Structural relaxation dynamics of $Fe_{83}B_{17}$ and $Al_{88.5}Y_{6.5}Ni_5$ amorphous alloys[①]

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Abstract: According to a new bifurcation theory model for the glass transition proposed by the authors, the experimental non-Debye relaxation law of the structural relaxation of metallic glasses below the glass transition temperature T_g, i. e. $\Phi(t) \sim \exp[-(t/\tau)^\beta]$, $0 < \beta < 1$, is theoretically deduced, then, changes of internal friction of $Fe_{83}B_{17}$ and $Al_{88.5}Y_{6.5}Ni_5$ amorphous alloys isothermally annealed at various temperatures below their glass transition temperatures were measured and the structural relaxation dynamics was experimentally studied. It is shown that the structural relaxation dynamics in terms of the internal friction accords with non-Debye law and the experimental result agrees well with the theoretical analysis.

Key words: amorphous alloys; structural relaxation; dynamics   **Document code: A**

1 INTRODUCTION

Structural relaxation dynamics of amorphous alloys can be generally summarized from experiments as non-Debye form, i. e. $\Phi(t) \sim \exp[-(t/\tau)^\beta]$, $0 < \beta < 1$. However this experimental law is hardly deduced from available theoretical models for the glass transition, because these models have not yet exactly described the physical nature of the glass transition[1~3].

According to a new theory model —bifurcation theory model for the glass transition proposed by the authors[4], the non-Debye relaxation dynamics of the amorphous alloys below the glass transition temperature is theoretically predicted. Then, by measuring internal friction decaying behavior of two typical amorphous alloys $Fe_{83}B_{17}$ and $Al_{88.5}Y_{6.5}Ni_5$ annealed below their glass transition temperatures, the theoretical prediction is experimentally verified.

2 THEORETICAL ANALYSIS

According to the bifurcation theory model proposed in Ref. [4], for a given alloy melt, temperature change of the melt system during solidification can be described as

$$\frac{dT_r}{dt} = \frac{\Delta H_m \cdot K_n \cdot v}{\alpha_c \cdot T_m \cdot A} \cdot$$
$$\exp[- B/(T_m T_r - T_m T_0)] \cdot$$
$$\exp[- 16\pi\alpha^3 \beta / 3T_r(1 - T_r)^2] -$$
$$\beta' \cdot T_r + \beta' \cdot T_e / T_m \qquad (1)$$

where T_r is reduced temperature, T_m is melting temperature, ΔH_m is latent heat, K_n is dynamical constant, v is nucleus volume, A and B and T_0 as well are constants, α_c is special heat of the melt, α is Turnbull ratio[5], β is reduced latent heat, β' is cooling ability of surrounding circumstance, and T_e is temperature of the surrounding circumstance.

It is shown by analyzing equation (1) that because of non-linearity of the solidification dynamical law and non-equilibrium of the cooling process (rapid cooling will result in the solidification system being far from equilibrium), for a given alloy melt system, an uncontinuous steady state temperature jump will occur in the melt system when the cooling rate is over some value and this uncontinuous jump can be understood as glass transition.

Generally, it is necessary to precisely solve equation (1) for completely understanding the relaxation dynamical law of the amorphous alloy. However it is almost impossible to analytically solve equation (1), thus we numerically solve equation (1) to understand the relaxation law of the amorphous alloy. Taking $Fe_{83}B_{17}$ for example, using a set of data as[6]: $T_m = 1448$ K, $\Delta H_m = 15840$ J/mol, $A = 3.3 \times 10^{-3}$ Pa•s, $B = 4630$ K, $T_0 = 638$ K, and $K_n = 10^{29}$ J/cm^6, $v = 10^{21}$ cm^3, $\alpha_c = 25$ J/(mol•K), $(16/3)\pi\alpha^3\beta = 1.2$. When $\beta' = 2000$ s^{-1} and $T_e = 700$ K (according to Ref. [6], T_g of $Fe_{83}B_{17}$ amorphous alloy is 760 K), the numerical solution of equation (1) is shown in Fig. 1.
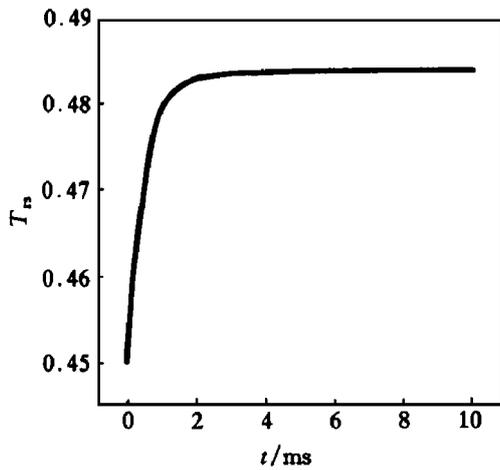
The fitting function of this curve is

Fig. 1   Relaxation behavior of
amorphous alloy below T_g
($Fe_{83}B_{17}$: $\beta' = 2\,000\,s^{-1}$, $T_e = 700\,K$)

$$T_r = 1 - \{0.52 + 0.034 \cdot$$
$$\exp[-(t/0.000\,44)^{0.88}]\} \qquad (2)$$

Confidence is 95%, correlation coefficient is 0.999, and sq$\cap$r is 1.025×10^{-7}. It is shown that the fitting is well. Equation (2) can be described as a general form as below:

$$\Phi(t) \sim \exp[-(t/\tau)^\beta], \quad 0 < \beta < 1 \qquad (3)$$

It is shown that the relaxation dynamics of the amorphous alloy below the glass transition temperature T_g accords with non-Debye relaxation law.

3   EXPERIMENTAL

Master ingots of $Fe_{83}B_{17}$ and $Al_{88.5}Y_{6.5}Ni_5$ were prepared in vacuum induction furnace. Amorphous ribbons about 5 mm in width and 30~ 50 μm in thickness are made by the melt-spinning technique under a preserving nitrogen atmosphere. The amorphism of the ribbons was examined by Simens D5000 X-ray diffractometer with CuK_α. The diffraction results show that the ribbons of $Fe_{83}B_{17}$ and $Al_{88.5}Y_{6.5}Ni_5$ are entirely amorphous as shown in Fig. 2.

The internal frictions of $Fe_{83}B_{17}$ amorphous samples isothermally annealed at 373 K and 473 K and $Al_{88.5}Y_{6.5}Ni_5$ amorphous samples at 343 K and 393 K respectively are in situ measured by a conventional low frequency torsion pendulum with a XWC-100AB auto balance recorder for registering the amplitude attenuation curves, from which the internal friction values were calculated to study the relaxation dynamics.

4   ERSULTS AND DISCUSSION

Changes of internal friction values with annealing time of $Fe_{83}B_{17}$ and $Al_{88.5}Y_{6.5}Ni_5$ amorphous alloys isothermally annealed at various temperatures were measured by a conventional low frequency tor-
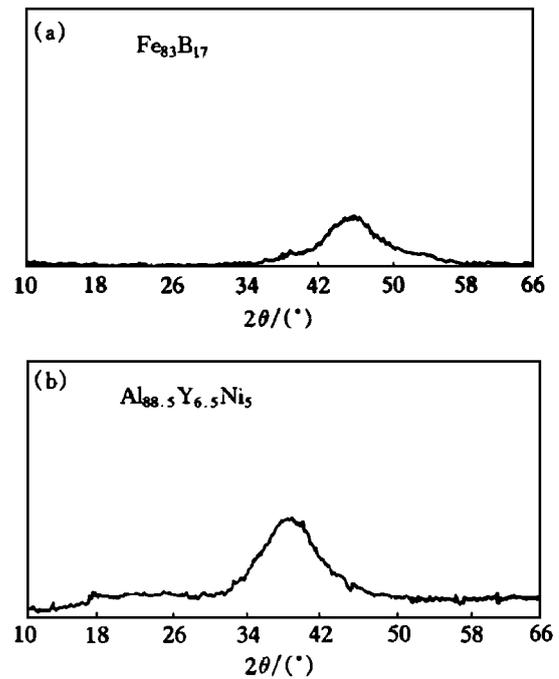

Fig. 2   X-ray diffraction patterns of $Fe_{83}B_{17}$ and
$Al_{88.5}Y_{6.5}Ni_5$ amorphous alloy sample ribbons

sion pendulum with a frequency of 0.1~ 1 Hz. The results are shown in Fig. 3 and Fig. 4. It can be seen from Figs. 3 and 4 that the internal friction values decrease with annealing time at the same annealing temperature and increase with annealing temperature for the same annealing time. This is because of longer annealing time at the same annealing temperature resulting in increasing the viscosity and reducing the anelasticity, thus reducing the internal friction value, and higher annealing temperature resulting in viscoplastic flow (creep deformation), thus increasing the internal friction value[7, 8]. Curves in Figs. 3 and 4 are fitted to study the relaxation dynamics. The fitting functions are listed in Table 1.
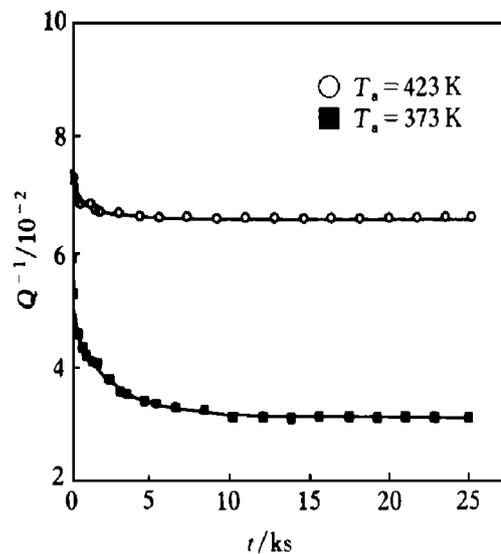

Fig. 3   Changes of internal friction upon
annealing time of $Fe_{83}B_{17}$ amorphous alloy
isothermally annealed at various temperatures

Table 1   Fitting of decaying curves of $Fe_{83}B_{17}$ and $Al_{88.5}Y_{6.5}Ni_5$ amorphous alloys isothermally annealed at various temperatures

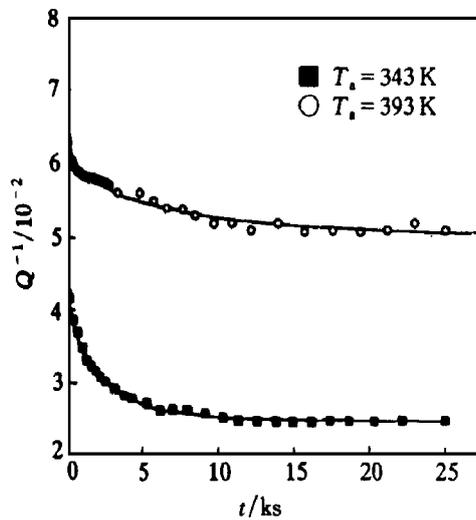| Alloy	Annealing temperature/ K	Fitted relaxation function	sq^r	Confidence	Correlation coefficient
$Fe_{83}B_{17}$	373	$Q^{-1}= 0.031+ 0.028\cdot \exp[-(t/1.25)^{0.57}]$	2.32×10^{-7}	0.95	0.998
	473	$Q^{-1}= 0.066+ 0.027\cdot \exp[-(t/0.62)^{0.45}]$	4.50×10^{-8}	0.95	0.995
$Al_{88.5}Y_{6.5}Ni_3$	343	$Q^{-1}= 0.025+ 0.018\cdot \exp[-(t/1.99)^{0.74}]$	8.95×10^{-8}	0.95	0.999
	393	$Q^{-1}= 0.049+ 0.014\cdot \exp[-(t/1.33)^{0.58}]$	3.70×10^{-7}	0.95	0.991

Fig. 4   Changes of internal friction upon annealing time of $Al_{88.5}Y_{6.5}Ni_5$ amorphous alloy isothermally annealed at various temperatures

It can be seen from Table 1 that the structural relaxation dynamics represented by the change of the internal friction can be summarily described as

$$\Phi(t) \sim \exp[-(t/\tau)^\beta] , \quad 0< \beta< 1 \quad (4)$$

This result is consistent with the theoretical pre-diction in Section 2 and Refs. [9~ 11].

5   CONCLUSIONS

It is shown through theoretical analysis and experimental study that the structural relaxation dynamics of amorphous alloys below the glass transition temperature is in accord with non-Debye relaxation law,

i. e. $\Phi(t) \sim \exp[-(t/\tau)^\beta]$, $0< \beta< 1.$

REFERENCES

[1]   Jackle J. Models of the glass transition [J]. Rep Prog Phys, 1988, 39: 149.

[2]   Hunt A. Non-Debye relaxation and the glass transition [J]. J Non-Cryst Solids, 1993, 160: 183.

[3]   Fredrickson G H. Recent developments in dynamical theories of the liquid-glass transition [J]. Ann Rev Phys Chem, 1988, 39: 149.

[4]   CAO Biao and CHEN Zhen-hua. Multiple steady states in rapid solidification and the glass transition [J]. Science in China (Series E), (in Chinese), 1998, 41(3): 247.

[5]   Turnbull D. Metastable structures in metallurgy [J]. Metall Trans A, 1981, 12A: 695.

[6]   Davis H A. Rapidly quenched metals III[A]. In: Cantor B ed. Proc 3rd inter conf on rapidly quenched metals, Vol. 1 [C]. London, 1978.

[7]   Morito N and Egami T. Internal friction and reversible structural relaxation in metallic glass $Fe_{32}Ni_{36}Cr_{14}P_{12}B_6$ [J]. Acta Metall, 1984, 32: 603.

[8]   Myung W N, et al. Structural relaxation and crystallization of amorphous $Ti_{60}Cu_{30}Ni_{10}$ alloy [J]. J Non-Cryst Solids, 1995, 192/193: 401.

[9]   Komatsu T, et al. A nonlinear analysis of the kinetics of reversible structural relaxation in Co-Fe based metallic glasses [J]. J Appl Phys, 1988, 64(10): 4853.

[10]   Mitchler P D, Roshro R M and Ruan W. Nonequilibrium relaxation dynamics in the spin glass and ferromagnetic phases of CrFe [J]. Philos Mag B, 1993, 68(4): 539.

[11]   LIU Jun-ming and SHUI Jia-peng. Structural relaxation of the metallic glass [J]. Acta Metallurgica Sinica, (in Chinese), 1995, 31: B318.

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