Effect of Cold-Rolling on Damping Characteristics of Multi-Component Al-12%Si Alloy Measured by Dynamic Mechanical Analyzer

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Compared to pure Al, a multi-component Al-12%Si alloy deteriorates the low-frequency damping capacity in the temperature regions of an athermal damping background and a high-temperature damping background (HTDB) because the dislocation motions during damping are impeded by the abundant silicon particles in Al-12%Si alloy. However, Al-12%Si alloy improves the creep resistance in the HTDB temperature region because of an increase in the activation energy of the HTDB. Severely cold-rolled Al-12%Si alloy significantly increases the damping capacity and hardness, and a conspicuous internal friction peak appears at approximately 270°C which corresponds to the occurrence of grain recrystallization. The effect of cold-rolling becomes insignificant after recrystallization occurs. [doi:10.2320/matertrans.M2012418]

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1. Introduction

Aluminum is an extremely useful engineering material because of its low density ($2.70 \times 10^3 \text{ kg/m}^3$) and good corrosion resistance in most industrial environments. Pure aluminum typically has low strength and poor wear resistance, but these properties can be improved by alloying other elements. Silicon is the most important alloying element in aluminum casting alloys, because it can increase fluidity in the molten state and ease feeding during solidification.¹⁾ Al-Si alloys also demonstrate good welding characteristics, high strength to weight ratio, good wear resistance, low coefficient of thermal expansion, high thermal conductivity, high corrosion resistance, etc., and so they are widely used in automobile and aerospace applications, such as engine blocks, cylinder liners, pistons, valve lifters, etc.²⁻⁴⁾

It has been reported that the mechanical properties of Al-Si alloys are influenced by the silicon content of the alloy.⁵⁻⁷⁾ Al-Si alloys with a Si content of more than 12 mass% normally consist of the primary silicon phase in the eutectic matrix.⁵⁾ Unfortunately, the primary silicon in hypereutectic Al-Si alloys is usually very coarse and results in poor mechanical properties.^{6,7)} In order to ensure good mechanical properties, it is therefore important to refine and modify the primary silicon in hypereutectic Al-Si alloys.^{8,9)} Grain refinement in hypereutectic Al-Si alloys has been achieved by using techniques such as increasing the solidification rate,¹⁰⁾ the semi-solid process,¹¹⁾ spray forming¹²⁾ and cold working.^{13,14)} In addition, precipitation-hardenable elements, mainly Mg, Cu and Ni, are also added to multi-component Al-Si alloys to improve their mechanical properties.¹⁻³⁾

The ability of a material to absorb energy during vibration is its internal friction or damping capacity. The ability to quell vibration is very important in engineering materials. The damping characteristics of pure aluminum have been investigated by Kê,^{15,16)} who stated that there was an internal

friction peak present in polycrystalline aluminum at approximately 300°C for a frequency of 1 Hz, which corresponds to the grain-boundary relaxation. Kê concluded that the viscous slip model provides a satisfactory description of grain-boundary relaxation in aluminum. Many studies have investigated the mechanical properties of Al alloys,¹⁷⁻²¹⁾ but studies of the damping properties of Al-Si alloys are rare. In this study, the damping characteristics of a multi-component hypereutectic Al-12%Si alloy are investigated and the results are compared with those for pure Al. Previous studies have reported that hypereutectic Al-Si alloys can be cold-worked to obtain a grain refinement structure.^{13,14)} However, the effect of cold-working on the damping properties of Al-Si alloys has not been reported. In order to determine the effect of cold-rolling on an alloy's damping properties, cold-rolled Al-12%Si specimens with a 70% reduction in thickness are also studied.

2. Experimental Procedures

Super purity 99.99 mass% aluminum was used as the pure Al in this study. The multi-component Al-12%Si alloy used in this study was prepared by the direct chill casting method. The cast ingot was homogenized and extruded at 350°C and then cut into plates of 6 mm thickness. The chemical composition of the as-extruded plate was determined using a glow-discharge emission spectrometer (LECO GDS-750A) and the results are shown in Table 1. From Table 1, it is seen that the multi-component Al-Si alloy used in this study contains mainly 12.3 mass% Si and has the alloyed elements Cu, Ni, Mg, etc. This alloy is abbreviated as Al-12%Si in this paper. Some of the as-extruded Al-12%Si plates were cut into plates of 20 mm width and 100 mm length and then

Table 1 Chemical composition (mass%) of as-extruded Al-12%Si alloy.

Element	Si	Mg	Fe	Cu	Ni	Ti	Al
Concentration (mass%)	12.3	0.70	0.30	2.35	2.30	0.025	Balance

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mechanically polished using a grinder/polisher to reduce their thickness to 5 mm for the further cold-rolling. The cold-rolling process was conducted at room temperature using a BDR150 × 200 2HI-MILL rolling machine manufactured by Daito Seiki Co., Japan. The rolling direction was along the direction of extrusion. In order to avoid cracking during cold-rolling, the reduction in the thickness of the plate was limited to 0.3 mm or less for each rolling pass. In this study, the total reduction in thickness was 70%, i.e., the plate thickness was reduced from 5 to 1.5 mm.

The damping capacity of Al–12%Si alloy was tested using a dynamic mechanical analyzer (DMA) (TA 2980 DMA) configured with a single cantilever and a liquid nitrogen cooling apparatus. The specimens for DMA measurements were cut from pure Al plate, as-extruded plate and 70% cold-rolled plate with dimension of 40 × 10 × 1.5 mm³. Each DMA specimen was heated from 0 to 300°C at a constant heating rate of 3°C/min and the testing frequency and strain amplitude were set at 0.1 to 5 Hz and 1×10^{-3} to 1×10^{-5} , respectively. For the microstructural examination, the specimens of Al–12%Si alloy were prepared using the standard metallographic procedure with Keller's reagent as the etching solution. Microstructural observations were performed using a LEO 1530 field emission scanning electron microscope (SEM) with an operating voltage of 15 kV and a Leica DM2500M optical microscope (OM). Microvickers hardness, Hv, was measured using a Mitutoyo HM hardness tester with an applied load and time of 100 g and 15 s, respectively. The Hv values were determined from the average of 10 measurements for each specimen.

3. Results and Discussion

3.1 The dependence of strain amplitude on the damping capacity of pure Al, as-extruded and cold-rolled Al–12%Si alloy

Figures 1(a) and 1(b) show the SEM secondary electron images of as-extruded and 70% cold-rolled Al–12%Si alloy, respectively. From Fig. 1, there are many Si particles in the α -Al matrix, some of which have been spalled during the preparation of the metallographic specimens. SEM energy dispersive spectroscopy (EDS) was conducted to measure the chemical compositions of the particles and the matrix shown in Fig. 1. The results of the SEM EDS experiments indicate that, most of the particles in Fig. 1 are Si-rich ones, but a few particles exhibit the hard intermetallic phases of aluminides with Cu, Ni, etc.²²⁾ It is notable that Fig. 1(b) shows the characteristics of mechanical fibering²³⁾ which is the evidence that the particles in Fig. 1 are harder and stronger than the matrix and they are essentially not deformed during cold-rolling.

Figure 2 plots the variation in internal friction (Q^{-1}) with the strain amplitude (ϵ) of pure Al, as-extruded and 70% cold-rolled Al–12%Si alloy measured at a constant frequency (1 Hz) and temperature (25°C). Figure 2 shows that the Q^{-1} values of the specimens are independent of or weakly dependent on the applied strain amplitude, ϵ , when ϵ is less than 3×10^{-5} and then increase significantly as ϵ increases. Accordingly, the damping capacity can be divided into two components,^{24,25)}

Fig. 1 Microstructural secondary electron images of (a) as-extruded and (b) 70% cold-rolled Al–12%Si alloy observed by SEM microscope.

Fig. 2 Damping capacities (Q^{-1}) versus strain amplitude (ϵ) for pure Al, as-extruded Al–12%Si alloy and 70% cold-rolled Al–12%Si alloy.

$$Q^{-1}(\epsilon) = Q_0^{-1} + Q_H^{-1}(\epsilon) \quad (1)$$

where Q_0^{-1} represents a damping capacity that is independent of or only weakly dependent on the strain amplitude, and $Q_H^{-1}(\epsilon)$ represents a damping capacity that increases as the strain amplitude increases. Figure 2 shows that the Q_0^{-1} value of pure Al is about 7.5×10^{-3} but that of Al–12%Si alloy with or without 70% cold-rolling is only 3×10^{-3} . These values are comparable to those for Mg alloys, such as Mg–

9.5Li–0.5Zn (LZ100) alloy ($Q_0^{-1} = 6 \times 10^{-3}$)²⁶⁾ and Mg–14.3Li–0.8Zn (LZ141) alloy ($Q_0^{-1} = 1.1 \times 10^{-2}$)²⁷⁾ but are slightly lower than those for pure Mg of 99.96 mass% purity (about 2.5×10^{-2})²⁵⁾ and Sn–Bi solder (3×10^{-2})²⁸⁾ measured at the same frequency and temperature. From Fig. 2, it is seen that the critical strain, which is defined as the transition strain from the strain amplitude independent region to the dependent region, is about 3×10^{-5} for both pure Al and Al–12%Si alloy. This value is also comparable to those for pure Mg (2×10^{-5})²⁵⁾ LZ100 alloy (3×10^{-5})²⁶⁾ and Sn–Bi solder (3.2×10^{-5})²⁸⁾ measured under the same condition. These characteristics indicate that the damping properties of pure Al and Al–12%Si alloy are similar to those of magnesium alloys at room temperature. Figure 2 also shows that the damping capacity, $Q_H^{-1}(\varepsilon)$, for pure Al is higher than that for Al–12%Si alloy with or without 70% cold-rolling when they are measured at the same ε value. This feature can be explained by the Granato–Lücke theory^{29,30)} since the dislocation motions during damping are impeded by the abundant silicon particles in Al–12%Si alloy.

3.2 Damping characteristics of pure Al and as-extruded Al–12%Si alloy

Figures 3(a) and 3(b) show the heating internal friction curves of Q^{-1} versus temperature for pure Al and as-extruded Al–12%Si alloy, respectively, measured at a constant amplitude (15 μm) and heating rate (3°C/min) but at different frequencies from 0.1 to 5 Hz. From Fig. 3, one can find that the damping capacity of each heating $Q^{-1}(T)$ curve increases gently at temperatures below $\approx 150^\circ\text{C}$ and then rises significantly until 300°C . The heating $Q^{-1}(T)$ curve for temperatures below $\approx 150^\circ\text{C}$ is termed an athermal damping background (ADB) and that for temperatures above $\approx 150^\circ\text{C}$, which exhibits an exponential damping background, is termed a high-temperature damping background (HTDB).^{31–33)} Normally, at an elevated temperature, say above one-half of the absolute melting temperature of the specimen, a HTDB shows a much higher damping capacity than that for an ADB. However, the damping capacity for an ADB becomes a more important indicative parameter when greater damping is required at room temperature. Compared to as-extruded Al–12%Si alloy, pure Al has a much higher damping capacity in both the ADB and HTDB temperature regions. This phenomenon indicates that the damping properties of pure Al are obviously deteriorated in an Al–12%Si specimen.

Figure 3(b) also shows that there is an internal friction peak at approximately 200°C (termed P_2 peak), as indicated by the arrow, in each heating $Q^{-1}(T)$ curve for as-extruded Al–12%Si alloy. This internal friction peak is also seen for pure Mg, Mg–Ni alloys with 6.2–22.6 mass% Ni²⁵⁾ and Mg–10.5Li–0.5Zn (LZ110) alloy.²⁶⁾ These studies reveal that this P_2 peak corresponds to the sliding of the grain boundaries. As shown in Fig. 3(b), the peak temperature of the P_2 peak gradually shifts from 187 to 220°C as the applied frequency increases from 0.1 to 5 Hz. This indicates that the P_2 peak exhibits a thermally activated relaxation characteristic. Consequently, the activation energy of the P_2 peak can be calculated from the Arrhenius equation:³⁴⁾

$$\tau = \tau_0 \exp(H/kT) \quad (2)$$

Fig. 3 Heating $Q^{-1}(T)$ curves for (a) pure Al and (b) as-extruded Al–12%Si alloy measured with different frequency from 0.1 to 5 Hz.

where τ and τ_0 are the relaxation time and relaxation constant, respectively, H is the activation energy, k is the Boltzmann constant and T is the absolute temperature. At the peak temperature, the relaxation time τ and the angular frequency ω satisfy the relationship $\tau\omega_p = 1$. Here, the angular frequency is defined as $\omega = 2\pi f$, where f is the applied frequency. Therefore, eq. (2) can be rewritten as

$$\omega_p^{-1} = \tau_0 \exp(H/kT_p) \quad (3)$$

where ω_p and T_p are the angular frequency and the absolute temperature at the peak temperature, respectively. Figure 4 plots the Arrhenius relationship for $\ln(\omega)$ versus $1000/T_p$ for the P_2 peak of as-extruded Al–12%Si alloy. From the slope of the fitting line in Fig. 4, the activation energy (H) of the P_2 peak can be calculated as $H_{P_2} = 2.11$ eV. This value is close to that for cold-rolled LZ141 alloy ($H_{P_2} = 2.07$ eV) previously reported.²⁷⁾ It is suggested that the sliding behavior of the grain boundaries should be very similar for Al–12%Si and LZ141 alloys.

3.3 High-temperature damping backgrounds (HTDBs) for pure Al and as-extruded Al–12%Si alloy

Figures 3(a) and 3(b) also show that the damping capacity in the HTDBs for pure Al and as-extruded Al–12%Si specimens increases as the frequency decreases at the same temperature. This feature indicates that the HTDBs for both pure Al and as-extruded Al–12%Si specimens cause a viscoelastic relaxation characteristic which can be described by Schoeck's equation:^{33,34)}

Fig. 4 Arrhenius relation of $\ln(\omega)$ versus $1000/T_p$ for the P_2 peak of as-extruded Al-12%Si alloy shown in Fig. 3(b).

$$Q^{-1}(T) = Q_{at}^{-1} + \frac{K}{[\omega \exp(H/kT)]^n} \quad (4)$$

where Q_{at}^{-1} is the damping capacity of the ADB, H is the activation energy, ω is the angular frequency ($\omega = 2\pi f$, f is the applied frequency), k is the Boltzmann constant, T is the absolute temperature and n and K are constants. It is more convenient to use the logarithmic representation of eq. (4) to analyze the damping of HTDBs:

$$\ln[Q^{-1}(T) - Q_{at}^{-1}] = \ln K - n \ln \omega - n \frac{H}{kT}. \quad (5)$$

Figure 5(a) shows the logarithmic plot of $\ln[Q^{-1}(T) - Q_{at}^{-1}]$ versus $\ln \omega$ for various temperatures from 250 to 290°C for the HTDB data for pure Al determined from Fig. 3(a). Here, the Q_{at}^{-1} is the stable damping capacity of the ADB for pure Al measured at 5 Hz and 0°C.³⁵⁾ As shown in Fig. 5(a), the plot of $\ln[Q^{-1}(T) - Q_{at}^{-1}]$ versus $\ln \omega$ shows a linear dependence which is in accordance with the expectation of viscoelastic relaxation behavior. From the slope of the fitting line shown in Fig. 5(a), the n value measured at each temperature can be determined. The n value determined in each temperature ranges from 0.19 to 0.22 and their mean value is 0.20. Figure 5(b) shows the plot for $\ln[Q^{-1}(T) - Q_{at}^{-1}]|_{\ln \omega=0}$ versus $1/T$ for pure Al in which the $\ln[Q^{-1}(T) - Q_{at}^{-1}]|_{\ln \omega=0}$ is the $\ln[Q^{-1}(T) - Q_{at}^{-1}]$ value measured at $\ln \omega \rightarrow 0$ for each fitting line in Fig. 5(a). From Fig. 5(b), the activation energy of the HTDB for pure Al can be determined from the slope of the fitting line as the value of $H = 0.87$ eV. The average n value and activation energy of the HTDB for pure Al after 70% cold-rolled are also determined in the same manner and are calculated as $n = 0.32$ and $H = 0.87$ eV, respectively. Figure 6(a) shows the logarithmic plot for $\ln[Q^{-1}(T) - Q_{at}^{-1}]$ versus $\ln \omega$ for the HTDB data for Al-12%Si alloy in Fig. 3(b). From Fig. 6(a), the mean n value for as-extruded Al-12%Si alloy can be determined as 0.33. Figure 6(b) plots $\ln[Q^{-1}(T) - Q_{at}^{-1}]|_{\ln \omega=0}$ versus $1/T$ for Al-12%Si alloy from the results of Fig. 6(a), so the activation energy of the HTDB for Al-12%Si alloy can be calculated as $H = 1.24$ eV. Table 2 lists the n and H values of the HTDBs for pure Al and Al-12%Si alloy as well as for other alloys, such as soft solders,^{28,36)}

Fig. 5 The plots of (a) $\ln[Q^{-1}(T) - Q_{at}^{-1}]$ versus $\ln \omega$ and (b) $\ln[Q^{-1}(T) - Q_{at}^{-1}]|_{\ln \omega=0}$ versus $1/T$ for pure Al.

Fig. 6 The plots of (a) $\ln[Q^{-1}(T) - Q_{at}^{-1}]$ versus $\ln \omega$ and (b) $\ln[Q^{-1}(T) - Q_{at}^{-1}]|_{\ln \omega=0}$ versus $1/T$ for as-extruded Al-12%Si alloy.

Table 2 The n value and activation energy H of the HTDB for pure Al, Al–12%Si alloy, soft solders,^{28,36)} magnesium alloys^{26,33,37,38)} and TiAl/NiAl intermetallics.³²⁾

		n	H (eV)
Al alloys (this study)	Pure Al	0.20	0.87
	Pure Al after 70% cold-rolled	0.32	0.99
	Al–12%Si alloy (as-extruded)	0.33	1.24
	Al–12%Si alloy after 70% cold-rolled (2nd-round)	0.29	1.26
Soft Solders	Pure Sn (99.99%) ³⁶⁾	0.12	0.98
	Pb–Sn Solder Alloy ³⁶⁾	0.23	0.43
	Sn–Bi Solder Alloy ²⁸⁾	0.32	0.77
	In–Sn Solder Alloy ²⁸⁾	0.29	0.27
Mg Alloys	As Hot-extruded AZ80 Alloy ³³⁾	0.27	1.69
	After 20% Cold-rolled AZ80 Alloy ³³⁾	0.31	1.37
	Mg–1Ca (mass%) Alloy ³⁷⁾	—	1.35
	Mg–9.5Li–0.5Zn (mass%) Alloy ²⁶⁾	—	0.59
	Mg–11.2Li–0.95Al–0.43Zn ³⁸⁾	0.21	0.75
TiAl and NiAl Intermetallics	Ti–46Al–9Nb (at%) ³²⁾	—	4.2–4.3
	Ti–46.5Al–4 (Cr, Nb, Ta, B) (at%) ³²⁾	—	3.8–3.9
	Ni _{49.5} Al _{50.5} Single Crystal ³²⁾	—	3.3

magnesium alloys^{26,33,37,38)} and TiAl/NiAl intermetallics,³²⁾ etc. Weller *et al.*^{32,39,40)} stated that the HTDB in TiAl alloys is associated with the diffusion-assisted climb of dislocations because the activation energies of TiAl alloys calculated from the high-temperature damping experiments and those from the creep experiments are comparable. Therefore, as demonstrated in Table 2, the diffusion-assisted climb of dislocations should be easier for Al alloys, soft solders and Mg alloys than for TiAl and NiAl intermetallics, since the H value of the former group is less than 2.0 eV while that of the latter group is greater than 3.0 eV. In addition, Table 2 also shows that the H value of the HTDB for Al–12%Si alloy is higher than that of pure Al. Although adding 12%Si into pure Al deteriorates its damping capacity significantly, as illustrated in Fig. 3, the abundant silicon and hard particles in the multi-component Al–12%Si alloy also simultaneously impede the dislocation climbing process and improve the creep resistance of the specimen at elevated temperatures.

3.4 The effect of cold-rolling on the damping characteristics of Al–12%Si alloy

In order to investigate the effect of cold-rolling on the mechanical and damping properties of Al–12%Si alloy, some as-extruded Al–12%Si specimens were cold-rolled at room temperature to produce a 70% reduction in thickness. Table 3 lists the mean Hv values for the specimens of pure Al, as-extruded and 70% cold-rolled Al–12%Si alloy. From Table 3, pure Al exhibits a low hardness of 32.1 Hv and this hardness increases to about 62.6 Hv for Al–12%Si alloy. Table 3 also shows that the hardness of Al–12%Si alloy is further increased to 105.6 Hv after 70% cold-rolling.

Figures 7(a) and 7(b) show the heating internal friction curves of Q^{-1} versus temperature for the 70% cold-rolled Al–12%Si specimen measured at a constant amplitude (15 μ m) and heating rate (3°C/min) but different frequencies from 0.1 to 5 Hz for the first-round and the second-round experiments,

Table 3 Microvickers hardness (Hv) of pure Al and Al–12%Si alloy with various conditions.

	Mean Hv
Pure Al	32.1 $\pm$ 0.6
As-extruded Al–12%Si	62.6 $\pm$ 1.1
Al–12%Si after 70% cold-rolled	105.6 $\pm$ 0.3
Al–12%Si after 70% cold-rolled and DMA measurement	58.2 $\pm$ 0.5

Fig. 7 Heating $Q^{-1}(T)$ curves for 70% cold-rolled Al–12%Si alloy with different frequency from 0.1 to 5 Hz measured at (a) first-round and (b) second-round.

respectively. From Fig. 7(a), the 70% cold-rolled Al–12%Si specimen has a much higher damping capacity than the as-extruded Al–12%Si alloy shown in Fig. 3(b). This feature can be explained by the abundant defects and dislocations that are introduced after the cold-rolling process. Figure 7(a) also reveals that cold-rolled Al–12%Si exhibits a conspicuous internal friction peak around 270°C. However, unlike the P_2 peak shown in Fig. 3(b), the peak temperature at approximately 270°C does not shift if the applied frequency is changed. From Fig. 7(b), the significant internal friction peak around 270°C disappears and the damping capacity $Q^{-1}(T)$ of each heating internal friction curve decreases to that seen in Fig. 3(b). In Fig. 7, the hardness of the DMA specimen tested at 1 Hz between the first-round and the second-round experiments was measured to be 58.2 Hv, as listed in Table 3. From Table 3, it is seen that the hardness of the 70% cold-rolled Al–12%Si specimen decreases significantly from 105.6 to 58.2 Hv after heating to 300°C during the DMA test.

Fig. 8 Microstructural OM image of 70% cold-rolled Al–12%Si alloy after the first round DMA test.

Figure 8 shows the OM observation of the 70% cold-rolled Al–12%Si alloy which has been conducted the first round DMA test. From Fig. 8, the recrystallized grain boundaries, as indicated by the arrows, can be observed obviously. Figure 8 also shows that there are abundant small intermetallic particles of aluminides with Cu, Ni, etc. in the matrix.²²⁾ According to the results of Figs. 7 and 8 and Table 3, it is concluded that the internal friction peak appearing around 270°C, as shown in Fig. 7(a), corresponds to the occurrence of grain recrystallization, instead of grain boundary relaxation or grain sliding effect. Figures 9(a) and 9(b) plot $\ln[Q^{-1}(T) - Q_{at}^{-1}]$ versus $\ln \omega$ and the $\ln[Q^{-1}(T) - Q_{at}^{-1}]|_{\ln \omega=0}$ versus $1/T$, respectively, for the HTDB data for the second-round cold-rolled Al–12%Si alloy in Fig. 7(b). From Figs. 9(a) and 8(b), the mean n and H values are determined as 0.29 and 1.26 eV, respectively. These values are also listed in Table 2 and are very similar to those for the as-extruded Al–12%Si alloy. This characteristic shows that the effect of cold-rolling, which leads to an increase in the hardness and damping capacity of Al–12%Si alloy, becomes insignificant after recrystallization occurs.

4. Conclusions

Pure Al has a higher low-frequency damping capacity than the multi-component Al–12%Si alloy in both the ADB and HTDB temperature regions because the dislocation motions during damping are impeded by the abundant silicon and hard particles. As-extruded Al–12%Si alloy demonstrates a P_2 peak in the heating $Q^{-1}(T)$ curve and its activation energy H is determined as 2.11 eV. The H values of the HTDBs for pure Al and as-extruded Al–12%Si alloy are calculated as 0.87 and 1.24 eV, respectively. This indicates that the creep resistance is improved at elevated temperatures in Al–12%Si alloy. Severely cold-rolled Al–12%Si alloy results in a higher damping capacity in the HTDB temperature region and a conspicuous internal friction peak around 270°C. This significant internal friction peak corresponds to the occurrence of grain recrystallization because it no longer exists when the same specimen is used in the second-round DMA experiment. The hardness of 70% cold-rolled Al–12%Si alloy obviously decreases from 105.6 to 58.2 Hv after the first-round DMA test. The effect of cold-rolling on the Al–

Fig. 9 The plots of (a) $\ln[Q^{-1}(T) - Q_{at}^{-1}]$ versus $\ln \omega$ and (b) $\ln[Q^{-1}(T) - Q_{at}^{-1}]|_{\ln \omega=0}$ versus $1/T$ for 70% cold-rolled Al–12%Si alloy measured at second-round.

12%Si specimen, which results in a better damping capacity and a higher hardness, becomes insignificant after recrystallization occurs.

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