STABLE NONLINEAR RELAXATIONS IN A MULTIPHASIC Al–Zn ALLOY①

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ABSTRACT

The experiments reveal the characteristics of stable damping in a multiphasic Al–Zn eutectoid alloy: (1) The whole damping (Q^{-1}) has the same dependence on measured frequency (f), i.e. $Q^{-1} \propto f^{-n}$, where n is a parameter and is independent of temperature. (2) In a low-temperature (low–T) and low-strain-amplitude (low–A_ε) region, $Q^{-1} = (B / f^n) \exp(-nH / kT)$, where B is a parameter, H the atomic diffusion activation energy, k Boltzmann's constant, and T the absolute temperature. n, $H_0 (= n\ H)$ and H are all independent of A_ε. The damping comes from an anelastic motion of the phase-interface. (3) In an intermediate region including a low–T and a high–A_ε, a middle–T and middle A_ε and a high–T and low–A_ε regions, the equation $Q^{-1} = (C / f^n) exp(-nH / kT)$ still holds, but the damping has a normal amplitude effect C, n, and H all vary with A_ε; the damping results from a nonlinear relaxation of phase-interface. (4) In a high–T and high-A_ε region, there is no longer a linear relationship between $\ln Q^{-1}$ and T^{-1}, whereas the relation $Q^{-1} \propto f^{-n}$ is still satisfied, where n increases as A_ε increases, and the damping has a normal amplitude effect but one which is weaker than that in the case (3). The damping may be attributed to another kind of nonlinear relaxation between phase-interfaces.

Key words: non-linear relaxations Al–Zn alloy damping

1 INTRODUCTION

Recently, Zhu[1] conducted the detailed study on the low frequency stable linear damping in a multiphasic Al–Zn eutectoid alloy which occur within a low-temperature and low-strain-amplititude region. It was found that the damping within this region obeys the equation $Q^{-1} = (B / f^n) \exp(-nH / kT)$, where H is the real process activation energy, B and n ($=0.21$) are two experimental parameters, f is the vibration frequency, k is the Boltzmann's constant and T the absolute temperature. A value of $H = 0.74$ eV was obtained, which is closely related to the viscosity during interface motion. Accordingly, a linear viscous interface motion model was put forward and can explain the experimental results as well. However, in order to meet the increasing industrial interest in superplasticity and newly-developed[2, 3] and potential[4] high damping applications of these kinds of multiphasic materials, great effort is still needed and should be focused on the understanding of nonlinear damping in the large strain amplitude range and the corresponding properties of non-linear motion properties of phase-interface. For this purpose, this paper systematically studied the stable nonlinear damping of the same alloy in a more higher strain amplitute and temperature region.

2 EXPERIMENT

Specimens of dimensions 60 mm × 4 mm × 1 mm were cut from an extruded piece of Al–60 at.–% Zn alloy. First, all specimens were

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solubilized in the solid state at 370 ℃ for 1 h and then quenched in water at a temperature of 26 ℃ . The stable damping was measured on a forced- vibration torsion pendulum of our own design as the temperature fell after each quenched and completely decomposed specimen was pre-annealed at 200 ℃ for 1 h in the chamber of the pendulum. The conditions for the specimens and experiments in this paper are identical to those in Ref.[1].

The damping Q^{-1} was calculated by using the equation $Q^{-1} = \tan\varphi$, where φ is defined as the phase angle at which the strain of the specimen lags the stress applied to the specimen. Because of the forced-vibration, the frequency of the periodic stress applied to the specimen was completely controlled by a low frequency signal generator but not, as in the case of a free-decay system, by the natural frequency of the specimen, which is dependent on the modulus of the specimen, and consequently by temperature. Thus the vibration frequency of the specimen in the forced-vibration system can be kept at a fixed value even during changing temperature measurement. Because of the forced-vibration, this pendulum permits a very convenient alternation and a very accurate determination of the vibration frequency as well as of the strain amplitude.

3 RESULTS AND DISCUSSION

(1) Division of Q_1^{-1}, Q_2^{-1} and Q_3^{-1}

Fig.1 shows the relation between damping $Q^{-1}$and strain amplitude (A_ε) at different temperature T (f= 1H$_z$). According to the dependence of Q^{-1}on A_ε, the damping Q^{-1}can be classified into three regions delimited by two dotted lines in Fig.1. Region I (called Q_1^{-1}) is located within a low-T and low–A_ε region, in which $\partial Q^{-1}/\partial A_\varepsilon = 0$, and the damping is independent of $A_\varepsilon$or is linear. Region II (called Q_2^{-1}) is located within an intermediate region including low–T and high–A_ε, middle–T and middle–A_ε, and high–T and low–A_ε regions, whithin which, $\partial Q^{-1}/\partial A_\varepsilon > 0$, $\partial^2 Q^{-1}/\partial A_\varepsilon^2 > 0$, and the damping has a normal strain amplitude effect. The region III (called Q_3^{-1}) is located within a high–T and high–A_ε region, in which, $\partial Q^{-1}/\partial A_\varepsilon > 0$, but $\partial^2 Q^{-1}/\partial A_\varepsilon^2 < 0$.

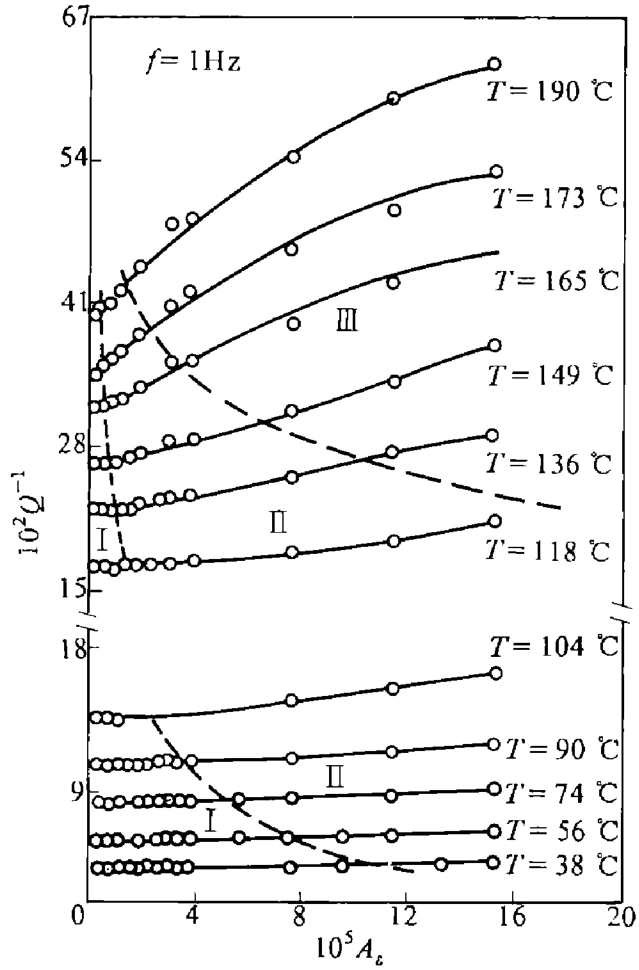

Fig. 1 Variation of damping with strain amplitude A_ε at different temperatures; (f= 1 Hz)

If we call the critical A_ε value at which the damping transits from Q_1^{-1} to Q_2^{-1} as A_ε, the critical A_ε value at which, $\partial^2 Q^{-1}/\partial A_\varepsilon^2 = 0$ or the damping transits from Q_2^{-1} to Q_3^{-1} as $A_{\varepsilon 2}$, from Fig.1 we find that, as T increases, both $A_{\varepsilon 1}$ and $A_{\varepsilon 2}$ for each curve decrease. If we plot the different pairs of $A_{\varepsilon 1}$, T and $A_{\varepsilon 2}$, T in a semilogarithmic form as shown in Fig.2, there are well-defined linear relationships between $\ln A_{\varepsilon 1}$ and T (called line a) and between $\ln A_{\varepsilon 2}$ and T (called line b), i.e.

$$A_{\varepsilon 1} \propto \exp(-c_1 T) \quad (1)$$

and

$$A_{\varepsilon 2} \propto \exp(-c_2 T) \quad (2)$$

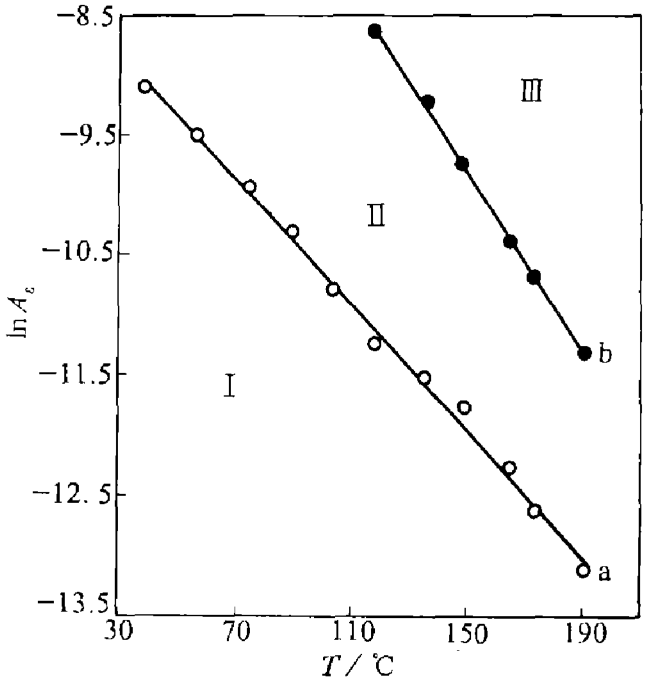

Fig. 2 Diagram of damping regions

(f= 1Hz)

(2) Dependence of the Whole Damping on f

Fig.3 shows the dependence of the whole damping on f. Fig.3 (a)~(d) are the four sets of plot of $\ln Q^{-1}$ against $\ln f$ for different T respectively corresponding to four constant levels of A_ε, i.e., 1.9×10^{-5}, 2.7×10^{-5}, 7.7×10^{-5}, 1.2×10^{-4}. It can be seen from Fig.3 that the relationship between $\ln Q^{-1}$ and $\ln f$ in the whole damping region as shown in Fig.1 is always linear, i.e.

$$\ln Q^{-1} \propto -n\ln f \quad (3)$$

and the slope's absolute value n is always independent of T but becomes larger with increasing A_ε in region Ⅱ and region Ⅲ. However within the region Ⅰ, n (=0.21) is independent A_ε[1].

In addition, the borders between the regions as in Fig.2, discussed in section (1), have different respondence to f. As indicated in Fig.2, as f increases, line b moves forwards high−T and high−A_ε regions while line a almost remains at the same position.

In the following, we will present and discuss individually the experimental results of different kinds of dampings, that is, Q_1^{-1}, Q_2^{-1} and Q_3^{-1} in different damping regions as described above.

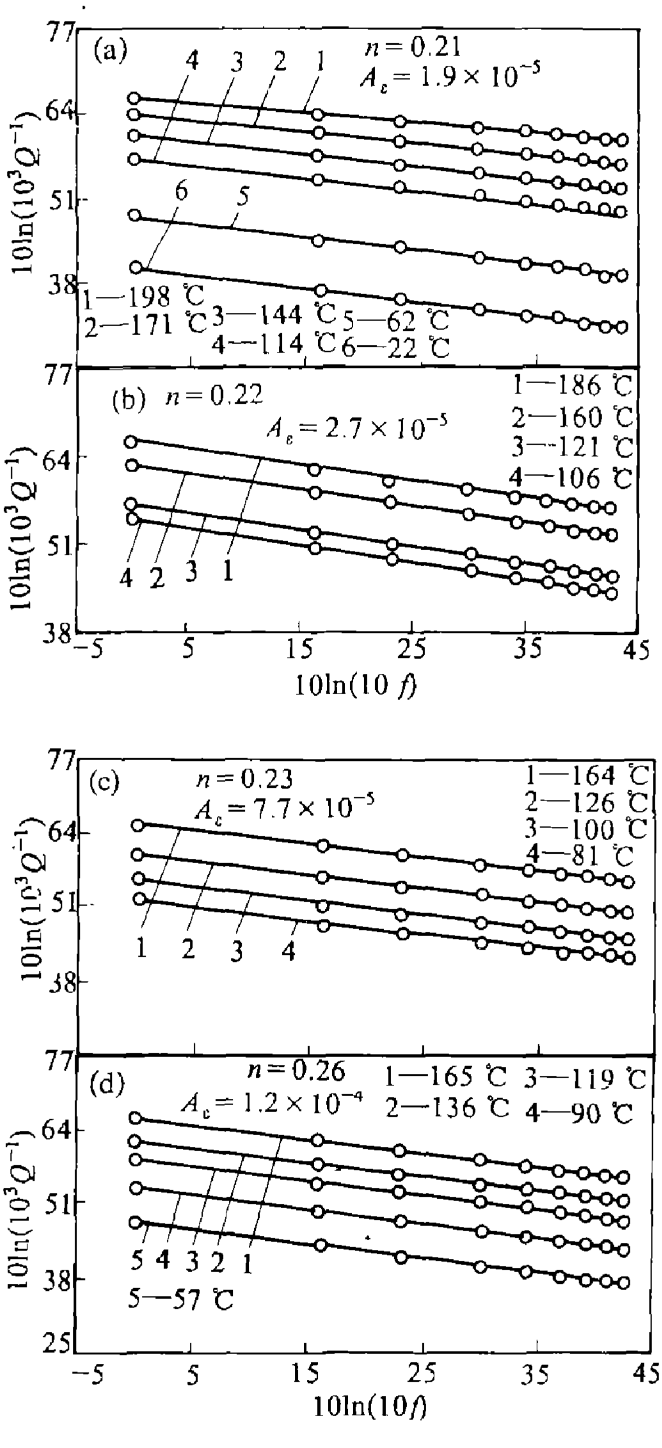

Fig. 3 Linear relation of $\ln Q^{-1}$ with $\ln f$ at different temperatures

(a)—$A_\varepsilon = 1.9\times 10^{-5}$, n=0.21; (b)—$A_\varepsilon = 2.7\times 10^{-5}$, n=0.22; (c)—$A_\varepsilon = 7.7\times 10^{-5}$, n=0.23; (d)—$A_\varepsilon = 1.2\times 10^{-4}$, n=0.26

(3) Damping Q_1^{-1}

The damping Q_1^{-1} in region Ⅰ is just what has been studied in the Ref. [1] and comes from a linear viscous phase interface motion. For comparion with and discussion on other region dampings afterward, we still present here briefly the characteristics of Q_1^{-1}. Q_1^{-1} has the following properties:

1) Q^{-1} is independent of A_ε, i.e. $\partial Q^{-1}/\partial A_\varepsilon = 0$ (see Fig.1 and Fig.4(a), in which the straight line $\ln Q^{-1}$— T^{-1} at different A_ε level remains at the same position);

2) as described in section (2), $\ln Q^{-1} \propto -n \ln f$ or $Q^{-1} \propto f^{n}$, $n=0.21$ (n is independent of T and of A_ε);

3) $Q^{-1} \propto \exp(-H_a / kT)$, with the apparent activation energy $H_a = 0.16$ eV (The value H_a is independent of A_ε and is measurable from the slope of the straight line $\ln Q^{-1}$— T^{-1} in Fig.4(a));

4) the real activation energy H_r associated with the relaxation process is obtained using equation $H_r = k\,(\mathrm{d}\ln f/\mathrm{d}T^{-1})$ by measuring the shift of the constant value of Q^{-1} with changing T and f. H_r is found to be 0.74 eV. Here, we have the relation $H_a = nH_r$.

The combination of items (1) to (4) leads to the final expression

$$Q^{-1} = (B/f^{n})\exp(-nH_r/kT) \tag{4}$$

In terms of the linear viscous phase-interface motion model suggested in Ref.[1], the parameters H_r, n, and H_a in expression (4) have their specific physical meanings and are very important to the understanding of motion properties of phase interface. In this model, the relation $H_a = nH_r$ $(0 < n \leqslant 1)$ is always obeyed. If the interface moves without restoring force or produces linear viscoelastic damping, we should have $n=1$. In contrast, if $n<1$, it means that interface moves with a certain restoring force and will produce anelastic damping. The model also indicated that the closer to zero the restoring force, the longer the relaxation time and closer to 1 the value of H_a/H_r or n. Therefore, the value of n can be employed as a paramenter to determine interface damping properties. In region I, $n=0.21$ which is less than 1, so the damping Q_1^{-1} originates from a linear viscous motion with a restoring force, that is, anelastic relaxation of the interface.

(4) Damping Q_2^{-1}

As mentioned above, the damping in the region Ⅱ is strongly strain amplitude–dependent, i.e., Q^{-1} increases rapidly as A_ε increases or $\partial Q^{-1}/\partial A_\varepsilon > 0$ and $\partial^2 Q^{-1}/\partial A_\varepsilon^2 > 0$. But we measured the relation between Q^{-1} and T and found that the semilogarithmic plot of $\ln Q^{-1}$—T^{-1} still gives a well-defined straight line as long as the measurement is carried out in region Ⅱ. We can see this fact in Fig.4 (b) and Fig.4 (c) which respectively represent the linear relations of $\ln Q^{-1}$—T^{-1} in a high–A_ε and low–T region and low–A_ε region dampings. If we assume that

$$\ln Q^{-1} \propto -H_a / kT \tag{5}$$

the value of the apparent activation energy H_a can be obtained from the slope of the straight line $\ln Q^{-1}$—T^{-1}. As the damping is A_ε–dependent, the value of H_a is also A_ε dependent. Namely H_a increases as A_ε increases. This can be seen in Fig.4 (b) and Fig.4 (c) in which the slopes of the straight line vary as A_ε changes.

However, the experiment reveals that, when the frequency increases, the different straight line $\ln Q^{-1}$— T^{-1} at different A_ε levels still shifts in different parallel manners to low temperature. The above results indicated that the amplitude-dependent damping in region Ⅱ is a kind of relaxation; here we call it type–Ⅱ nonlinear relaxation. This means that the damping can be expressed as a form (here not a Boltzmann superposition form of the distribution of interface motion processes due to their nonlinearity)

$$Q^{-1} = f(\omega\tau) \quad (\omega = 2\pi f). \tag{6}$$

If we assume that the nonlinear relaxation is a kind of phase interface (between equiaxial α and β phases of the alloy) controlled by interface atom diffusion processes, the relaxation time τ should obey the Arrhenius relation $\tau = \tau_0 \exp(H/kT)$. We can calculate from Eq. (6)[1] the real activation energy associated with the relaxaion process by the equation

$$H_r = -k[\partial \ln f / \partial(1/T)]_{Q^{-1}} \quad (7)$$

here H_r, in fact, is a weighted average $H_r(f, T)$ of the real activation energy in terms of Eq. (6) and Eq. (7)). In other words, H_r can be obtained using Eq.(7) by measuring the shift of constant value of Q^{-1} at constant A_ε level with change of T and f. With changing f, we have measured the shift of constant value of $Q^{-1}$and corresponding shifted value of T from a series of the shifted lines of each straight line $\ln Q^{-1}$—T^{-1} at each A_ε level as shown in Fig.4 (b, c).

Alternatively, with changing T, we also measured the shift of a constant value Q^{-1} and corresponding shifted value of f from a series of the shifted straight lines of $\ln Q^{-1}$—$\ln f$ as shown in Fig. 3 (b, c) at different A_ε level. In doing so, we have obtained a series of pairs of data, $\ln f$—T^{-1} for the damping at different A_ε level within the damping region Ⅱ. If we plot the relation $\ln f$—T^{-1} for different A_ε levels, there still exists a linear relation between $\ln f$ and T^{-1}. H_r can be calcuated from the slope of this linear relation. However, as mentioned above, when f changes, the different straight lines $\ln Q^{-1}$—T^{-1} in region Ⅱ at different A_ε levels shift in different parallel manners. In other words, for different straight line $\ln Q^{-1}$—T^{-1}, the value of slop of the the linear relation $\ln f$—T^{-1} or the values of H_r is different. That is, H_r decreases when A_ε increases. This can be found in Fig.5 in which line 1 and line 3 repectively stand for the linear relations of $\ln f$—T^{-1} when $A_\varepsilon = 1.9\times10^{-5}$ and 1.2×10^{-4} within a low-T range, but with different value of H_r, i.e., 0.74 and 0.69 eV. The fact that H_r decreases as A_ε increases indicates that during the nonlinear relaxation process, the stress field may help the localizd atom or defect jump over the energy barrier or the thermally-activated process.

We have measured many sets of the parameters H_r, H_a and n with different A_ε levels and found that although as A_ε increases, H_r decreases, H_a and n increase as indicated in the data results of Table 1. They always obey the equation

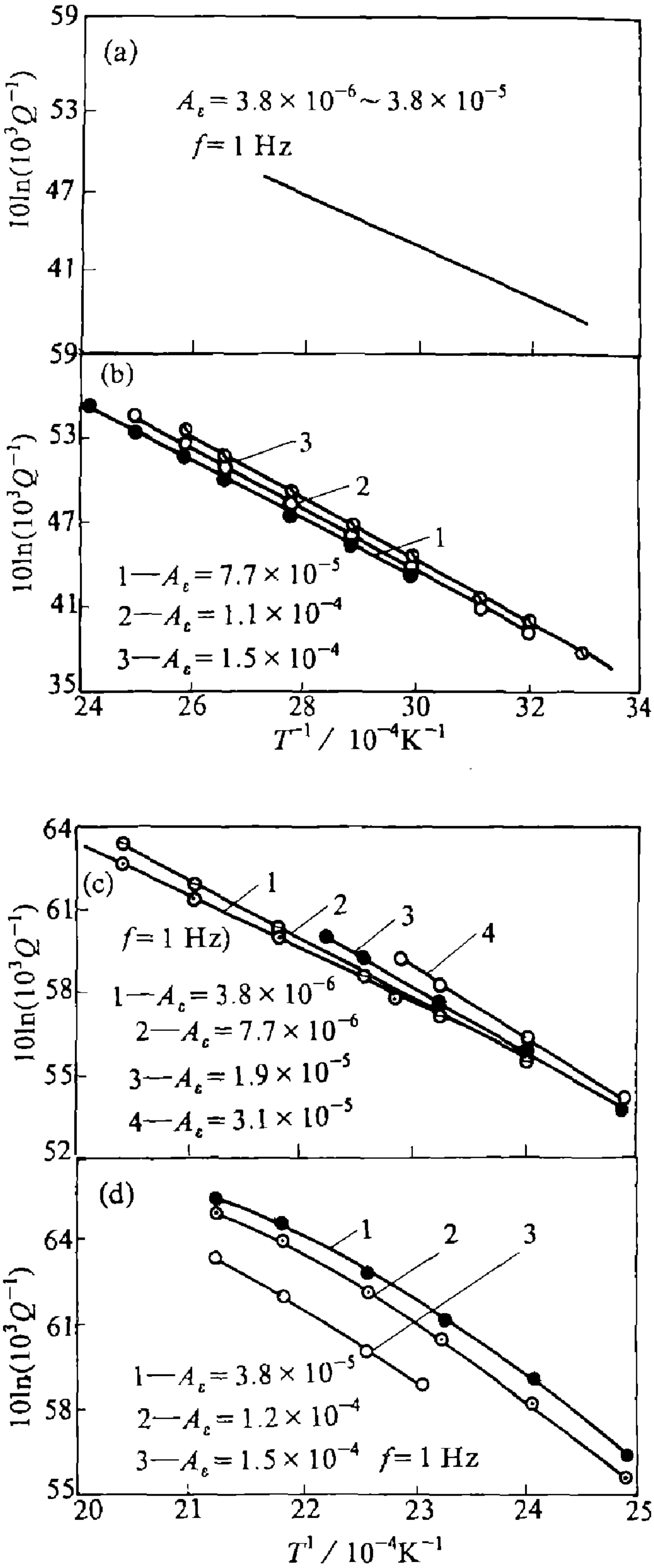

Fig. 4 Semilogarithmic plots of $\ln Q^{-1}$—T^{-1} with different A_ε and when $f = 1$ Hz in the different damping regions

(a)—low-T and low-$A_\varepsilon(Q_1^{-1})$; (b)—low-T and high-$A_\varepsilon(Q_2^{-1})$; (c)—high-T and low-$A_\varepsilon(Q_2^{-1})$; (d)—high-T and high-$A_\varepsilon(Q_3^{-1})$;

$$H_a = nH_r (0 < n \leqslant 1). \quad (8)$$

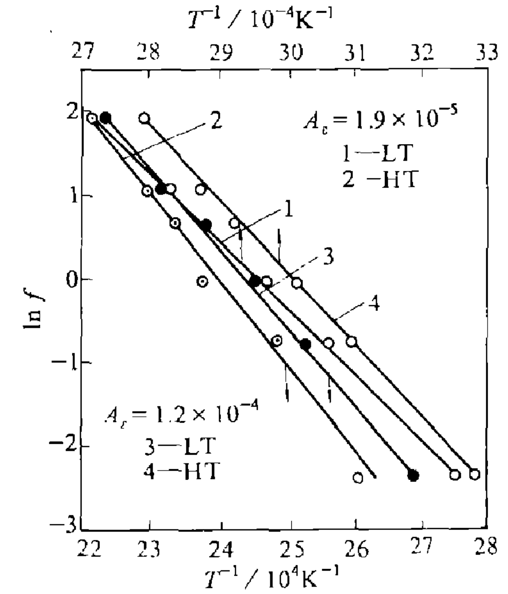

Fig. 5 Linear plots of ln$f$—T^{-1} for a shift at constant level of Q^{-1} in different damping regions

1—$A_\varepsilon = 1.9 \times 10^{-5}$, low—$T$, $H_r = 0.74$ eV, (10ln (1000 Q^{-1}) = 42.5);

2—$A_\varepsilon = 1.9 \times 10^{-5}$, high—$T$, $H_r = 0.92$ eV; (10ln (1000Q^{-1}) = 56.5)T^{-1};

3—$A_\varepsilon = 1.2 \times 10^{-4}$, low—$T$, $H_r = 0.69$ eV, (10ln (1000Q^{-1}) = 42.5)T_{-1};

4—$A_\varepsilon = 1.2 \times 10^{-4}$, high—$T$, $H_r = 0.78$ eV, (10ln (1000Q^{-1}) = 56.5)

With combination of Eq. (3), Eq. (5), Eq. (8) and the dependences of H_r and n on A_ε, we get the expression of the damping in region Ⅱ

$$Q^{-1} = (C / f^n)\exp(-nH_r / kT). \quad (9)$$

Although Eq.(9) has the same form as Eq.(4) in damping region Ⅰ, the parameters n, H_r and H_a, and the constant C in Eq.(9) are all amplitude-dependent so that Q_2^{-1} is strongly amplitude-dependent. If we write Eq. (9) in the linear form

$$\ln Q^{-1} = \ln C - n\ln f - nH_r / kT, \quad (10)$$

we can conclude that as both n and nH_r increase with increasing A_ε, the term ln$C$ must be a much more intensively incremental function of A_ε in order to maintain Q^{-1} as an incremental function of A_ε. This can be judged from Fig.4 (b) and Fig.4 (c).

Besides, from the discussion on the parameter n in section (3), it is easy to realize that during the nonlinear relaxation, as the strain amplitude (or stress) increases; the restoring force of the interface will decrease. The distribution width of the real activation will narrow[5] as some small energy barrier will disappear due to the aid of stress-activation. Therefore, n will become larger.

Table 1 Depedence of damping parameters (H_r, n and H_a)on A_ε in the region Ⅱ

	$A_\varepsilon \times 10^{-5}$	H_r / eV	n	H_a / eV	$H_a = nH_r$
high—T low—A_ε region	1.9	0.89	0.21	0.190	yes
	2.7	0.88	0.22	0.194	yes
low—T high—A_ε region	7.7	079	0.23	0.178	yes
	12.0	0.74	0.26	0.187	yes

As disscused in section (2), the dividing line b moves toward high—T and high—A_ε area as f increases. This proves that the type—Ⅱ nonlinear relaxation will extend into more high—T and A_ε region as f increases.

(5) Damping Q_3^{-1}

The damping Q_3^{-1} in region Ⅲ in Fig.2 is A_ε dependent, but its dependence on A_ε is weaker than that of Q_2^{-1}, i.e., $\partial Q / \partial A_\varepsilon > 0$, but $\partial^2 Q^{-1} / \partial A_\varepsilon^2 < 0$. If we plot the relation between lnQ^{-1} and T^{-1}, there is no longer such a linear semilogarithmic relation was found for Q_1^{-1} and Q_2^{-1}. This can be seen in Fig.4 (d) which indicates that the damping Q_3^{-1} increases with T in a slower way than an exponential and this tendency becomes more pronounced as A_ε increases further. We can assume that as A_ε increases to the critical avlue $A_{\varepsilon 3}$, the phase interface breaks away from some pinning pionts such as the triangle of phase interface and be coupled with each other just as dislocation motion in a solid breaks away from its pinning points under an applied periodic stress field. In this way, the interface will move more easily so that Q^{-1} does not increase with increasing A_a as rapidly as in the case of Q_2^{-1}.

When f increases, we find that the curve of $\ln Q^{-1}—T^{-1}$ still move in a parallel manner to higher temperature and the relations $Q^{-1}\propto f^{n}$ and $n<1$ (where n is enlarged as A_ε increases as shown in Fig.3) are still obeyed. We have measured a series of parallel curves of $\ln Q^{-1}—T^{-1}$ with increasing f and a series of parallel straight lines of $\ln Q^{-1}—\ln f$ with increasing T and found that the curve $\ln Q^{-1}—T^{-1}$ shifts to higher T, while the straight line $\ln Q^{-1}—\ln f$ shifts to higher f.

From the above results, it can be concluded that the damping Q_3^{-1} is still a kind of nonlinear relaxation (here called type—Ⅲ) and can be written as

$$Q^{-1}=F(\omega\tau), \qquad (11)$$

if the relaxation time τ still obeys the Arrhenius relation $\tau=\tau_0\exp(H/kT)$ which is controlled by some kind of atomic diffusion process which may be different from the atomic diffusion in the case of damping Q_2^{-1} as described in section (4). As mentioned in section (4), the weighted average H_r of the real activation energy H as involved in equation (11) can be obtained by measuring the shift of the constant value of Q^{-1}at constant A_ε with changing T and f. Line 4 in Fig.5 gives the linear relation $\ln f—T^{-1}$ at a constant value of $Q^{-1}$when $A_\varepsilon=1.2\times10^{-4}$ for the case of Q_3^{-1}. From the slope of the linear relation, we get a value of $H_r=0.78$ eV for line 4 in Fig.5. Just as in the case of Q_2^{-1}, we also find that H_r in Q_3^{-1} decreases as A_ε increases. This indicates that there is a similar effect of the stress field on the activation energy during type—Ⅲ nonlinear relaxation as that analysed in section (4).

As described above, the parameter n of Q_3^{-1} also increases as A_ε increases. This shows that as the applied stress field becomes larger, the restoring force of the relaxation becomes smaller just as in the case of the damping Q_2^{-1}.

The variations in H_r and n with increasing applied stress field as described in dampings Q_2^{-1} and Q_3^{-1} may not only enable us to further clarify the damping mechanisms but also help us to understand the superplasticity mechanism of the alloy. This kind of research awaits further exploration.

4 CONCLUSIONS

(1) The nonlinear damping in region Ⅱ comes from a nonlinear relaxation of the phase interface, and has an exponential relationship with temperature, i.e., $Q^{-1}=(C/f^{n})\exp(-nH_r/kT)$;

(2) The nonlinear damping in region Ⅲ comes from another kind of nonlinear relaxation. There is no longer such an exponential relationship with temperature as that in region Ⅱ, and these is a less evident strain amplitude effect on the damping than that in the region Ⅱ;

(3) Both in region Ⅱ and region Ⅲ, the nonlinear dampings have the same dependence on frequency, $Q_2^{-1}\propto f^{-n}$, and the parameter n increases and the real activation energy decreases as the strain amplitude increases. This is due to the fact that, in the both cases, the restoring force of the relaxations becomes smaller with increasing strain amplitude and some small energy barriers of the relaxations are overcome by stress-activation as the strain amplitude increases.

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