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A study of the nanoindentation creep behavior of $(La_{0.5}Ce_{0.5})_{65}Al_{10}Co_{25}$ metallic glass based on fractional differential rheological model

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ABSTRACT

A fractional differential rheological model was proposed to describe the nanoindentation creep behavior of metallic glasses (MGs) at room temperature. The model had been proved to not only include the conventional rheological model, but can be used to obtain the empirical formula that has been commonly used to characterize nanoindentation creep behavior of MGs. The reversible and irreversible parts of time-dependent deformations of $(La_{0.5}Ce_{0.5})_{65}Al_{10}Co_{25}$ metallic glass were obtained through nanoindentation creep experiments, and the results were used to investigate the effects of the creep load P_{max} and the loading rate $\dot{P}$ on the creep behavior and the variations of the model parameters. The results indicate that the fractional differential rheological model can describe the creep deformation quite well. Parameters analysis shows that viscoelastic part of creep and β relaxation has many common points. The variation of irreversible viscoplastic part of creep with creep load is the main cause of indentation size effect. The load rate $\dot{P}$ has effect on all components of creep deformation, which is reflected by the variations of the rheological model parameters. The viscosity and retardation time are related to the loading history as indicators that characterize the system's instantaneous viscosity at the onset of creep. The fractional order and creep stress exponent varies with loading rate have similar pattern, which could reflect the flowing ability upon the completion of the creep experiment.

1. Introduction

The mechanical behaviors of metallic glasses (MGs) either at ambient temperature or at elevated temperature has been the research focus of material science or condensed matter physics for decades [1–3]. Different components of the mechanical response at the temperatures close to or above the glass transition temperature T_g have been extensively investigated by experiments [4–8] and simulations [9–11] which have correlated local movements of structure with experimental phenomenon such as mechanical relaxation process *etc*. Whereas high temperature deformation is well described using rheological models that average the operation of many local atomic-scale events, inhomogeneous flow of MGs is less analytically tractable.

Of late, nanoindentation has been extensively used to investigate the mechanical response, typically the time-dependent behaviors of MGs [12–23], due to its superiority for observation of deformation mechanism under well-controlled conditions. Just as the deformation behavior of material can be portioned into elastic and plastic components, the time-dependent deformation can also be separated into viscoelastic and viscoplastic parts, respectively. However, only very limited analysis as to how the nanoindentation time-dependent deformation of MGs partitions into these has been conducted systematically yet [14,15]. On the other hand, many phenomenological models and approaches have been proposed for describing the nanoindentation creep process of MGs. The first one is the classical rheological model composed of a series of linear springs and dashpots, in which creep displacement can be expressed as a sum of exponential decays. It has been reported that the simplest Kelvin model consists of one spring and one dashpot connected in parallel (two fitting parameters) can fit the experimental results as well [12,13]. While several other researches confirmed that the two elements Kelvin model fails to describe creep of amorphous alloys and generalized Kelvin model with more elements should be used [13–18]. Yang [24] verified that the number of two-element Kelvin model in series should be at least three to fit the creep curves well in detail. Furthermore, there is still an open question that the microscopic interpretation of the fitting parameters varies from one theory to another. An alternative is the empirical equation introducing five fitting parameters originally proposed by Li and Ngan [25]. Good agreements between the creep experimental data and the fitting results have been reported in previous investigations

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[19–23], but unfortunately, the empirical law and fitting parameters do not have a mechanical interpretation at present.

Although the creep behaviors of MGs concerned with structural relaxation [13,14,20], loading rate, holding load [21,22] and compositions [15,22] have been qualitatively explained through the concepts of free volume, a coherent understanding of structure-creep relation still remains elusive. Recently, the presence of structural heterogeneity in nano- or micro-scale domain verified by experiments [26–28] and simulations [29,30] has been proposed to have pronounced effects on MGs deformation behaviors. The structural heterogeneity has supplied a foundation for a coherent and unified theory that cements an interrelation between the relaxation and deformation dynamics in MGs [31–35]. In an effort to well understand the creep nature of MGs, mechanism-based model considering the microstructural features of the materials is necessary to develop for describing and interpreting the different components of the creep deformation.

A fractional differential rheological model which can simulate the fractal characteristics of MGs structural heterogeneity [27,36–38] has been proposed in our previous works [39,40]. It has been proved that the model is more accurate for characterizing viscoelastic deformation behaviors of various MGs and the rheological parameters have good correlations with physical properties such as T_g and Poisson's ratio. In the present work, we attempt to develop the fractional differential rheological model to describe the creep behavior of metallic glasses at room temperature. The relationships of the model with the conventional rheological model and the empirical formula are investigated as well. The influences of the creep load and loading rate on the different creep components of $(La_{0.5}Ce_{0.5})_{65}Al_{10}Co_{25}$ metallic glass is analyzed. The correlation of the model parameters and related structural significance is discussed.

2. Rheological model

Fig. 1(b) and (c) schematically illustrates the flow event in MGs based on the concept of potential energy landscape (PEL) [7,41]. There are two flow models: the β-mode is the stochastically and reversible activated hopping events and the α-model is irreversible hopping events. The left panel in Fig. 1(b) represents STZ accommodating the flow during glass transition or plastic deformation which is confined within the elastic matrix and corresponds to the β relaxation process. When the applied strain is very limited or in the beginning of the elastic region, only little reversible flow units with smallest energy barriers and shortest intrinsic relaxation time can be activated. Enlightened by the simulation method as utilized by Ye et al. [12], a fractional Kelvin model on the left side of Fig. 1(a), which corresponds to reversible part of time-dependent deformation, was proposed due to the fractal distribution features of structural heterogeneity [39,40]. Under external applied energy action of temperature T or stress τ, the atomic mobility increases in the viscous region surrounded by the elastic matrix, and the viscosity decreases by inducing the decrease of energy barriers [42]. When T or τ reaches a critical threshold, the peripheral elastic matrix collapses, and the percolation of these flow units associates with the irreversible α relaxation process or plastic flow. At this point, the material displays glass transition or viscous flow behavior. Similarly, the fractal growth characteristics of microscopic heterogeneous structures become more pronounced after heat treatment [27] or yielding [37]. The fractional dash-pot on the right side of Fig. 1(a) corresponds to viscous flow events. The dotted line in Fig. 1(a) indicates the possible presence of inhomogeneous deformation during creep [43]. Based on these characteristics, viscoplastic body should be included in the rheological model theory. However, inhomogeneous creep (pop-in) has not been observed at room temperature in most creep experiments of MGs. Therefore, based on the deformation behaviors in the creeping

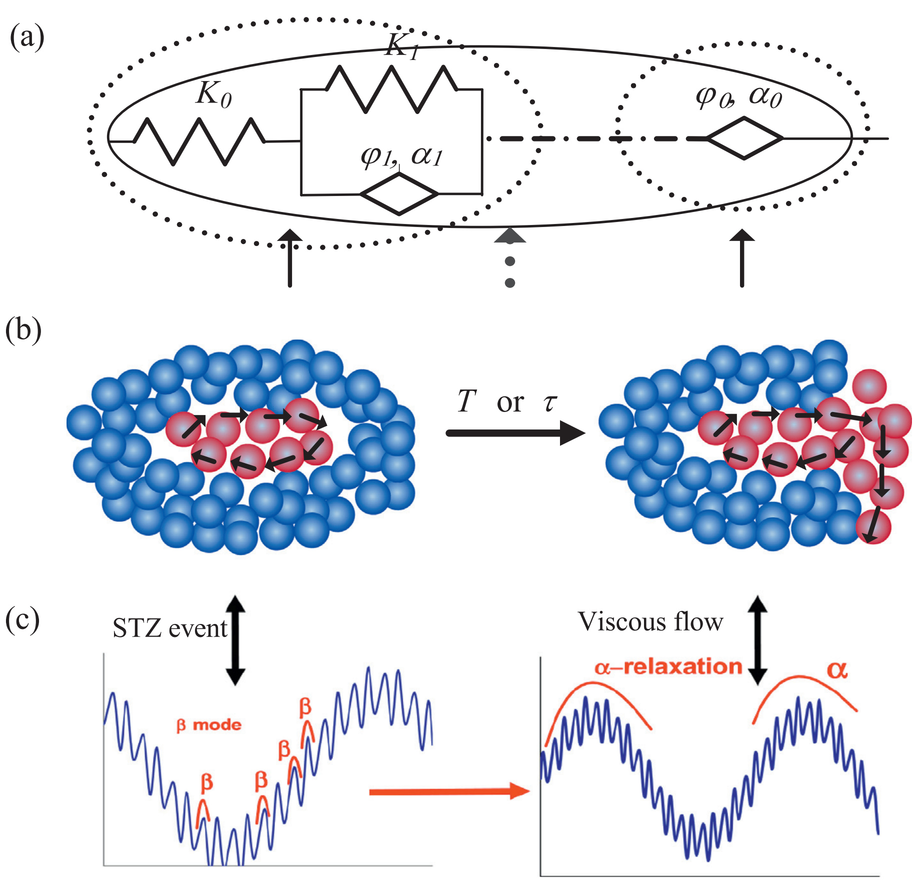

Fig. 1. Microstructure diagram of a dynamic event in a two-dimensional metallic glass (b), and the corresponding potential energy spectrum (c) [7] and rheological model (a).