Zener Relaxation in CuAl Single Crystals Studied by Isothermal Mechanical Spectroscopy

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Abstract : The Zener relaxation was studied in Cu-Al single crystals. All samples were cut with the same orientation and the Al concentrations were ranged between 3 and 19 at. % Al (solid solution).

For low temperature experiments ($< 550^{\circ}\text{K}$), perfect Debye peaks are observed in all samples and the relaxation strength is proportional to the concentration square according with the pair reorientation Zener theory.

At higher temperatures and for samples with higher Al concentration only, the internal friction peaks are broader. In the same time, the relaxation strength first increases and then decreases with the measurement temperature according to the short-range ordering LeClaire-Lomer theory with respectively the influence of only neighbouring and more distant atoms.

1. INTRODUCTION

The Zener relaxation is a type of mechanical relaxation process which has been observed in a variety of substitutional solid solutions, and firstly by Zener [1] in α -brass. Generally, the relaxation strength Δ is dependent on single crystal orientation, increases with solute content c and decreases with measurement temperature [2]. The first theoretical interpretation was provided by Zener [1] who described the relaxation in terms of the reorientation under the influence of the stress of pairs of nearest-neighbour solute atoms. An alternative theory [3,4] suggested that the Zener relaxation is a consequence of stress induced changes in short-range order. Δ must be proportional to c^2 in the first case and to $c^2(1-c)^2$ in the second.

2. EXPERIMENTAL PROCEDURE

A series of Cu-Al single crystals with compositions of 3.1, 5.4, 7.3, 9.3, 11.4, 13.7 and 19 at.% Al were grown from ultra pure Cu and Al by Bridgman technique at the Laboratoire de Métallurgie Physique of the University of Poitiers. The specimens were cut in flat bars (50 mm $\times$ 6 mm $\times$ 1 mm) parallel to a $< 111 >$ direction and inspected by X rays experiments. For Cu-Al alloys, the limit of the solid solution is 20 at.% Al.

Isothermal internal friction measurements were performed using an inverted torsional pendulum subjected to subresonant forced vibrations [5]. Measurement frequencies were ranged between 10^{-4} and 40 Hz with ten discrete frequencies per decade. Internal friction factor Q^{-1} is directly $\tan \theta$ where θ is the phase angle between the applied stress and the resulting strain. Relaxation strength $\Delta = (M_U - M_R) / M_R$ was obtained by measuring directly

the unrelaxed modulus M_U and the relaxed modulus M_R . The maximum vibration amplitude was $\epsilon_M = 5 \times 10^{-6}$

3. EXPERIMENTAL RESULTS

3.1 Temperature dependence of the relaxation strength

Generally, the relaxation strength was found decreasing with temperature and the theories predict a temperature dependence of the relaxation strength of the type [5]: $\Delta = T_0 / (T - T_c)$ where T_0 and T_c are constants. Low frequency experiments do not confirm this dependence. So, figure 1 relative to a 19 at.% specimen shows the Zener peak evolution with the measurement temperature. The peak corresponding to the lowest temperature (536 K) is exactly a Debye peak. For higher measurement temperature, the peak is wider and higher. Only for measurement above 680 K, the peak height is decreasing, as shown in figure 2. In this figure, internal friction values measured at 1 Hz and 16 Hz in isothermal experiments are plotted against the measurement temperature.

Figure 1 - Cu-19%Al single crystal
Zener relaxation peaks for various measurement
temperatures

Figure 2 - Cu-19%Al single crystal
Internal friction measured at two frequencies

Such a behaviour was found for each specimen with solute content larger than 7 at. %.

3.2 Concentration dependence of the relaxation strength

In figure 3, the relaxation strength Δ is plotted against c^2 (fig. 3 a) and $c^2(1-c)^2$ (fig. 3 b). Evidently, Δ is proportional to c^2 only for relaxation peaks obtained at the lowest temperatures (and so at very low frequency) and found identical to Debye peaks. For experiments at higher temperatures, the relaxation peaks were found broader and, in that case, Δ is not proportional to c^2 .

As shown in figure 3 b, Δ is never proportional to $c^2 (1-c)^2$ as predicted by the LeClaire-Lomer theory.

Figure 3 a
Relaxation strength plotted against c^2

Figure 3 b
Relaxation strength plotted against $c^2(1-c)^2$

4 . DISCUSSION AND CONCLUSION

Table 1 shows the relaxation parameters, apparent activation energy (H_{app}) and limit relaxation time (τ_0) deduced from our experiments using Arrhenius plots.

Table 1 - Relaxation parameters

% at. Al	3	7.3	11.4	13.7	19
H_{app} (eV)	1.72	1.76	1.87	1.88	1.90
τ_0 (s)	1.6×10^{-14}	1.7×10^{-14}	1.5×10^{-15}	10^{-16}	2×10^{-16}

The apparent activation energy obtained for low atomic concentration is identical to the value (1.7 eV) obtained from resistivity measurements at low temperature [8] and can correspond to the elementary atomic relaxation mechanism.

For higher solute content, the peak broadening at high temperature induced an increasing of the apparent activation energy and a decreasing of the limit relaxation time.

Δ is proportional to c^2 only for measurements at low temperature ($T_M < 550$ K) and, in this case, the elementary mechanism is the reorientation of solute atom pairs as predicted by Zener [4].

For specimens with a large solute content and for measurement temperature ranging between 550 K and 680 K, the relaxation strength increases with measurement temperature. According

Generally, anisothermal experiments at fixed frequency (~ 1 Hz) as described in the literature, correspond to the second case.

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