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ON THE MECHANISM OF THE LOW TEMPERATURE INTERNAL FRICTION PEAKS IN
COLD-WORKED Al - 0.5 wt% Cu AND Al - 4 wt% Cu ALLOYS

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Abstract - A detailed analysis of the low-frequency internal-friction peak observed in cold-worked Al-0.5 wt% (0.21 at%) Cu around 214 K ($f = 2$ Hz) showed that it consists of two closely situated internal-friction peaks: a relaxation peak (R-peak) and a "phase transformation peak" (P-peak). A model of dragging by dislocations is suggested for the R-peak in which the copper atom-vacancy pairs are the mobile pinning agents. Experiments on Al-4 wt% (1.6 at%) Cu showed that the frequency-independent P-peak observed around 224 K cannot be attributed to the presence of G.P. [1] zone. This peak may be associated with some clustering stage of the Cu atoms in aluminum just before the formation of the G.P. [1] zone and may be correlated to an ordering phenomenon.

I. Introduction- In a preceding paper, we reported the observation of an internal-friction peak around 214 K ($f = 2$ Hz) in cold-worked Al-0.5 wt% (0.21 at%) Cu (1). The peculiarities of this peak led us to assume that it consists of two closely situated internal-friction peaks: a relaxation peak (R-peak) at a lower temperature and a "transformation peak" (P-peak) at a somewhat higher temperature. The R-peak may be attributed to the interaction of Cu atom-vacancy pairs with dislocations in aluminum similar to the low temperature peaks observed in other cold-worked dilute aluminum alloys: Al-Mg (2), Al-Ga (3). On the other hand, the P-peak may be attributed to a clustering state of copper atoms around dislocations just before the formation of G.P. [1] zone and it may be specific for the case of Al-Cu alloy. A detailed analysis will be made in this report and special emphasis will be put on the mechanism of the R-peak which may be valid for the low temperature relaxation peaks observed in other cold-worked dilute Al alloys.

II. On the Relaxation Peak (R-peak) Observed in Cold-worked Al-0.5% Cu

II.1 Analysis on experimental results

The internal-friction curves of Al-0.5% Cu (85% reduction in area) after an annealing of 15 min at 325 K and 425 K are shown by curves I

and II of Fig. 1 respectively with the background subtracted. For $f = 1.95$ Hz, the peak temperature T_p of these two curves are respectively 217.5 K and 225.0 K. In Fig. 2 are shown the corresponding curves with $f = 0.485$ Hz.

It can be seen from Figs. 1 and 2 that the high-temperature side of peak I (325 K anneal) is much more sloped than the low-temperature side while the peak II (425 K anneal) is nearly symmetrical on both sides. According to our previous analysis (1), only the P-peak is left after the 425 K anneal, so that the R-peak can be obtained approximately by subtracting curve II from curve I in Figs. 1 and 2. The results are shown in Fig. 3 for $f = 0.485$ Hz (curve II) and $f = 1.95$ Hz (curve I) from which we get $T_p = 203.5$ K, 210.5 K respectively for these two frequencies. The activation enthalpy and the time factor thus determined are $H = (0.73 \pm 0.2)$ eV, $\tau_0 = 10^{-17 \pm 3}$ sec which are reasonable for a relaxation process associated with the interaction between point-defect-complexes and dislocations.

II.2 Concerning the annealing effect

As was shown in the preceding paper, a series of R-peaks were observed after the Al-0.5%Cu specimen was twisted $\pm 1\%$ at 77 K. However, the R_3 -peak disappeared after an annealing at room temperature (305 K) and the R_4 -peak became dominant. This R_3 -peak seems to be the same as the P_β -peak observed by Hasiguti et al (4) which was attributed to the interaction between vacancies and dislocations in aluminum. The activation enthalpy for P_β -peak as determined by Hasiguti et al is 0.44 eV. The T_p of P_β -peak is 235 K with $f = 1$ kHz and the T_p of our R_3 -peak is 175 K with $f = 0.63$ Hz. These data yield an activation enthalpy of 0.44 eV which is identical to that determined by Hasiguti et al for the P_β -peak.

It is well known that the vacancy in aluminum is mobile at room temperature, so that it is reasonable to assume that the disappearance of the P_β -peak after a room temperature annealing is due to the release of the vacancies from dislocations to form copper atom-vacancy pairs.

Furthermore, the copper atom-vacancy pairs dissociate after the 425 K anneal so that the R-peak attributed to the interaction between copper atom-vacancy pairs with dislocations disappears after such an anneal and only the P-peak is left.

The annealing effect described above gives very strong support to the proposition that the R-peak observed in Al - 0.5% Cu is attributable to the interaction between copper atom-vacancy pairs with dislocations in aluminum.

III. On the Mechanism of the Relaxation Peak (R-peak)

III.1 Phenomenological representation of the mobile-pinning-point model

The models proposed so far for the low-temperature peaks of Hasiguti type seem to be all based on the thermal depinning of dislocations. As we have mentioned in the preceding paper, the low-temperature interal-friction peaks in cold-worked dilute aluminum alloys (or in dilute copper alloys) are quite different from the so-called Hasiguti peaks which are suppressed by the presence of solute atoms and disappeared upon annealing at room temperature. A possible reason for the preference of an immobile-solute atom model may be due to the consideration that the migration rate of substitutional solute atoms in the lattice is too low at such a low temperature at which the relaxation process was observed. Now let us propose a mobile pinning-point model and make a semi-quantitative treatment concerning the interaction between copper atom-vacancy pairs with dislocations in aluminum, the mobile pinning agent is now the copper atom-vacancy pair. Such a dragging model will give rise to a viscous term in the differential equation governing the motion of the dislocation and can be illustrated by a three-parameter model of anelastic solid (Fig. 4). In Fig. 4, μ is the shear modulus, ΔJ is the compliance defect and η is the viscosity coefficient due to dragging of the pinning point. We have

$$\Delta J = \rho l^2 / 6\mu, \quad \text{.....(1)}$$

$$\begin{aligned} Q_{\max}^{-1} &= (\Delta J / J_U) / 2(1 + \Delta J / J_U)^{1/2} \\ &= (\rho l^2 / 12) / (1 + \rho l^2 / 6)^{1/2}, \quad \text{.....(2)} \end{aligned}$$

where ρ is density of effective dislocation, l is the length of dislocation segment which is pinned at both ends and J_U is the unrelaxed compliance.

Because the binding enthalpy H_B (> 0.1 eV) between the mobile pinning-point and dislocation is much larger than kT , the concentration of mobile pinning-point at dislocation C_d ($= C_b \exp (H_B / kT) / (1 + C_b \exp (H_B / kT))$) is larger than 10^{-2} and the amplitude of measurement A_g is about 10^{-5} , we can use the creep rate equation derived by J. Friedel (6) and calculate the viscosity coefficient in the three-parameter model. From (6) and (7), we have

$$\dot{\gamma} = 2\rho D \tau_b^3 / kT$$

$$\text{and } \eta = \tau / \dot{\gamma} = kT / 2\rho D b^3, \quad \text{.....(3)}$$

$$\text{then } \tau_\sigma = \eta \Delta J = kT l^2 / 12\mu D b^3, \quad \text{.....(4)}$$

where D is the diffusion coefficient of the mobile pinning-point and b is the Burger's vector.

III.2 Comparison with experimental results

1. Eqn. (2) shows that $Q_{\max}^{-1}$ varies with ρl^2 . Because l^2 decreases with an increase of ρ , ρl^2 is not sensitive to the amount of cold-work. This means that the height of the R-peak (with the background subtracted) should be about the same for specimens subjected to different amount of cold-work. This agrees with experimental results when we compare the curves shown in Fig. 3 for the cold-drawn specimen (85 % reduction in area) with curve 2 in Fig. 6 of the preceding paper (1) for the twisted specimen (deformed ± 1 % in torsion).

2. Eqn. (4) shows that τ_s is proportional to Tl^2/D . This means that the peak temperature T_p should depend appreciably upon l . Thus when measurements are carried out with the same frequency, T_p should increase with an increase of l , that is, decreases with an increase of the amount of cold-work. This also agrees with experimental results. The T_p of the R-peak for the cold-drawn specimen (85 % reduction in area) is about 213.5 K with a measuring frequency of about 0.5 Hz (curve II of Fig. 3), while the T_p of the R-peak shown by curve 2 in Fig. 6 of the preceding paper (1) for the twisted specimen (± 1 % in torsion) is about 222 K with a measuring frequency of about 0.6 Hz.

3. From Eqn. (4) we get $\tau_s = kT\rho l^2/12\rho Db^3$, and from Eqn. (2) we get $\rho l^2 \sim 1.2 \times 10^{-2}$ with $Q_{\max}^{-1} \sim 10^{-3}$. Thus with $\rho \sim 10^9 \text{ cm}^{-2}$, $\mu = 2.7 \times 10^{11} \text{ dyne cm}^{-2}$, $b = 2.85 \times 10^{-8} \text{ cm}$ and the experimental values $f_p = 0.485 \text{ Hz}$ and $T_p = 203.5 \text{ K}$, we have

$$\tau_s = \frac{1.2 \times 10^{-2} \times 1.38 \times 10^{-16} \times 203.5}{12 \times 10^9 \times 2.7 \times 10^{11} \times (2.85 \times 10^{-8})^3} \approx \bar{\tau} = 1/2\pi f_p.$$

This gives $D = 1.42 \times 10^{-14} \text{ cm}^2 \text{ sec}^{-1}$. Now $D = D_0 \exp(-H/kT)$, and $D_0 = 0.65 \text{ cm}^2 \text{ sec}^{-1}$ according to (8), so we get $H = 0.6 \text{ eV}$. This value of H agrees with the migration activation enthalpy of copper-vacancy pair (0.68 eV)* and is close to the experimental value of the R-peak ($0.7 \pm 0.2 \text{ eV}$). This gives a strong support to the proposition that the R-peak is associated with the stress-induced migration of mobile copper atom-vacancy pairs in the stress field of moving dislocations in Al.

* Because a copper atom-vacancy pair would dissociate at 425 K in Al, its binding enthalpy should be about 0.04 eV. The diffusion activation enthalpy of copper in Al is 1.40 (8) and the formation enthalpy of vacancy in Al is 0.76 eV (9), so the migration activation enthalpy of copper atom-vacancy pair in Al is $1.40 - 0.76 + 0.04 = 0.68 \text{ eV}$.

IV. On the Phase Transformation Peak (P-peak) Observed in Cold-worked Al - 0.5 wt% Cu and Al - 4wt% Cu Alloys

As is shown in Fig. 5, the P-peak does not shift with a change of frequency of measurement, so that it is not a relaxation peak.

Internal-friction measurements were taken with an Al - 4wt% (1.67 at%) Cu specimen (cold-worked 80% R.A.) in cold-worked state (curve I) and after an annealing at 300K for 15 min. It is seen from Fig. 6 (a) that the P-peak was lowered after the 300K annealing (curve II). When the specimen was annealed at 375K for 5 hr during which G.P. [1] zones should develop fully in the specimen, the P-peak was lowered to almost un-noticeable (curve III). For an Al - 4wt% Cu specimen quenched and then cold-worked (60% R.A.) and annealed again at 300K, 400K and 500K for 15 min, the P-peak disappeared completely as shown in Fig. 6(b), I-III. Accordingly the P-peak cannot be attributed to the presence of G.P. [1] zones.

It seems that the P-peak may be associated with some clustering state of copper atoms in Al just before the formation of G.P. [1] zone, and resulted from some ordering phenomenon having a definite critical temperature.

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REFERENCES

- (1) J.X. Zhang, T.S. Kê, G.Y. Li, G. Fantozzi, P.F. Gobin and M. Weller, Phys. Stat. Sol., (a) 70, 159 (1982).
- (2) Z.L. Pan, Z.G. Wang, Q.H. Kong and T.S. Kê, Acta Physica Sinica, 29, 1180 (1980); Materials Science and Engineering, 49, 101(1980).
- (3) Q.H. Kong, G.Y. Li. and T.S. Kê, J. de Physique, 42, C5-265(1981).
- (4) R.R. Hasiguti, N. Igata and G. Kamoshita, Acta Met., 10, 442(1962).
- (5) A.S. Nowick and B.S. Berry, Anelastic Relaxations in Crystalline Solids, Academic Press, 1972 (p.359), (p.56).
- (6) J. Friedel, Dislocations, Pergamon Press, 1964 (p.409).
- (7) A.H. Cottrell, Dislocations and Plastic Flow in Crystals, Oxford University Press, London, 1953 (p.136).
- (8) N.L. Peterson and S.J. Rothman, Phys. Rev., B1, 3264 (1970).
- (9) B.T.A. McKee, A.G.D. Jost and I.K. Mackenzie, Canad. J. Phys., 50, 415 (1972).

Figure Caption

- Fig. 1. Q^{-1} - T curves of Al - 0.5% Cu (85% reduction in area) after an annealing of 15 min at 325 K and 425 K respectively with $f = 1.95$ Hz. I. 325 K anneal; II. 425 K anneal
- Fig. 2. The corresponding Q^{-1} -T curves as in Fig. 1 with $f = 0.485$ Hz. I. 325 K anneal; II. 425 K anneal
- Fig. 3. The R-peaks obtained by subtracting curve II from curve I in Figs. 1 and 2. I. $f = 1.95$ Hz; II. $f = 0.485$ Hz

- Fig. 4. A three-parameter model of the R-peak: the mobile pinning-point model
- Fig. 5. Effect of measuring frequency on P-peak with I.F. background subtracted (observed in cold-worked Al - 0.5% Cu annealed at 425 K for 15 min). Curve I: $f = 0.485$ Hz; curve II. $f = 1.95$ Hz
- Fig. 6. Effect of annealing on the P-peak of cold-worked Al - 4 wt% (1.67 at%) Cu (80 % reduction):
- (a) Curve I-III. specimen annealed and then cold-worked (80% reduction). I. cold-worked state; II. annealed again at 300 K for 15 min; III. annealed again at 375 K for 5 hr
 - (b) Curve I-III. specimen quenched and then cold-worked (60% reduction) and annealed again at 300K, 400K and 500K for 15 min respectively

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 6 (a).

Fig. 5.

Fig. 6(b).