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A LOW TEMPERATURE COLD WORK INTERNAL-FRICTION PEAK IN Al-0.5 Wt % Ga

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Abstract.—An internal friction peak (around \(-84^\circ\text{C}\), \(f = 0.8\) hz) was observed in Al-0.5 wt % (0.19 at %) Ga cold-drawn to 12% reduction in area at 20°C. This peak was stable when measurements were taken below 20°C with descending and ascending temperatures and the height of the peak decreased after an anneal at elevated temperatures. It disappeared completely after an anneal at 200°C. The peak height first increased and then decreased with the amount of cold-working at 20°C and a 12% reduction in area seems to be close to the optimum amount of cold-working. The activation enthalpy associated with this internal friction peak measured with the method of changing of frequency is 0.85 \(\pm 0.05\) eV. A dislocation-kink dragging model is suggested in which the mobile agents that interact with dislocation kinks are Ga atom-vacancy pairs.

The effect of the temperature of previous deformation on the behavior of the internal friction peak is discussed. It is contemplated that the broadening of the peak when the previous plastic deformation was made at \(-196^\circ\text{C}\) may be due to the formation of Ga atom-divacancy pairs.

1. Experiment.—Internal friction measurements were made with an inverted pendulum by free decay method. In-situ tensile deformation was carried out by an electromagnetic set up and the tensile force applied to the specimen can be regulated continuously by changing the magnitude of the electric current passing through an induction coil. The elongation of the specimen was measured by a reading telescope.

The Al-0.5 wt % (0.19 at %) Ga specimens were prepared by melting 99.999 aluminum and 99.99 Ga (produced in China) in a vacuum induction furnace. The ingot obtained was rolled and drawn into wires. The final cold-working was made by cold-drawing a rod of diameter 2.6 mm to 0.85 mm. This corresponds to a cold-working of 89% reduction in area. The wire was annealed at 400°C for one hour and was used as the initial state of the specimen.

2. Results.—(a) Temperature internal-friction peak. An Al-0.5 wt % Ga
specimen of diameter 0.84 mm was cold-drawn at 20°C to a diameter of 0.80 mm (corresponding to a cold-working of 12% reduction in area) and was then mounted on the torsion pendulum. Internal friction measurements were taken repeatedly with descending and ascending temperatures and the $Q^{-1}$ - $T$ (temperature) curve obtained is shown in Fig. 1. A peak appeared at $-8.4^\circ$C with $f = 0.8$ Hz. The height of the peak was about $1 \times 10^{-3}$.

![Fig. 1. $Q^{-1}$-T curve of Al 0.5 wt% Ga deformed 12% reduction in area at 20°C ($f = 0.8$ Hz).](image)

The internal friction of the above specimen was measured after an anneal of half an hour at successively higher temperatures and the curves obtained are shown on Fig. 2. It is seen that the peak temperature did not change noticeably after the specimen had been annealed at different temperatures only that the height of the peak decreased successively and disappeared completely after an anneal at 200°C.

The effect of the amount of cold-working at room temperature (5, 12 and 36% extension) on the temperature internal friction peak at $-84^\circ$C ($f = 0.8$ Hz) is shown in Fig. 3. An optimum amount of cold-working seems to be 12% extension.

![Fig. 3. Effect of amount of cold-working at room temperature on the $-84^\circ$C peak.](image)
The internal friction of the Al-0.5% Ga specimen extruded 12% at room temperature was measured with frequencies of vibration 0.22, 0.85 and 2.30 Hz in a torsion pendulum and also with 1254 Hz in an acoustic internal friction apparatus in vacuum and the peak temperature were found to be -89, -84, -81 and -53 (°C) or 184, 189, 192 and 220 (K) respectively. The internal friction curve obtained with 1254 Hz is shown in Fig. 4. The activation enthalpy associated with the relaxation process is 0.85 ± 0.05 eV as calculated with a computer and the frequency factor is $2.4 \times 10^{23}$. (b) Effect of the temperature of previous deformation on the temperature internal friction peak. An Al-0.5% Ga specimen was deformed 0.5% in tension in situ of the torsion pendulum at liquid nitrogen temperature (-196°C) and the internal friction measured with ascending temperatures is shown in Fig. 5. It is seen that an internal friction peak appeared around -84°C similar to that of Fig. 1 but that the peak is very broad in contrast with that of Fig. 1. The behavior of this peak is also very different. While the internal friction peak shown in Fig. 1 for a specimen deformed 12% at 20°C is very stable during measurements with decending and ascending temperatures up to 20°C (the temperature of previous deformation), the peak shown in Fig. 5 disappeared when the temperature of the specimen was raised to -50°C and internal friction measurements taken with decending temperatures. No peak was observed when the same specimen was cooled to liquid nitrogen temperature and internal friction measurements taken again with ascending temperatures. This specimen was deformed again in tension at liquid nitrogen temperature and was aged there for one and one-half hours until the internal friction became stable. An internal friction peak was observed again around -84°C when
internal friction measurements were taken with ascending temperatures.

3. Discussions. In 1949, internal friction peak (as a function of temperature of measurement) has been observed in cold-worked Al-0.5% Cu with peak temperature in the range of 25°C to 50°C ($f = 1$ Hz). (1,2) In 1979, two temperature internal friction peaks were observed in cold-worked Al-0.03 wt % Mg around 60°C and -30°C. (3). The higher temperature peak has been attributed to the interaction of Mg atoms with dislocations in aluminum similar to the peak previously observed in Al-0.5% Cu specimens. A dislocation-kink atmosphere-dragging model has been suggested for the relaxation mechanism of these peaks (4,2,5). The lower temperature peak in cold-worked Al-0.03% Mg has been attributed to the interaction of Mg atom-vacancy pairs with dislocations in aluminum (3). We think that the lower-temperature internal-friction peak observed in Al-0.5% Ga around -84°C may also be attributed to the interaction of Ga atom-vacancy pairs with dislocations in aluminum.

Similar low-temperature peaks have been observed in cold-worked dilute aluminum alloys (6) as well as in cold-worked dilute copper alloys (7). Such low-temperature peaks are different from the Hasiguti peaks which are suppressed by the presence of solute atoms. The models proposed so far for such low-temperature peaks seem to be all based on the thermal depinning of dislocations. A possible reason for the preference of such an immobile-solute atom model may be due to the consideration that the migration rate of substitutional solute atoms in the lattice is too slow at such a low temperature at which the relaxation process was observed.

Now let us focus our attention to dilute aluminum alloys in which the dislocations are not extended. In proposing a dislocation-kink atmosphere-dragging model for the explanation of the internal friction peaks exhibiting an anomalous amplitude effect of Al-0.5% Cu and Al-0.1% Mg, we have emphasized the point that in order that the substitutional solute atom atmosphere can be dragged to move along with the dislocation, the solute atoms constituting the atmosphere must have a diffusion coefficient about ten orders of magnitude larger than the usual value. The argument is as follows: (4,2) The average distance $x$ that a diffusing particle having a diffusion coefficient $D$ can migrate in time $\tau$ is $x \approx (Dt)^{1/2}$. Consider the case of the $Q^{-1}$ peak observed in Al-0.5% Ga (-84°C, $f = 0.8$ Hz). We have $\tau \omega \approx 1$ at the peak temperature 153 K, where $\omega$ is the angular frequency, so that $\tau \approx 1/\omega = 1/2\tau f = 0.2$ sec. Assuming the atmosphere be dragged along to move an average distance of $b$ (Burger's vector) in time $\tau$ during the $Q^{-1}$ measurements, e.g., the average migration distance of Ga solute atoms is $b = 2.86 \times 10^{-8}$ cm,
then the diffusion coefficient of Ga solute atoms at 153 K should be about $10^{-15}$ cm$^2$/sec. By estimation, the D of Ga in normal aluminum lattice at 153 K can only be about $10^{-25}$ cm$^2$/sec which is smaller by ten orders of magnitude. This difficulty cannot be taken care of even when we consider the influence of the stress field of the dislocation which can only raise D for 3 or 4 orders of magnitude. Another factor which may speed up the D of Ga atoms is by the help of vacancies. A Ga atom-vacancy pair, when formed, will diffuse faster than that of a Ga atom alone, but this still cannot take care of the great difference in D except if the diffusion of such Ga atom-vacancy pairs are migrating along dislocation core or dislocation kink (4,2). The essence of the dislocation-kink atmosphere-dragging model is that the migrating agent (e.g., Ga atom-vacancy pair) is migrating forward from one Peierls valley to another via the sidewise motion of a dislocation kink.

The disappearance of the -84°C $Q^{-1}$ peak after an anneal higher than 150°C is obviously due to the dissociation of the Ga atom-vacancy pairs.

Concerning the effect of the temperature of previous deformation on the behavior of the -84°C peak, we can only say that the concentration of excess vacancies created at a tensile deformation at -196°C is much higher than that created by deformation at 20°C. Ga atoms may thus form a cluster with more than one vacancy. The relaxation process associated with such a cluster complex may be very complicated resulting in a distribution of relaxation times. This may be the reason that the $Q^{-1}$ peak shown in Fig. 5 is very broad. It is obvious that a cluster complex of vacancies with Ga atoms is much less stable than a single Ga atom-vacancy pair, so it should dissociate when annealed at a lower temperature. Once it has been dissociated by annealing, it can not form again simply by lowering the temperature. Only when deformed again at -196°C can the cluster complex be formed once more with the re-appearance of the -84°C peak.

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