Inherent internal friction of B2 → R and R → B19' martensitic transformations in equiaxial TiNi shape memory alloy

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The inherent internal frictions IF_{B2-R}^R + IF_1 and IF_{R-B19'}^R + IF_1 of Ti_{50}Ni_{50} alloy are studied under isothermal conditions. The tanδ values of IF_{B2-R}^R + IF_1 and IF_{R-B19'}^R + IF_1 are both proportional to σ_{yield}^{1/2} and thus the damping mechanism of IF_{B2-R}^R + IF_1 and IF_{R-B19'}^R + IF_1 is related to the stress-assisted martensitic transformation and stress-assisted motions of twin boundary. The tanδ value of IF_{R-B19'}^R + IF_1 is larger than that of IF_{B2-R}^R + IF_1 because of the larger transformation strain and the greater twin boundaries associated with the R → B19' transformation.

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TiNi-based alloys exhibiting a thermoelastic martensitic transformation are known as the most important shape memory alloys (SMAs) with a good shape memory effect and superelasticity [1]. It has also been reported that TiNi SMAs perform a high level of mechanical damping and are suitable for energy dissipation applications [2–9]. The high damping obtained in TiNi SMAs is attributed to the movement of their twin boundaries [5]. In addition, the occurrence of R-phase can significantly soften the storage modulus E_0 and thus promote the damping capacity of TiNi SMAs [10].

It has been proposed that the internal friction of a first-order phase transformation can be decomposed into three terms: IF_{Tr}, IF_{PT}, and IF_1 [11–14]. The first term IF_{Tr} is a transitory internal friction which appears only at low frequency and non-zero heating/cooling rates. The second term IF_{PT} is the internal friction due to phase transformation, but it does not depend on the heating and cooling rates. The third term IF_1 is the intrinsic internal friction of the austenitic or martensitic phase.

All of the aforementioned reports focus on studies involving IF_{Tr} characteristics; however, the inherent internal friction (IF_{PT} + IF_1) of TiNi SMAs associated with the phase transformation under isothermal conditions has not been systematically investigated. In this study, equiaxial TiNi SMA was severely cold-rolled and then annealed at 650 °C for 2 min to obtain a two-stage B2 → R → B19' transformation during cooling. The damping capacity tanδ values of B2 → R → B19' martensitic transformation were measured using a dynamic mechanical analyzer (DMA) under isothermal conditions at different temperatures. The isothermal damping characteristics of B2 → R and R → B19' transformations are discussed.

Equiaxial Ti_{50}Ni_{50} alloy was prepared by conventional vacuum arc remelting. The as-melted ingot was hot-rolled at 850 °C into a 2 mm thick plate and then the plate was solution-treated at 850 °C for 2 h followed by quenching in water. Then, the plate was cold-rolled at room temperature along the hot-rolling direction and reached a final 30% thickness reduction. No annealing was conducted during cold-rolling so as to avoid the occurrence of recrystallization. Subsequently, the cold-rolled plate was cut into test specimens, sealed in an evacuated quartz tube and annealed at 650 °C for 2 min.

Transformation temperatures of cold-rolled and annealed specimens were determined by differential scanning calorimetry (DSC) using TA Q10 DSC equipment. The weight of the specimen used in DSC was about 30 mg and the heating and cooling rates were set at 10 °C/min. Specimens for DMA experiment were cut to the dimensions 40 × 5 × 1.26 mm³ along the rolling direction to eliminate the influence of rolling texture [15]. Tanδ and storage modulus E_0 were measured by...
TA 2980 DMA equipment using various cooling rates, amplitudes and frequencies. The inherent damping characteristics of the specimens were also investigated by DMA, but tested under isothermal conditions. The detailed procedure for the isothermal DMA test was conducted as follows. The specimen was initially cooled at a constant cooling rate, starting from 150 °C, and was kept isothermally for 30 min at the set temperature. After this, the specimen was heated to 150 °C to ensure it had returned to the B2 parent phase. Then, the specimen was cooled to another temperature and kept isothermally at that temperature for 30 min, and so on. During the isothermal conditions, the set temperature was chosen to be in between +80 °C and −80 °C in which the B2 → R → B19′ two-stage martensitic transformation can be covered.

Figure 1(a) and (b) shows the DSC and DMA curves, respectively, of 30% cold-rolled Ti50Ni50 alloy annealed at 650 °C for 2 min. In Figure 1(a), there are two transformation peaks, i.e. B2 → R and R → B19′, in the forward transformation and one B19′ → B2 transformation peak in the reverse. Figure 1(b) illustrates the tan δ and storage modulus E₀ curves of the specimen of Figure 1(a). Only the cooling curves with T = 1 °C/min, ω = 1 Hz and amplitude of σ₀ = 5 μm are shown in Figure 1(b) for clarity. Two peaks also appear in the tan δ curve which correspond to the B2 → R and R → B19′ transformation peaks observed in the DSC curve shown in Figure 1(a). The peak temperatures measured by DSC and DMA tests show a small shift due to different cooling rates and specimen sizes. Except for the aforementioned tan δ transformation peaks, an extra broad peak is also observed in Figure 1(b) at about −65 °C. This extra peak is known as the relaxation peak [4], but it is not observed in the DSC curve.

Figure 2 plots the tan δ values vs. isothermal interval (0–30 min) of Figure 1 specimen under isothermal conditions. In Figure 2, tan δ values of both the B2 → R and R → B19′ transformations decrease with increasing isothermal intervals and reach a steady value after 10–15 min. From the B2 → R and R → B19′ peaks, the decayed tan δ values during isothermal conditions represent the aforementioned transitory internal friction IFTr which is associated with the magnitude of T, and the steady tan δ values after 15 min of isothermal conditions are the inherent internal friction IFPT + IFI during phase transformation which is independent of T. At the same time, the IFTr of the B2 → R transformation under isothermal conditions, say IFTr, will collapse much faster than the IFTr of the R → B19′ transformation.

In order to investigate the inherent internal friction for the B2 → R and R → B19′ transformations, DMA tan δ tests under 30 min of isothermal conditions were conducted at different temperatures and the results are exhibited in Figure 3. The tan δ curve of Figure 1(b)
(measured at $\dot{T} = 1^\circ C/min$) is also plotted in Figure 3 for the purposes of comparison. When the isothermal temperature is set at about $30^\circ C$, as indicated by the arrow, an inherent tan $\delta$ peak corresponding to the $B_2 \rightarrow R$ transformation, i.e. $IF_{B_2}^{R \rightarrow B_{19}'} + IF_1$, appears with a tan $\delta$ value of 0.018. The temperature shift between the $IF_{B_2}^{R \rightarrow B_{19}'} + IF_1$ peak of Figure 3 and the $B_2 \rightarrow R$ transformation peak of Figure 1(b) is due to the cooling rate effect. When the isothermal temperature is set at about $5^\circ C$, as indicated by the double arrow, another inherent internal friction peak corresponding to the $R \rightarrow B_{19}'$ transformation, i.e. $IF_{R}^{B_{19}' \rightarrow B_{19}'} + IF_1$, appears with a tan $\delta$ value of 0.024.

Figure 4(a)–(c) shows the inherent tan $\delta$ curves measured under isothermal conditions at different $T$, $\nu$ and $\sigma_0$, respectively. As shown in Figure 4(a), all the damping behaviors during phase transformation are similar when measured at different $T$. Figure 5(a) plots the tan $\delta$ values of $IF_{PT}^{B_2 \rightarrow R} + IF_1$ and $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ as a function of $\dot{T}$ measured in Figure 4(a). This figure shows that the magnitudes of $IF_{PT} + IF_1$ measured at different $T$ are almost the same for the $B_2 \rightarrow R$ and $R \rightarrow B_{19}'$ transformations. It indicates that both $IF_{PT}^{B_2 \rightarrow R} + IF_1$ and $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ are independent of $T$. Additionally, from Figure 4(b) and (c), the tan $\delta$ values of $IF_{PT}^{B_2 \rightarrow R} + IF_1$ and $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ decrease with increasing $\nu$ but increase with increasing $\sigma_0$. Figure 5(b) plots the tan $\delta$ values of $IF_{PT}^{B_2 \rightarrow R} + IF_1$ and $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ as a function of $\nu$ measured in Figure 4(b). It makes clear that the relation between $IF_{PT} + IF_1$ and $\nu$ is non-linear; however, a linear relation between $IF_{PT} + IF_1$ and $1/\nu^{1/2}$ for both $IF_{PT}^{B_2 \rightarrow R} + IF_1$ and $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ is observed and shown in Figure 5(c). Figure 5(d) plots the tan $\delta$ values of $IF_{PT}^{B_2 \rightarrow R} + IF_1$ and $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ as a function of $\sigma_0$ measured in Figure 4(c). In Figure 5(d), the magnitudes of both $IF_{PT}^{B_2 \rightarrow R} + IF_1$ and $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ are linearly proportional to $\sigma_0$. Also in Figure 5, note that the tan $\delta$ values of $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ are always larger than those of $IF_{PT}^{B_2 \rightarrow R} + IF_1$ measured at various parameters.

As shown in Figure 1(b), for cold-rolled and annealed Ti$_{50}$Ni$_{50}$ SMA, there are two internal friction peaks corresponding to $B_2 \rightarrow R$ and $R \rightarrow B_{19}'$ transformations when the DMA test is conducted at constant $\dot{T}$. After the specimen is isothermal-treated (i.e. $\dot{T} = 0$) at peak temperatures of the $B_2 \rightarrow R$ and $R \rightarrow B_{19}'$ transformations, however, the tan $\delta$ values decrease and only $IF_{PT}^{B_2 \rightarrow R} + IF_1$ and $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ linger, as shown in Figure 3. In Figure 5(a), both $IF_{PT}^{B_2 \rightarrow R} + IF_1$ and $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ are independent of $\dot{T}$ and hence their damping mechanisms cannot be explained by Delorme’s model [11]. As illustrated in Figure 5(c) and (d), both the

Figure 4. The inherent tan $\delta$ curves measured under isothermal conditions at (a) $\nu = 1$ Hz and $\sigma_0 = 5$ μm with different $\dot{T}$, (b) at $\dot{T} = 1^\circ C/min$ and $\sigma_0 = 5$ μm with different $\nu$ and (c) at $\dot{T} = 1^\circ C/min$ and $\nu = 1$ Hz with different $\sigma_0$.

Figure 5. Tan $\delta$ values of $IF_{PT}^{B_2 \rightarrow R} + IF_1$ and $IF_{PT}^{R \rightarrow B_{19}'} + IF_1$ obtained in Figure 4 as a function of (a) $\dot{T}$, (b) $\nu$ (c) $1/\nu^{1/2}$ and (d) $\sigma_0$. 
tan\(\delta\) values of IF_{B2\rightarrow R} + IF_{PT} and IF_{R \rightarrow B19^\prime} + IF_{PT} are linearly proportional to \(\sigma_0/\nu^{1/2}\) when the applied \(\nu\) and \(\sigma_0\) are within 10 Hz and 15 \(\mu\)m, respectively. This feature is closely related to the formation of abundant twin boundaries and phase interfaces during the B2 \(\rightarrow\) R \(\rightarrow\) B19\(^{\prime}\) martensitic transformation. The amplitude of stress-assisted martensitic transformation can increasingly correspond with increasing \(\sigma_0\) and hence lead to a higher energy dissipation of IF_{PT}. This characteristic corresponds with Dejonghe’s model [12] which proposed that the tan\(\delta\) value of IF_{PT} is linearly proportional to the \(\sigma_0\) measured at \(T = 0\). Besides, the tan\(\delta\) value of IF_{PT} in R-phase and B19\(^{\prime}\) martensite which is corresponding to the stress-assisted motions of twin boundary also increases with increasing \(\sigma_0\). Consequently, we conclude that tan\(\delta\) values of IF_{B2\rightarrow R} + IF_{PT} and IF_{R \rightarrow B19^\prime} + IF_{PT} are linearly related to \(\sigma_0/\nu^{1/2}\) and independent of \(T\). This indicates that the damping mechanism of IF_{PT} + IF_{PT} is mainly generated from stress-assisted martensitic transformation and stress-assisted motions of twin boundary, generated from the stress-assisted martensitic transformation but not from thermal-induced martensitic transformation.

Meanwhile, as illustrated in Figures 4 and 5, the tan\(\delta\) values of IF_{R \rightarrow B19^\prime} + IF_{PT} are always larger than those of IF_{B2\rightarrow R} + IF_{PT} under the same conditions. This is owing to the transformation strain of R \(\rightarrow\) B19\(^{\prime}\) being larger than that of B2 \(\rightarrow\) R transformation [5]. Moreover, it is well known that there is an abundance of twin boundaries in the R-phase and B19\(^{\prime}\) martensite of TiNi SMAs. These twin boundaries can self-accommodate the strain which comes from the stress-induced movement of twin boundaries between the variants of R-phase or B19\(^{\prime}\) martensite. Both R-phase and transformed B19\(^{\prime}\) martensite subsist during the R \(\rightarrow\) B19\(^{\prime}\) transformation, while only transformed the R-phase appears during the B2 \(\rightarrow\) R transformation. Accordingly, more twin boundaries result in a greater dissipation of energy and a higher tan\(\delta\) peak during the R \(\rightarrow\) B19\(^{\prime}\) transformation.

In conclusion, both tan\(\delta\) values of inherent internal friction IF_{B2\rightarrow R} + IF_{PT} corresponding to the B2 \(\rightarrow\) R transformation and IF_{R \rightarrow B19^\prime} + IF_{PT} corresponding to the R \(\rightarrow\) B19\(^{\prime}\) transformation are linearly proportional to \(\sigma_0/\nu^{1/2}\) but independent of \(T\). The damping mechanism of IF_{B2\rightarrow R} + IF_{PT} and IF_{R \rightarrow B19^\prime} + IF_{PT} is mainly generated from the stress-assisted martensitic transformation and stress-assisted motions of twin boundary, but not from thermal-induced martensitic transformation. The tan\(\delta\) values of IF_{R \rightarrow B19^\prime} + IF_{PT} are always larger than those of IF_{B2\rightarrow R} + IF_{PT} due to the larger transformation strain and the greater amount of twin boundaries associated with R \(\rightarrow\) B19\(^{\prime}\) transformation.

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