will perform the shape memory effect more obviously. It is obvious that the prediction results of the proposed model are in good agreement with the experimental results [31], therefore the proposed model can predict the influence of the curing process on the epoxy shape memory polymer. According to the Eq. (17)-Eq. (19), the expressions of elastic modulus, relaxation time, and viscosity coefficient are
similar, thus, the trend of the relaxation time and viscosity parameters for the dashpots of the rheological components evolve with temperature are similar.

In order to verify the correctness of the proposed model during shape memory process, the numerical simulation results are compared with the experimental data [8] in below figures. The relevant parameters are shown in (Table 3).

(Figure. 7) plots the curves of stress versus strain during a shape memory cycle obtained from the proposed model and experimental data [8], and the red circles represent the experimental data while the black solid line represents the calculation results of the proposed model. The comparison results between the experimental data
and the numerical simulation results of the proposed model indicate that the numerical simulation results have a preferable propensity to the experimental data. The tiny difference of the stress maximum during the cooling process can be explained by the precision for controlling the temperature, because different cooling rate will cause stress difference due to the viscosity of the shape memory polymer. The curves have verified the accuracy and practical applicability of the proposed constitutive model which can describe the relation of stress versus strain clearly during the shape memory process.

(Figure. 8) plots the curves of temperature versus stress during a shape memory cycle obtained from the numerical simulation results of the proposed model and the experimental data [8]. The red circles represent the experimental data while the black solid line
represents the calculation results of the proposed model. It can be observed that a tiny difference between the numerical simulation results and experimental data occurs during the cooling process, process \( \textcircled{2} \). This phenomenon can be explained by the precision for controlling the temperature as the decreasing rate of the shape memory polymer temperature cannot be controlled to become completely identical with the theoretical condition. Therefore, the comparison results between the experimental data [8] and the numerical simulation results of the proposed model indicate that the numerical simulation results have a preferable propensity to the experimental data. The curves have verified the accuracy and practical applicability of the proposed constitutive model.

Figure 8. Curves for the relation of temperature versus stress during shape memory process.

Figure 9. Curves for the relation of temperature versus strain during shape memory process.
which can describe the relation of temperature versus stress clearly during the shape memory process.

(Figure 9) plots the curves of temperature versus strain during the shape memory process obtained from the numerical simulation results of the proposed model and the experimental data [8]. The red circles represent the experimental data while the black solid line represent the calculation results of the proposed model. It is obvious that the red circles in process ④ have waves which due to that the shape memory polymer temperature during the heating process is difficult to be the same with the theoretical conditions. This can also explain the tiny difference between the numerical simulation results and experimental data in process ④. Therefore, the comparison results between the experimental data [8] and the numerical simulation results of the proposed model indicate that the numerical simulation results have a preferable propensity to the experimental data. The curves have verified the accuracy and practical applicability of the proposed constitutive model which is able to describe the relation of temperature versus strain clearly during the shape memory process.

Conclusion

A constitutive model is proposed to describe the epoxy SMP with regulable phase transition temperature. The model considers the interpretation of the microstructure of the epoxy SMP using the schematic diagram of the microstructure of the SMP. And it is discretized into a number of glassy phase units and rubbery phase units to explain the micro mechanism of SMP during the shape memory process. Meanwhile, the model considers the viscoelasticity of the SMP, and uses the schematic diagram of the rheological presentation to present the viscoelasticity of the glassy phase and rubbery phase, respectively. According to the micro mechanism and rheological presentation of SMP, the volume fraction function is introduced to describe the transforming relationship with temperature of the glassy phase, rubbery phase, and their material parameter. Based on the experimental data [31], the material parameter function of the photo curing time is established to predict the variation of the material parameter during curing process. The numerical simulation for the loading process indicates that stress relaxation behavior is more obvious with lower loading temperature. The simulation results of the elastic modulus present that the variation amplitude of the elastic modulus with temperature increase with the rising of the curing time, which indicates that the cured epoxy shape memory polymer will perform shape memory effect more obviously. The comparison of the numerical simulation results with the experimental data for the stress relaxation, material parameters, and the mechanical behaviors during the shape memory process illustrates that the proposed model presents great performance in predicting the mechanical behavior of the cured SMP.

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