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LETTER TO THE EDITOR

An investigation of the influence of cerium on the recrystallization of aluminium from background internal friction measurements

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Abstract. The relation between the recrystallization of metals and background internal friction is established. Internal friction as a function of temperature was measured, after annealing at 720 K for 2 h, for 4N pure aluminium samples with cerium content of 0.0–3.0 wt% (six in number) in Ke's vacuum torsion pendulum. From the changes of the background internal friction with cerium content, it has been shown that when cerium content (Ce%) is less than 0.5%, cerium has an insignificant effect on the recrystallization of aluminium; when Ce% is more than 0.5%, the opposite is true: cerium increases the recrystallization temperature of aluminium significantly.

It is well known that rare earth elements have many useful properties: they can modify metals and alloys, refine grains [1], purify grain boundaries [2] etc. These effects of cerium on aluminium and its alloys have been much studied [1], but the influence on the recrystallization of aluminium has not been investigated extensively. Here, we investigated if from an aluminium–cerium (Al–Ce) alloy's grain boundary background internal friction or high-temperature internal friction measurements.

We know that the recrystallization of metal is related to the crystal defect density, especially dislocation density induced by cold working. The higher the defect density is, the easier the recrystallization, or the lower the recrystallization temperature, because of the high stored energy, which results in a high recrystallization drive force.

It is generally thought that grain boundary background internal friction arises from the interior of the grain and its value directly relates to the degree of cold working or dislocation density. Background internal friction is very high for a specimen whose annealing is incomplete [3]. On the basis of the fact that the true activation energy controlling the background process was found to be equal to that of self-diffusion of atoms [4], it has been pointed out [5] that the background internal friction results from a diffusion controlled dislocation motion. This involves the bowing of a dislocation segment, which is pinned at its ends and is surrounded by an atmosphere of solute atoms. For a sample containing Nv dislocations per unit volume, the relaxation strength Δ is given by the approximate relation [5]

$$\Delta = NvL^3/18 \qquad (1)$$

where L is the average dislocation segment length. We can see that the background internal friction is dependent on Nv and L: at given solute concentration, background internal friction increases with a rise in Nv; incomplete annealing will give rise to high background internal friction, or high background internal friction corresponds to a high recrystallization temperature.

Six 4N samples with different Ce contents (0.0, 0.1, 0.5, 0.9, 1.2, 3.0% in weight) were cold drawn to a diameter of 0.9 mm for internal friction measurement. The samples were *in situ* annealed at 720 K for 2 h in Ke's torsion pendulum in a vacuum of about 5×10^{-4} torr, and this was followed by internal friction measurement with the temperature decreasing at about 1 K min^{-1}. The vibration frequency for all measurements was about 0.5 Hz.

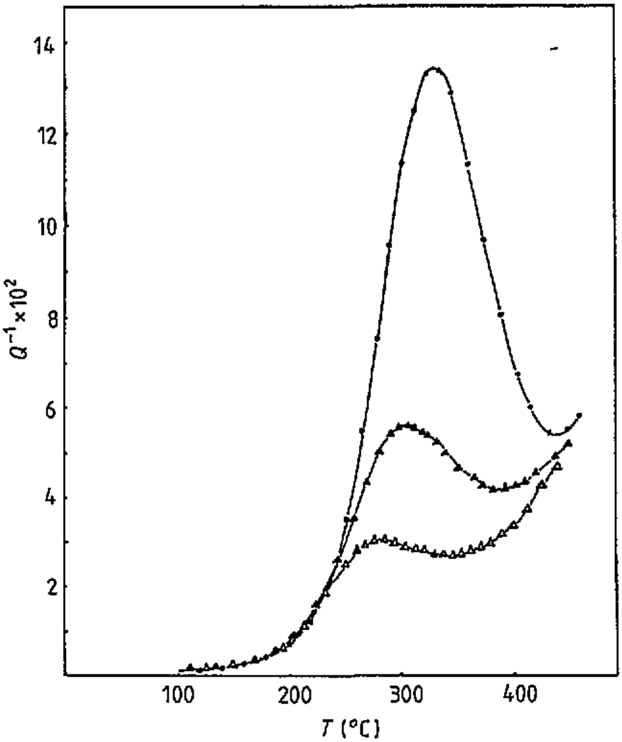

Figure 1. Original curves of grain boundary internal friction Q^{-1} versus temperature T for Al (●), Al–0.1% Ce (▲), Al–0.5% Ce (△) (720 K for 2 h; temperature decreasing at 1 K min^{-1}; $f \approx 0.5$ Hz).

The curves of internal friction Q^{-1} versus temperature T for all samples are shown in figures 1 and 2. We can see that the internal friction peak, which is related to the grain boundary and not discussed here, is superposed on the background internal friction which increases with rising temperature. When Ce% $<$ 0.5%, the background internal friction decreases with the Ce content, but when Ce% $>$ 0.5%, the background internal friction increases rapidly with Ce content. The previous work [2] mentioned that the cerium in aluminium partially forms compounds with other impurities in aluminium, and partially exists in the form of solid solution in the aluminium lattice; when the Ce content is up to 0.5%, the solid solution Ce is saturated. So the decrease in backgound internal friction results from the decrease in the L value in (1) because of the increase in Ce concentration in the dislocation line; when Ce content is less than 0.5%, Ce has an insignificant influence on the recrystallization of aluminium.

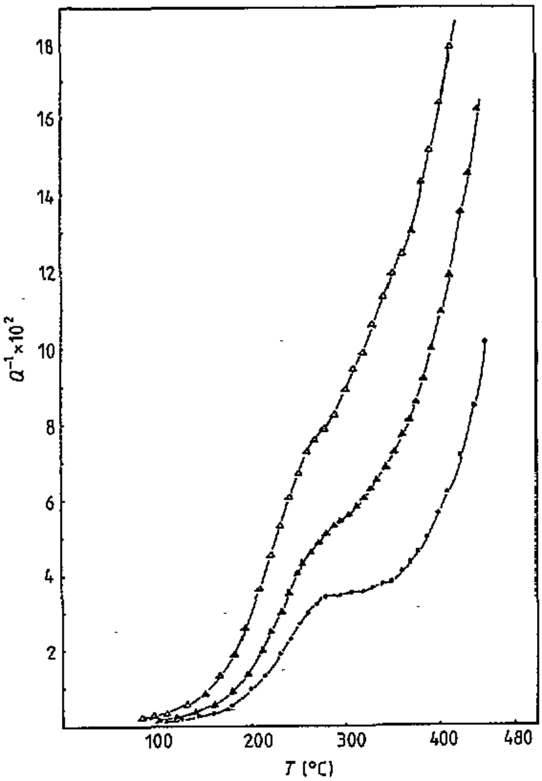

Figure 2. Original curves of grain boundary internal friction Q^{-1} versus temperature T for Al–0.9% Ce (●) (720 K for 2 h), Al–1.2% Ce (▲) (720 K for 2 h). Al–3.0% Ce (△) (750 K for 2 h) (temperature decreasing at 1 K min^{-1}, $f \approx 0.5$ Hz).

When Ce content is more than 0.5%, we can take the L value in equation (1) to be a constant independent of Ce content. Therefore, the high background internal friction arises from a high $N\upsilon$ value or incomplete annealing. In fact, when Ce% > 0.5%, the Al–Al_4Ce eutectic compound exists according to the Al–Ce phase diagram [6]. In cold deforming, the eutectic compund is crushed and dislocations move around the compound. Obviously, the dislocation density is higher at the same degree of deformation compared with the samples with no compound. In addition, the Al–Al_4Ce eutectic compound would increase the resistance to the motion of dislocations during annealing at high temperature, and make the recrystallization rate slow. Therefore, when Ce% is more than 0.5%, because of the existence of the eutectic compound, the recrystallization temperature of aluminium increases significantly, displayed in the higher and higher background internal friction with rising Ce content.

For the sample Al–1.2% Ce, after additional high-temperature annealing at 890 K for 7 h in vacuum, Q^{-1} versus T is shown in figure 3. It can be seen that the background internal friction is almost the same as that of the sample with 0.5% Ce. So after complete annealing, the background internal friction changes little when Ce% is more than 0.5% at which the solid solution Ce is saturated.

From figure 2, we also see that there seemingly exists a smaller peak at a temperature higher than that of the main peak for the sample with 3% Ce, but it is not obvious because of the high gradient of background internal friction. It has been indicated, by repeating

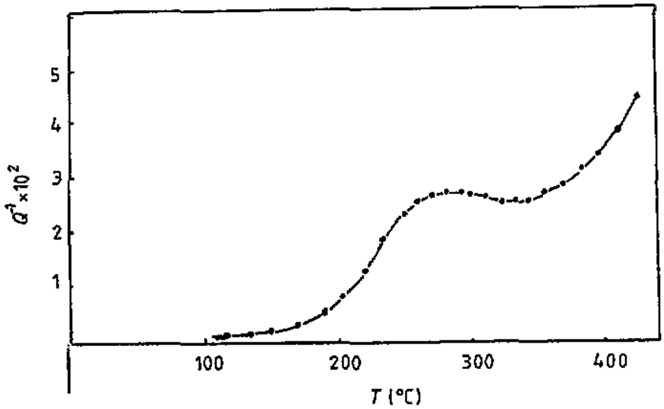

Figure 3. Q^{-1} against T curves for specimen Al–1.2% Ce (720 K 2 h + 890 K 7 h), $f \approx 0.5$ Hz.

the measurement, that the smaller peak does exist. The background internal friction of the original curves in figure 2 can be subtracted according to the method presented in [7]. The corresponding curves are seen in figures 4–6. We see that the smaller peak at higher temperature is very obvious, and also exists for the samples with 0.9% and 1.2% Ce. However, after complete annealing, the smaller peak disappears (see figure 3). It is obvious that the existence of the smaller peak, which will be further investigated, is related to high background internal friction.

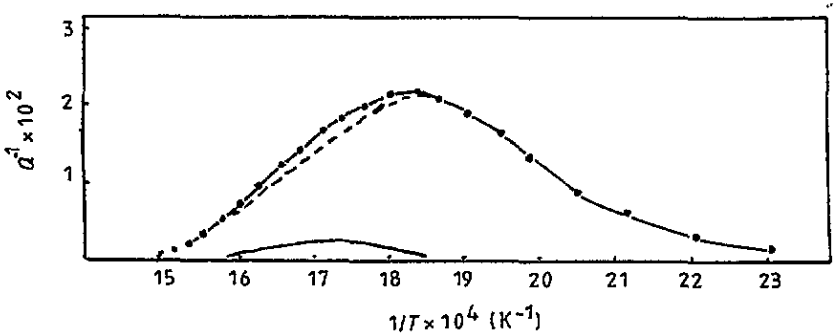

Figure 4. Q^{-1} against $1/T$ curve obtained from figure 2 for the sample with 0.9% Ce after subtraction of background. $f \approx 0.5$ Hz.

We have reached the following conclusions.

(i) When Ce content is less than 0.5%, Ce has an insignificant effect on the recrystallization of aluminium; when Ce content is more than 0.5%, because of the existence of the eutectic compound, Ce significantly increases the recyrstallization temperature of aluminium, displayed in the higher and higher background internal friction with rising Ce content.

(ii) When Ce content is more than 0.5%, there exists a smaller peak at a temperature higher than that of the main peak, which is related to incomplete annealing because of its disappearance after sufficent annealing.

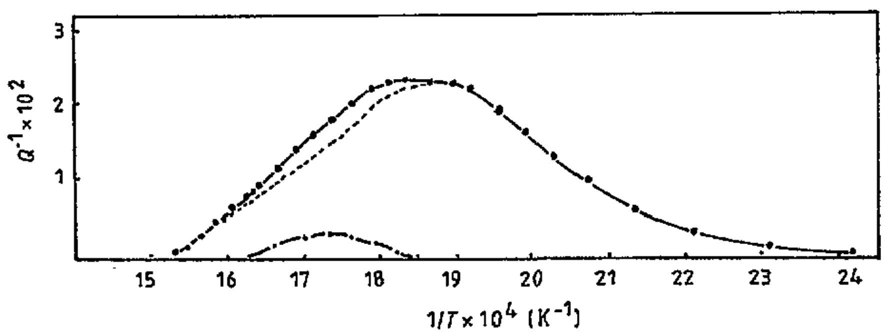

Figure 5. The Q^{-1} against $1/T$ curve obtained from figure 2 for the sample with 1.2% Ce after subtraction of background. $f \approx 0.5$ Hz.

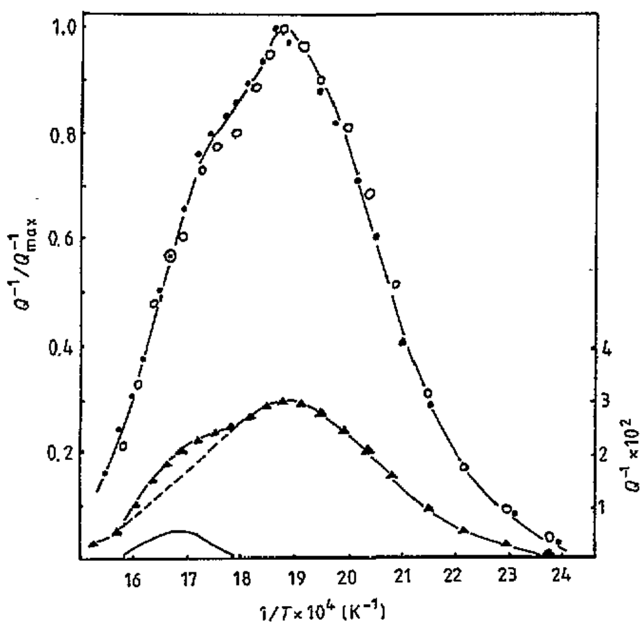

Figure 6. The Q^{-1} against $1/T$ curve obtained from figure 2 for the sample with 3.0% Ce after subtraction of background; $f \approx 0.5$ Hz. ●, first measurement; ○, second measurement (with normalization); ▲, second measurement (not normalized).

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