Temperature dependence of elastic parameters and internal frictions for TiNi alloy

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Using ultrasonics, TiNi's acoustic characteristics are observed in order to fully understand its memory effects. Longitudinal and transverse wave velocities, eight kinds of elastic parameters, and dilational and shear internal frictions are simultaneously measured as functions of temperature in cooling and heating runs between 223 and 374 K in TiNi alloy, using an ultrasonic pulse method. An abrupt decrease from around 300 K in Young and shear moduli, Debye temperatures and internal friction peaks during a cooling run shows a premartensitic TiNi (II)/TiNi(III) transformation by electron-phonon coupling, accompanied by higher elasticity. A rapid decrease from around 250 K is observed in all four elastic moduli (Young, shear and bulk moduli, and Lamè parameter) and Debye temperature and internal friction peaks indicate a TiNi (III)/disordered complex TiNi martensitic transformation due to a volume-nonpreserving deformation.

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I. INTRODUCTION

The TiNi alloy, with a nearly equiatomic composition (hereafter referred as TiNi) is a typical metallic compound, whose peculiar memory effects and thermal anomalies have been studied extensively.¹⁻⁵ However, in addition to these properties, it is also important to observe TiNi's acoustic characteristics in order to fully understand its memory effects, especially since acoustic waves traveling through solids are known to be sensitive to the details of the atomic arrangement.⁶ Transverse wave velocity and damping offer useful information about the atomic displacement of TiNi. Our interest lies in simultaneously determining both dilational and shear internal frictions, all four elastic moduli, and other elastic parameters of TiNi when it is transformed martenistically in thermal processes. To accomplish this, we use ultrasonics, since it is the only method available for measurement of the high-frequency elastic parameters and losses, which arise from the atomic motion underlying lattice-relaxation processes.^{7–10} We also compare the ultrasonic method with the static method in terms of stress effects.

Using an ultrasonic pulse method that we developed we investigated longitudinal and transverse wave velocities, their anisotropy factor, elastic parameters (Young, shear, Bulk moduli, Lamè parameter, Poisson's ratio, and Debye temperature) and dilational and shear internal frictions for TiNi in cooling and heating runs of thermal cycles between 223 and 374 K in terms of the nonharmonity of energy potentials between atoms. We observed elastic changes in the crystal morphology associated with their atomic arrangement. As far as we know, no previous research has been done on simultaneous measurement of all the parameters for TiNi, using both longitudinal and transverse waves of the same frequency. Since the longitudinal wave interacts with the specimen's electrons and the transverse one lacks such interactions, simultaneous measurement provides information about structural changes, lattice instabilities and electronic contributions for TiNi. In particular, the temperature dependence of the shear and bulk moduli (or Lamè parameter) can explain the coupling of the conduction electrons to volumepreserving or volume-nonpreserving distortions, respectively.

For phonon studies of TiNi, neither longitudinal nor transverse wave velocities have been extensively studied as functions of temperature. Pace and Saunders¹¹ reported that there is a large increase in ultrasound absorption accompanied by a pronounced decrease in velocity of 10-, 12-, 15-, and 25-MHz longitudinal waves at around 333 K. They also observed the temperature dependence of the bulk modulus and Poisson's ratio near the transition temperature. Bradley¹² also reported that a longitudinal velocity with a frequency of 5 MHz reveals one valley between 306 and 345 K in the range from 263 to 403 K depending on temperature cycling, annealing, pressure, and time. In contrast to the ultrasound method, Wasilewski¹³ measured a relatively elastic modulus with longitudinal damping between 123 and 873 K, using a flexural resonance frequency method in the range between 0.6 and 50 kHz. He also observed a drop in the elastic modulus at around 300 K, and two peaks in damping at around 270 and 520 K. Hasiguti and Iwasaki¹⁴ also measured a shear modulus and transverse internal friction using a torsionpendulum method of about 1 Hz in the temperature range from 103 to 1073 K. They observed a valley at around 270 K for the elastic modulus, a group of several sharp peaks in the range from 223 to 313 K, and a large peak at 873 K.

Their data are in accordance with well-established dropping behaviors for elastic moduli and longitudinal wave damping in the temperature region near the transition temperature. However, their studies did not include a consecutive complex martensitic transformation of the TiNi alloy, i.e., TiNi(I) \rightarrow TiNi(II) \rightarrow TiNi(III) \rightarrow disorder complex TiNi \rightarrow TiNi(IV), since-high frequency properties cannot be measured by the resonance frequency and the torsion-pendulum methods. Nor have ultrasonic studies by Pace and Saunders¹¹ and Bradley¹² involved measurements of the transverse wave velocity.

II. ELASTIC PROPERTIES OF POLYCRYSTALS

When studying the properties of solids, it is useful to use the wave velocity anisotropy factor,¹⁵

$$A = \frac{\sqrt{3}V_s}{V_1}.$$
 (1)

This factor not only depends on the intrinsic characteristics of the materials, but also on the grain boundary orientation, preferential grain growth, residual stress, and deformation mode. For a material that is elastically isotropic, the factor A = 1. The degree of anisotropy of certain crystals at room temperature is shown by the following values of A: aluminum, 0.859; titanium, 0.855 (Ref. 16); iron, 1.515; (Ref. 17); alumina, 1.015; zirconia, 0.898 (Ref. 18); SiC, 1.098; (Ref. 19) polymethyl methacrylate, 0.856; (Ref. 17); polyimide, 0.825; (Ref. 8); and polycarbonate, 0.785.⁹ The smaller the factor, the softer the crystal.

Ultrasonic wave velocity measurements are related to the long-wavelength acoustic phonons,²⁰ enabling the elastic Debye temperature Θ_D to be obtained from;

$$\Theta_D = \left(\frac{h}{k}\right) \left(\frac{3N}{4\pi V}\right)^{1/3} V_m, \qquad (2)$$

where *h* and *k* take their usual values, *N* denotes the number of mass points in an average atomic volume *V*. The mean velocity V_m can be calculated by

$$V_m = \frac{1}{3} \left(\frac{1}{V_l^3} + \frac{2}{V_s^3} \right),$$
 (3)

Internal friction is a property which depends on the nonideal elastic behavior, (anelasticity), which yields information about the various stages of incipient crystallization such as strain relief, softening, rotation of side chains and micro-Brownian motion. However, no one has drawn a physical line between longitudinal and transverse wave frictions. Increasing rates of internal friction \mathbf{Q}_l^{-1} and \mathbf{Q}_s^{-1} at temperature *t* or longitudinal and transverse waves, respectively, were calculated using the ratio of logarithmic echo amplitude of the ultrasonic pulse wave at *t* to the corresponding amplitude measured at the lowest test temperature.²¹

III. EXPERIMENT

The hot wrought Ti-56 mass% Ni sample (0.09-mass % C, 0.09-mass % O) used in this study was first machined in the cubic form of $10 \times 10 \times 10$ mm by the wire cut method. Then it was annealed at 793 K for 1.8 ks in air and quenched in water. The density was precisely determined by the Archimedes method; the specimen was weighed in air and in distilled water. Longitudinal and transverse wave velocities, V_{I} and V_{S} , elastic parameters and internal friction values were accurately measured under a vacuum pressure of 0.1 MPa, using the ultrasonic pulse method with zero cross-time detection. The mode conversion method, which is used for measurement of many kinds of materials,^{7-10,16-19,21} could not be used in this study, because of the remarkable shear wave damping associated with occurrence of phase change. The PZT [Pb(Zr_xTi_{1-x})O] longitudinal and transverse wave resonators were directly cyanided onto the bottom and side of the specimen (Fig. 1). The measurement was first cooled from 298 to 223 K, then heated from 223 to 374 K, and then



FIG. 1. Schematic figure of a specimen with PZT longitudinal and transverse wave resonators.

cooled from 374 to 298 K, using cooling and heating a rate of approximately 0.08 K/s. Since the thermal expansion coefficient of TiNi has anomalies, its coefficient at room temperature²² $(1.05 \times 10^{-5}/\text{K})$ was used in the calculation of velocity and elastic parameters. The pulse was alternately applied to both resonators. To avoid propagation loss and lower resolution due to the high and low frequencies of ultrasonic waves, respectively, we used longitudinal and transverse wave PZT resonators at a frequency of 2.0 MHz.

IV. RESULTS

A. Temperature dependence of wave velocity

Sound velocity provides a sensitive tool for locating phase transitions, determining phase diagrams, and studying the phase-transition order. Figure 2 shows the longitudinal and transverse wave velocities as functions of temperature. The longitudinal velocity decreases with decreasing of temperature down to 285 K, and then reversibly increases down to 249 K. Subsequently it drops down to 238 K, and finally increases down to 223 K. This rapid decrease and increase indicate lattice softening and hardening, respectively. In heating run, the velocity first decreases up to 287 K and then rapidly rises up to about 317 K and finally saturates. The velocity fairly decreases with decreasing temperature in a temperature region from 374 to 300 K. The cyclic behavior of the transverse velocity is similar to that of the longitudinal one, except for one valley at around 290 K.

In comparison with the cyclic behaviors of cooling and heating runs, what appear as two separate transitions in cool-



FIG. 2. Temperature dependence of longitudinal and transverse wave velocities of TiNi.



FIG. 3. Acoustic wave anisotropy factor vs temperature in TiNi.

ing run merge into a single anomaly on heating. The salient point at around 235 K during cooling suggests an irreversible shear movement of atoms.²³ Indeed, the two abrupt decreases of both velocities from around 300 and 250 K in a cooling run could be due to electronic and morphological transitions associated with atomic rearrangement, respectively, as described later.

In order to investigate changes in crystal morphology, we show the temperature-dependent anisotropy factor in Fig. 3. The factor curve is similar to that of transverse wave velocity. Since the anisotropy curve definitely indicates a change in crystal morphology associated with bonding strength and atomic coordination, $^{8,10,16-19,21}$ there is the possibility that two remarkable transitions occur from around 300 and 250 K in the cooling run. The decimal fraction shows the inactivity of the dilational mode or activation of the shear mode in elastic solids. In this case it is the latter, assumed from the dominating factor of the transverse wave velocity for TiNi.

B. Temperature dependence of elastic parameters

Young, shear and bulk moduli and Lamè parameter are shown in Fig. 4, as functions of temperature. The Young and shear moduli in the cooling run show a sluggish decrease from 374 K and then a sudden drop from 300 K. After this they show a valley at 287 K and again increase up to saturation at 249 K, decrease down to 238 K and finally increase down to 223 K. In the heating run both moduli reveal a monotonic decrease from 223 K and then a sudden increase from 291 K and a subsequent saturation. In other words, we can see two- and one-step transitions for both moduli in cooling and heating runs, respectively. This shows that the transition occurred between 300 and 290 K in both runs is reversible, but the 238-K transition in the cooling run is irreversible.

In comparison with the static Young's modulus,²⁴ the curve in the temperature region over 353 K is almost consistent with one obtained by tensile strength method, but the value at 300 K is 2.5 times higher than the tensile one. For this reason, the elastic modulus measurement during martensitic transformation under stress application is remarkably



FIG. 4. Young's, shear, and bulk moduli, and the Lamè parameter of TiNi, as functions of temperature. Arrows show the direction of the change in temperature.

affected by the strain rate. Thus the static method is not necessarily the appropriate one for the elastic determination of TiNi.

On the other hand, the bulk modulus and Lamè parameter apparently show one-step softening: they first sluggishly decrease from 300 K and then rapidly decrease from 249 K before finally generally increasing from 238 to 223 K in the cooling run. In the heating run, both parameters decrease monotonically up to 287 K, then suddenly increase up to 300 K, and finally somewhat decrease up to 374 K. These results show that bulk modulus and Lamè parameter which are characterized by volume-nonpreserving distortion are sensitive for the 249-K transition in the cooling run, while the 300-K softening is mainly affected by Young's modulus. In a comparison of shear and bulk moduli, the latter is more sensitive for the 300-K softening.

Since a ratio E (Young's modulus)/K (bulk modulus) can be conveniently taken as a measure of elasticity,²⁵ the ratio is shown in Fig. 5, as a function of temperature. The curve resembles that of anisotropy factor in Fig. 3. In comparison with ratios (Table 1) of other representative materials,^{7-10,16-19,26,27} the curve in Fig. 5 shows the lowest value 0.4 at 287 K, which is lower than that of urethane rubber.

The temperature dependence of Poisson's ratio is presented in Fig. 6. Poisson's ratio presents one large and one small peaks and one valley at 287, 241, and 249 K in the cooling run, respectively, and one large peak at 295 K in the heating run. Since the increase in Poisson's ratio means a softening of the crystal, the 287- and 295-K peaks in the cooling and heating runs indicate the final points of the martenistic transformation, respectively. Furthermore, the decrease from 295 to 374 K on heating in a qualitative way can be interpreted as analogous to the case of rubber stretching.^{28,29}

The elastic Debye temperature curve (Fig. 7) also shows two drops from around 300 and 250 K in the cooling run. The decrease in the Debye temperature, i.e., the decrease in



FIG. 5. Temperature dependence of Young's modulus/bulk modulus of TiNi.

the maximum frequency allowed, leads to an increase in the effective atomic distance. Thus the two droppings could be derived from an expansion of the crystal lattice, associated with the martensitic transformation. On the other hand, the increase from 295 K in the heating run shows a shrinkage of the crystal lattice.

C. Temperature dependence of internal frictions

The temperature dependence of wave velocities and elastic parameters we observed gives clear evidence of electronic and crystallographic atomic contributions. In this section, internal friction curves for longitudinal and transverse waves are measured as a function of temperature (Fig. 8). The dilational friction shows two small peaks at 295 and 243 K in the cooling run, and a small peak at 293 K in the heating run. Sliding or rotation of crystals and a variation in the potential energy between a pair of atoms for metallic, organic, and inorganic materials causes the dilational friction.^{7–10,16–19,30} As we can see from the physics of dilational friction and the atomic structure of TiNi,³ the 293- and 243-K peaks are probably due to electron-phonon interaction³¹ and structural readjustment in the TiNi lattice, associated with premartensitic and martensitic transformations, respectively.

There are three peaks at 290, 264, and 233 K in the cooling run, and one peak characterizes the shear friction at 234 K and a drop from 297 K in the heating run. The 290-K peak arises due to electron-phonon interaction caused by premartensitic transformation. The 233-K peak may be related to the growth of surface relief.³² As regards the origin of the



FIG. 6. Poisson's ratio of TiNi as a function of temperature.

264-K peak, since there are so many possibilities, e.g., movements of point defect-pinned dislocations,⁶ twinning and deformed band regions,³³ lattice instability,³⁰ etc., we cannot make an assignment of the 264-K peak at the present time. The drop from 297 K is due to a relief of strain as the volume shrinks, as deduced from the physics of shear friction.^{7–10,16–19,21,30}

V. DISCUSSION

The acoustic wave velocity, which is mainly the phonon velocity, varies with temperature and pressure due to the nonharmonity of the potential between pairs of atoms. In the ultrasonic method, the pressure effect is negligible. On the other hand, the resonance frequency and the torsion-pendulum methods excludes high-frequency vibration. In TiNi, indeed, complicated behaviors have not been measured by nonultrasonic techniques.^{13,14} For this reason, there are three possibilities, i.e., sample, stress, and frequency dependencies.

Here it should be noted that the flexural vibration and the resonance frequency methods show the possibility of deterioration due to high-frequency fatigue.³⁴ By analogy we infer that the elastic moduli during a stress-induced martensitic transformation are influenced by dynamic vibrations in the resonance and the torsion-pendulum methods under stress application, although it is believed that the low-frequency resonance and the torsional oscillator measurements are as sensitive as ultrasonic methods to bulk temperature-dependent changes in elastic constants. Furthermore, as can be seen from a comparison with Young's modulus in Fig. 4, the static elastic modulus measurement during martensitic

TABLE I. A ratio of Young's modulus *E* to the bulk modulus *K*, for TiNi alloy, low carbon and stainless steels, (Ref. 17) Ti-6Al-4V Inconel (Ref. 16) Al_2O_3 , ZrO_2 , Si_3N_4 , (Ref. 18), fused quartz (Ref. 26) polymethyl methacrylate (Ref. 6) polyimide (Ref. 7) and urethane rubber (Ref. 27) at room temperature.

TiNi	Low carbon steel	Stainless steel	Ti-6Al-4V	Inconel 718	Al ₂ O ₃	ZrO ₂	Si ₃ N ₄	Fused quartz	Polymethyl methacrylate	Polyimide	Urethane rubber
0.60	1.261	1.249	1.225	1.657	1.560	1.103	2.137	1.974	1.025	0.910	0.595



FIG. 7. Temperature dependence of the Debye temperature of TiNi.

transformation is extremely affected by a stress-strain measurement under stress application such as the tensile strength method. Furthermore, we could not detect an ultrasonic frequency dependency, because of its remarkable shear wave damping. The sample dependency is not clear; it needs further investigation. Thus it would be desirable to investigate the stress-induced martensitic TiNi alloy with an ultrasonic method.

Since the ratio of α (=5 mm), the half size of the specimen, to λ (=2.4 and 0.88 mm in longitudinal and transverse waves, respectively), the wavelength, α/λ (=2.2 and 5.4 in longitudinal and transverse waves, respectively), at room temperature, is almost equal to and greater than 2.5, the measured pulse velocity approaches the bulk velocity in an infinite elastic medium.³⁵ This high ratio can enable us to distinguish a physical meaning between pure mode-III shear, defined as the shear modulus, and mixed mode-II–mode-III shear, designated as the Lamè parameter.³⁰ In the ultrasonic pulse method, the shear modulus is a function of the transverse wave velocity only, while the Lamè parameter is a function of both longitudinal and transverse waves.



FIG. 8. Temperature dependence of internal frictions for longitudinal and transverse waves of TiNi.

We know that the reversible martensitic transformation below 363 K in TiNi has been well accepted as a shapememory effect, and some features of the transformation are well known in terms of irreversible shear movement of atoms.^{36,37} TiNi is characterized by consecutive martensitic transformations, i.e., high-temperature TiNi(I) phase \rightarrow intermediate TiNi(II) phase \rightarrow low-temperature TiNi(III) \rightarrow TiNi(IV) phase.³ We discuss this well-known phenomenon in terms of the elastic parameters and internal frictions.

The abrupt decrease from around 300 and 250 K for the anisotropy factor of Fig. 3, the four elastic parameters of Fig. 4, the Debye temperature of Fig. 7, and the slight increase in the Poisson's ratio during the cooling run show two apparent transitions driven by a change in the electronic and mechanical properties of the system. From comparison of large changes in the bulk modulus with small changes in the shear modulus (Fig. 4), we can conclude that the softening from 300 K is due to the volume-nonpreserving distortion, accompanied by expansion, rather than the volume-preserving (uniaxial shear) distortions. This leads to a large coupling between the softening and the volume-nonpreserving distortions, associated with the electron-phonon interaction.^{23,30} Thus the softening can be also interpreted in terms of a reduction of the screening of lattice distortions due to the depletion of the carrier density, which couples strongly to acoustic phonons,³⁰ as is shown from shear friction in Fig. 8. On the other hand, the softening from 250 K would be dominated by the volume-preserving deformation,²¹ accompanied by a cooperative diffusionless shear movement and an atomic arrangement. The volume-preserving deformation is affected by the growth and/or creation of favorably oriented twins within the martensite.³² The coherency and mobility of martensite-parent boundaries and twin boundaries are the origin of the shape memory effect. To the best of our knowledge, little research ever reported any theoretical model that anticipated or predicted such a softening.

By measuring both VI and Vs in the same sample one can separate the effects of bulk modulus K and shear modulus G. The thermodynamics of the second-order phase transition yields the following anomalies in the bulk and shear moduli and the strain at the transition temperature.³⁸

$$\frac{\Delta K}{K} = -\frac{\Delta C_p}{T_c} K \left(\frac{\partial T_c}{\partial P}\right)^2,\tag{4}$$

$$\frac{\Delta G}{G} = T\Delta SG \left(\frac{1}{T_c} \frac{\partial^2 T_c}{\partial \sigma_s^2} \right), \tag{5}$$

$$\Delta \varepsilon_a = T \Delta S \left(\frac{1}{T_c} \frac{\partial T_c}{\partial \sigma_a} \right), \tag{6}$$

where ΔS is the entropy change, σ_S is the shear stress, ε_a is the generalized strain, and σ_a is the conjugate stress. For a mean-field transition, a discontinuity occurs at *T* in the bulk modulus itself and in the temperature derivatives of *G* and ε_a . Thus the 300-K peak is a second-order transition, as also reported in Ref. 23.

E/K in Fig. 5 showed the lowest value 0.4 at 287 K after premartensitic TiNi(II)/TiNi(III) transformation. This bears a

close resemblance to high elasticity of rubber.³⁹ Indeed, Wasilowski⁴⁰ observed a rubber like elasticity in compression test. The high elasticity corresponds to the lowest value of the Debye temperature in Fig. 7, leading to an increase in the effective atomic distance. This suggests that at least part of the valence electrons is in a conducting state between 300 and 287 K. Indeed, the authors of Ref. 23 pointed out the possibility of a "covalent" (localized)→" conduction" (delocalized) electronic transformation. This suggestion is in accord with the vast difference in the electric resistivity observed between TiNi(II) and TiNi(III), (Refs. 4 and 41) and elastic moduli in Fig. 4, Poisson's ratio in Fig. 6, and internal frictions in Fig. 8. For transition metals, the electric ideal resistivity ρ_i generally varies as T above 100 K indicating that the electron-phonon scattering has entered the Debye elastic range. On the other hand, the 250-K softening is martensitic transformation associated with atomic displacement, because ρ_l shows a T dependence above 120 K.⁴² Thus we can conclude that the highest elasticity in materials such as rubbers and the Mn₇₃Cu₂₀Ni₅Fe₂ alloy⁴³ is derived from the lattice softening associated with delocalized electrons.

The lattice softening is a typical phenomenon for ferroelectric transition materials such as PZT and SrTiO₃. The ferroelectric transition is associated with the lowering of the frequency of transverse-optic phonon modes and the consequent incipient lattice instability as the temperature approaches a critical temperature (T_c) .^{44,45} The monotonic decrease from around 370 K in the anisotropy factor and Debye temperature suggests prodromal stage before the premartensitic TiNi(ii) TiNi(III) transition.¹¹ This can also be deduced from decrease in shear friction of Fig. 8.

The Debye temperature (Fig. 7) also shows a somewhat similar behavior for elastic parameters (Fig. 4), and an acoustic anisotropy factor (Fig. 3) between 300 and 238 K. The 300 and 250-K drops in the Debye temperature reveal lattice vibration and volume changes associated with TiNi(II)/TiNi(III) and TiNi(III)/disordered complex TiNi(III) transformations, respectively. In addition, the 250-K dropping is a first-order transition. This can also be assumed from different behaviors of longitudinal and transverse wave velocities in cooling and heating runs of Fig. 2.

The consecutive complex martensitic transformation of the TiNi alloy can be well detected by dilational and shear PHYSICAL REVIEW B 65 224210

internal frictions. Since the elastic strain field of the longitudinal wave changes the local electronic concentration of atoms, phonon damping occurs when the longitudinal phonon crosses the movement of dislocation. As can be deduced from physical meanings of internal frictions,^{22,26} the premartenistic TiNi(II)/TiNi(III) transformation at the 297-K peak is probably related to the electron-phonon interaction. The 243-K peak in dilational friction could be due to displacement from the triclinic phase to martensitic one with a disordered complex structure.^{3,37} Judging from the abovementioned results and discussions, it is clear that the highfrequency elastic parameters and internal frictions are sensitive probes for evaluating the electronic contribution and the crystal morphology of TiNi, associated with the nonharmonity of the potential between atoms.

VI. CONCLUSION

Characteristic elastic and damping behaviors in TiNi with nearly equiatomic compositions were measured simultaneously as functions of temperature between 374 and 223 K. After an abrupt decrease in Young and shear moduli and Debye temperature at around 300 K, the 300-K lattice softening is strongly associated with volume-preserving distortions, and premartensitic TiNi(II)/TiNi(III) transformation by electron-phonon interaction. The conduction state in the softening leads to higher elasticity. On the other hand, the four elastic moduli and the Debye temperature decrease from around 250 K, showing volume-nonpreserving deformation, associated with a TiNi(III)/disordered complex TiNi martensitic transformation. The 293-and 243-K peaks in the dilational friction could be attributed to the electron-phonon interaction and the atomic shearing in the TiNi lattice, respectively. These elastic parameters are sensitive probes for evaluating the electronic contribution and crystal transformation of TiNi, associated with the nonharmonity of the potential between atoms.

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- ¹W. J. Marcinkowski, J. A. Gilfrich, and K. C. Wiley, J. Appl. Phys. **34**, 1467 (1963).
- ²G. R. Purdy and J. G. Pan, Trans. Metall. Soc. AIME **221**, 636 (1961).
- ³F. E. Wang, W. J. Buehler, and S. T. Pickart, J. Appl. Phys. **36**, 3232 (1965).
- ⁴D. P. Dautovich and G. R. Purdy, Can. Metall. Q. 4, 129 (1965).
- ⁵K. Otsuka, T. Sawamura, and K. Shimizu, Phys. Status Solidi A 5, 457 (1971).
- ⁶W. P. Mason, *Physical Acoustic and Properties of Solids* (Van Nostrand, Princeton NJ, 1958).
- ⁷M. Fukuhara and A. Sanpei, J. Polym. Sci. Part B: Polym. Phys. **33**, 1847 (1995).

- ⁸M. Fukuhara and A. Sanpei, J. Polym. Sci. Part B: Polym. Phys. **34**, 1579 (1996).
- ⁹M. Fukuhara and A. Sanpei, Jpn. J. Appl. Phys. 35, 3218 (1996).
- ¹⁰ M. Fukuhara, A. H. Matsui, and M. Takeyama, Chem. Phys. **258**, 97 (2000).
- ¹¹N. G. Pace and G. A. Saunders, Philos. Mag. 22, 73 (1970).
- ¹²D. Bradley, J. Acoust. Soc. Am. **37**, 700 (1965).
- ¹³R. J. Wasilewski, Trans. Metall. Soc. AIME **233**, 1691 (1965).
- ¹⁴R. R. Hasiguti and K. Iwasaki, J. Appl. Phys. **39**, 2182 (1968).
- ¹⁵C. F. Smith and W. B. Crandall, J. Am. Chem. Soc. 47, 624 (1964).
- ¹⁶M. Fukuhara and A. Sanpei, J. Mater. Sci. Lett. 12, 1122 (1993).
- ¹⁷M. Fukuhara and A. Sanpei, ISIJ Int. **33**, 508 (1993).
- ¹⁸M. Fukuhara and I. Yamauchi, J. Mater. Sci. 28, 4681 (1993).

TEMPERATURE DEPENDENCE OF ELASTIC ...

- ¹⁹M. Fukuhara and Y. Abe, J. Mater. Sci. Lett. **12**, 681 (1993).
- ²⁰O. L. Anderson, J. Phys. Chem. Solids **24**, 909 (1963).
- ²¹H. Numata and M. Fukuhara, Fusion Technol. **31**, 300 (1997).
- ²²M. Nishida and T. Honma, J. Phys. (Paris), Colloq. 43, C-225 (1982).
- ²³F. E. Wang, B. F. DeSavage, and W. J. Buehler, J. Appl. Phys. **39**, 2166 (1968).
- ²⁴ A. Nishitarumizu, K. Kunoo, N. Uda, K. Ono, T. Nagayama, and A. Matsuo, Technol. Rep. Kyushu Univ. **73**, 673 (2000).
- ²⁵R. Kubo, *Elasticity in Rubber* (Shokabo, Tokyo, 1996), p. 78 (in Japanese).
- ²⁶M. Fukuhara and A. Sampei, Jpn. J. Appl. Phys. **33**, 2890 (1994).
- ²⁷E. M. Fukuhara and K. Saito (unpublished).
- ²⁸E. Deeg, Glastech. Ber. **31**, 124 (1958).
- ²⁹S. Spinner and G. W. Cleek, J. Appl. Phys. **31**, 1407 (1960).
- ³⁰M. Fukuhara and A. Sanpei, Phys. Rev. B **49**, 13 099 (1994).
- ³¹K. Chandra and G. R. Purdy, J. Appl. Phys. **39**, 2176 (1968).
- ³²K. Otsuka, T. Sawamura, K. Shimizu, and L. M. Wayman, Metal Trans. 2, 2583 (1971).

- ³³ M. J. Marcinkowski, A. S. Sastri, and D. Koskimari, Philos. Mag. 18, 945 (1968).
- ³⁴D. E. Macdonald, Eng. Fract. Mech. 8, 17 (1976).
- ³⁵L. Y. Tu, J. N. Brennan, and J. A. Sauer, J. Acoust. Soc. Am. 27, 550 (1955).
- ³⁶L. R. Testardi, Phys. Rev. B 12, 3849 (1975).
- ³⁷R. G. De Lange and J. A. Zijderveld, J. Appl. Phys. **39**, 2195 (1968).
- ³⁸H. D. Landau and E. M. Lifshitz, *Statistical Physics* (Pergamon, London, 1959), p. 438.
- ³⁹R. Houwink, Trans. Farady. Soc. **32**, 131 (1936).
- ⁴⁰R. J. Wasilewski, Scr. Metall. 5, 131 (1971).
- ⁴¹G. D. Sandrock, A. J. Perkins, and R. F. Hekemann, Metall. Trans. 2, 2769 (1971).
- ⁴²J. F. Goff, J. Appl. Phys. **35**, 2919 (1964).
- ⁴³M. Fukuhara, F. Yin, and K. Kawahara (unpublished).
- ⁴⁴R. A. Cowley, Phys. Rev. A **134**, 981 (1964).
- ⁴⁵M. Fukuhara, A. S. Bhalla, and R. E. Newnham, Phys. Status Solidi A **122**, 677 (1990).