Stress changed damping and associated transforming behavior in a Ti$_{48.5}$Ni$_{51.5}$ strain glass

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We report a changeable damping behavior by stress for Ti$_{48.5}$Ni$_{51.5}$ strain glass. This phenomenon originates from the change of its transforming route upon increasing stress. Under low stress, the damping behavior of Ti$_{48.5}$Ni$_{51.5}$ strain glass is due to the strain glass transition; however, the damping behavior under intermediate stress stems from a strain glass transition and a subsequent martensitic transition. More interestingly, under high stress, the damping behavior is caused by the martensitic transition. With a phenomenological model, the stress dependent transforming behavior of strain glass can be explained consistently. © 2011 American Institute of Physics. [doi:10.1063/1.3619830]

Damping (or internal friction) is defined as the capacity of a material to convert its mechanical energy of vibration into heat. It is an important functional property of materials for reducing the unwanted vibrations and acoustic noise. Very recently, a glass phenomenon called strain glass[1,2] was found in defect doped martensitic system. It results in a damping peak[1] with different damping mechanism from those of the so far discovered damping behaviors[3–6]. The strain glass undergoes a dynamic freezing transition (strain glass transition) of martensitic nano-domains (local ordered lattice strains), which serves as the damping mechanism to cause a broad damping (internal friction) peak and storage modulus dip with obvious frequency dispersion.[1] Recent studies further showed that strain glass can undergo a stress induced strain glass to martensite transition,[7,8] which results in the unexpected shape memory effect and superelasticity of the "non-martensitic" system. These findings make strain glass a practically important and physically interesting subject.

In this study, we will report a stress changed damping behavior of strain glass. We found that the characteristic of the internal friction peak of Ti$_{48.5}$Ni$_{51.5}$ strain glass is changed by an external bias stress. Moreover, the internal friction value of it is changed greatly by stress, which may lead to some applications. Our results show that the stress changed damping behavior in strain glass originates from the change of its transforming route with stress. We also further explained phenomenologically the origin of this stress dependent transforming behavior.

The Ti$_{48.5}$Ni$_{51.5}$ strain glass alloy samples were annealed at 1273 K for 1 h in evacuated quartz tubes and subsequently quenched into room-temperature water to obtain a homogenous supersaturated Ni-rich Ti-Ni solid solution. The bias stress dependent damping behavior (internal friction tan δ) and storage modulus for Ti$_{48.5}$Ni$_{51.5}$ strain glass were meas-

ured with a dynamic mechanical analyzer (DMA) of Q800 from TA Instruments. The dynamic mechanical measurement under bias stress was performed with a tensile fiber clamp, which can generate a constant bias stress superimposed on an oscillating measuring stress. The dynamic mechanical properties at zero bias stress were measured with a single cantilever clamp, because this measurement cannot be performed with the tensile fiber clamp, which always requires a preload.

The stress changed damping behavior of Ti$_{48.8}$Ni$_{51.5}$ strain glass is shown in Fig. 1, which is measured with a single frequency of 10 Hz. At low bias stress (0 MPa, 83 MPa, 139 MPa), the strain glass shows a broad internal friction peak. However, at intermediate bias stress (194 MPa, 306 MPa), it exhibits a broad internal friction peak at high temperature and a sharp one at low temperature. When the bias stress is further increased to high stress level (361 MPa, 385 MPa), it exhibits only one sharp peak. The internal friction value of the strain glass is also changed greatly by stress, as revealed in the inset of Fig. 1. At the temperature of 190 K, 220 K, and 250 K, the internal friction increases slowly with stress in the low stress
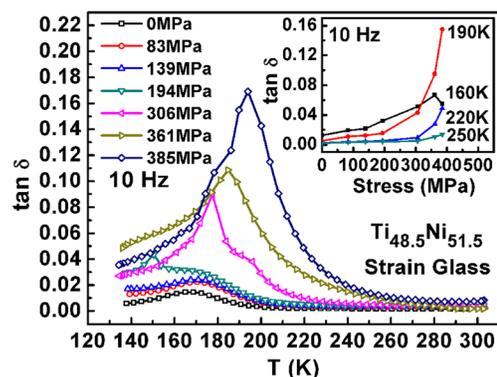

FIG. 1. (Color online) Stress changed damping behavior for Ti$_{48.5}$Ni$_{51.5}$ strain glass. The inset shows that the internal friction value of this sample can be changed greatly by bias stress in the temperature range from 160 K to 250 K. The testing frequency is 10 Hz.

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range but more steeply at higher stress level. However, the internal friction at 160 K shows similar increasing behavior up to a certain stress value and then decreases with stress. This indicates that there exists an upper limit stress value for the monotonous increase of the damping of strain glass.

The stress changed damping behavior of $Ti_{48.8}Ni_{51.5}$ strain glass is due to the change of its transforming mechanism with stress. This can be revealed from the bias stress dependence of its multi-frequency (0.4-10 Hz) data of internal friction and associated storage modulus (Fig. 2). As depicted in Fig. 2(a), at zero bias stress, the $Ti_{48.8}Ni_{51.5}$ strain glass exhibits broad internal friction peaks and storage modulus dips with frequency dispersion, which is the key feature of strain glass transition. The gradual freezing of the flipping process of martensitic nano-domains needs to overcome local energy barrier produced by point defects.[8,9] This leads to the mechanical energy dissipation and broad internal friction peak during strain glass transition. Its frequency-dependent behavior originates from wide size distribution of the nano-domains.[9]

Under a bias stress of 194 MPa, the $Ti_{48.8}Ni_{51.5}$ strain glass shows frequency dependent broad internal friction peaks and storage modulus dips at high temperature (Fig. 2(a)), caused by the freezing of martensitic nano-domains. However, it exhibits sharp internal friction peaks and storage modulus dips at low temperature and the temperature position of them does not change with frequency (Fig. 2(b)). This is the typical feature for the martensitic transition.[10] It was found that stress can induce a transition from B2 frozen strain glass into B19' martensite in $Ti_{48.8}Ni_{51.5}$ system.[7,8] However, Fig. 2(b) demonstrates the transition from frozen strain glass to martensite can also be induced by temperature with the help of certain bias stress. The sharp internal friction peak under 194 MPa stress is due to the movement of the phase boundaries between B19' martensitic variants and B2 frozen strain glass during its martensitic transition. The movement of twin boundaries has

little contribution to this sharp internal friction, because there are no twins inside the martensitic variants growing with a preferred orientation under stress.

When the bias stress increases to 385 MPa, the $Ti_{48.8}Ni_{51.5}$ strain glass exhibits only sharp internal friction peaks and storage modulus dips with typical features of martenstic transition[10] (Fig. 2(c)). Thus, this result manifests that the strain glass system undergoes the temperature induced martensitic transition rather than strain glass transition under sufficient large external stress. The sharp internal friction peak at high stress is also due to the movement of the phase boundaries between the B19' martensitic variants and B2 parent phase (or unfrozen state). The martensitic variants at 385 MPa stress grow larger than those at 194 MPa stress. So, the phase boundaries are larger for the case of 385 MPa stress, which leads to larger internal friction peak than that at 194 MPa stress.

The stress dependent internal friction value shown in the inset of Fig. 1 can be explained as the follows. In the low stress range, the slow increase of internal friction is due to that the size of martensitic nano-domains increases slowly with stress. When the stress increases further close to and above the critical stress for inducing martensite, the nano-domains grow rapidly to change into martensitic variants. This leads to the appearance of many phase boundaries and rapid increase of internal friction in the higher stress range. However, when the stress increases further to above a certain upper limit value, the number of the phase boundaries will decrease and become zero ultimately, because the stress induced strain glass to martensite transition tends to complete. Thus, the internal friction becomes decrease with stress in the very high stress range. This explains the peak shape of the stress dependent internal friction curve at 160 K. The stress dependent internal friction curves at 190 K, 220 K, and 250 K do not show peaks, which is because the corresponding upper limit stress values are higher than 385 MPa.

The above experimental results demonstrate that strain glass exhibits different transforming route at different stress level. Very interestingly, physically similar phenomenon was also found in ferroelectric glass – relaxor system.[11–15] It was found that the relaxor can undergo a glassy relaxor transition followed by a ferroelectric transition[12–14] or one ferroelectric transition[15] only when applied proper electrical field. Such a strong similarity for the field dependent transforming behavior between strain glass and relaxor indicates that *ferroic glass*[2] shares common origins.

The origin for the stress dependent transforming behavior in strain glass can be explained by its phenomenological model.[8] It can be expressed by a 2D free energy curve[8] shown in Fig. 3. The model has two important features. First, the free energy curve describes the instability of both strain glass and the "hidden" martensite. This is indicated by its bottom curve, i.e., the average free energy (F) vs the average-strain (ε) of the macroscopic strain state. The bottom curve shares similar shape to the Landau free energy curve of martensitic system, because the strain glass is derived from a normal martensitic system. Second, the free energy curve also described the average local energy barrier generated by point defects, which is indicated by the difference between upper dashed curve and the bottom curve. This is also essential for strain glass to explain its kinetic freezing
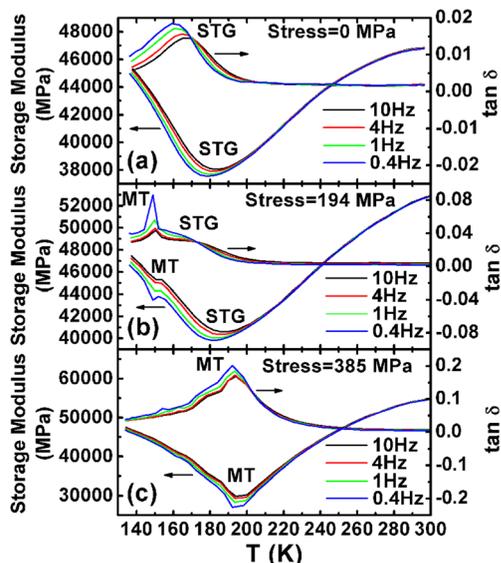

FIG. 2. (Color online) The dependence of internal friction and associated storage modulus of $Ti_{48.8}Ni_{51.5}$ strain glass on bias stress of (a) 0 MPa, (b) 194 MPa, and (c) 385 MPa. The results are measured with multi-frequency from 0.4 Hz to 10 Hz. They show that the change of the transforming route of strain glass upon stress leads to the stress changed damping behavior. The STG and MT in the figure represent the strain glass transition and the martensitic transition, respectively.
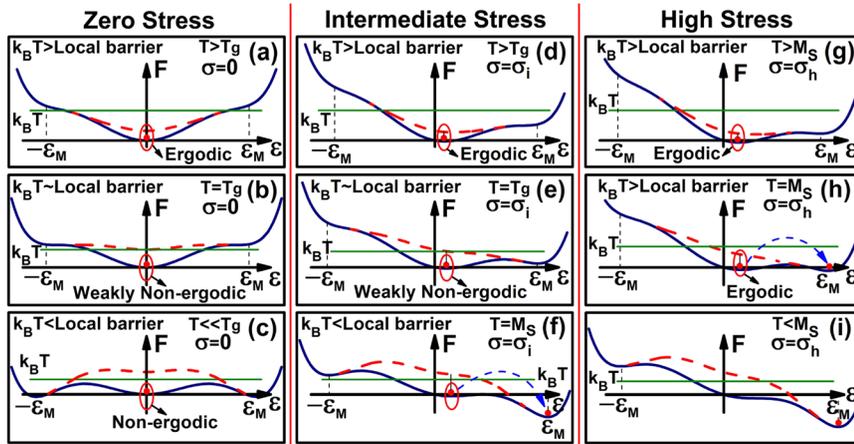
FIG. 3. (Color online) Temperature evolution of the free energy curve of strain glass at three different stress levels: (a)-(c) zero bias stress, (d)-(f) intermediate bias stress, and (g)-(i) high bias stress. It well explains the change of transforming route in strain glass system upon increasing bias stress.

transition. In the following, the free energy curve of strain glass will reveal that the stress dependent transforming route in this system stems from the competition between the thermodynamic driving force of martensitic state and the kinetic limitation of local energy barrier.

At zero stress ($\sigma = 0$), the driving force of the "hidden" martensite is not strong enough to overcome the kinetic limitation of local energy barrier, which leads to the strain glass transition. As shown in Fig. 3(a), the thermal activation $k_B T$ is much higher than the local barriers at $T > T_g$, the system stays in its ergodic unfrozen state. On cooling, the thermal activation decreases and the local barriers increase continuously. They become comparable at the freezing temperature T_g, which results in the breaking down of ergodicity and strain glass transition (Fig. 3(b)). On further cooling, the thermal activation becomes much lower than the local barrier (Fig. 3(c)) and the system cannot transform into the stable martensite state due to the strong kinetic limitation but freeze into the meta-stable strain glass state.

At intermediate stress σ_i, the kinetic limitation of local energy barrier and the driving force of martensite play a dominant role in sequence upon cooling, which leads to a strain glass transition at high temperature and a martensitic transition at low temperature. As depicted in Figs. 3(d)–3(f), the free energy curves of strain glass are titled by the intermediate bias stress σ_i in the whole temperature range. When cooling from high temperature ($T > T_g$), the strain glass undergoes a freezing transition from its ergodic unfrozen state (Fig. 3(d)) to its non-ergodic frozen state at T_g (Fig. 3(e)), before the martensitic state become stable. On further cooling, the $k_B T$ becomes smaller than the local barrier and decreases continuously; while the martensitic state becomes stable and its driving force increases continuously. Comparing with the stress free case, the driving force of martensite for the stressed system is much larger. Thus, on cooling to a certain temperature M_s ($< T_g$), the martensitic driving force can become large enough to overcome the kinetic limitation of local barrier. This leads to the martensitic transition from frozen strain glass to martensite at low temperature (Fig. 3(f)).

At high stress σ_h, the driving force of martensite is dominant comparing with the kinetic limitation, which causes the martensitic transition only in strain glass system. As shown in Figs. 3(g)–3(i), the free energy curve of strain glass is greatly tilted in the whole temperature range by the large stress σ_h. At high temperature range ($T > M_s$), the marten-

sitic state is meta-stable; the strain glass system stays in its ergodic unfrozen state (Fig. 3(g)). On cooling, the martensitic state becomes energetically stable at a temperature M_s before the thermal activation energy $k_B T$ decreases below the local barriers (Fig. 3(h)). Thus, the system undergoes martensitic transition directly at M_s rather than strain glass transition, since there is no kinetic limitation. It keeps stay in the stable martensitic state on further cooling (Fig. 3(i)).

In conclusion, we found a changeable damping behavior by stress in $Ti_{48.8}Ni_{51.5}$ strain glass. Such stress changed damping behavior of strain glass stems form its stress dependent transforming mechanism. The transforming route of strain glass changes in the sequence of strain glass transition, strain glass transition followed martensitic transition, and martensitic transition with increasing bias stress. The origin of the stress dependent transforming behavior is due to the competition between the thermodynamic driving force of martensitic state and the kinetic limitation of local energy barriers produced by point defects.

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