(2) At the same deposition rate, the grain-boundary spacings are essentially the same for the two metals at the same homologous temperature.

(3) At the same homologous temperature, nickel has a thicker average twin spacing than copper due to the higher twin-boundary energy of nickel.

(4) Observation of fine random grains in nickel indicated that small variations in unspecified sputtering conditions can change the microstructure.

References

1. S. D. DAHLGREN, *J. Vac. Sci. Technol.* **11** (1974) 832.
2. S. D. DAHLGREN, E. D. MCCLANAHAN, J. W. JOHNSTON and A. G. GRAYBEAL, *ibid* **7** (1970) 398.
3. M. D. MERZ and S. D. DAHLGREN, to be published.
4. L. E. MURR, "Electron Optical Applications in Material Science" (McGraw-Hill, New York, 1970) p. 397.

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Isochronal annealing studies on quenched aluminium–manganese alloys

The solid solubility of Mn in Al decreases with decrease in temperature from a maximum value of 1.55 wt% at 658° C [1]. Lattice parameter measurements suggest that decomposition of the splat cooled Al–6.7 wt% Mn alloy occurs in a single stage above 350° C [2]. The annealing stages obtained by electrical resistivity measurements in two alloys quenched from the solid-state are reported here.

The alloys prepared by melting 99.999% pure Al and 99.999% Mn were drawn into wires 0.9 mm diameter. Spectroscopic analysis showed that the two alloys contained 0.35 and 1.0 wt% Mn with traces (< 0.001 wt%) of Mg and Cu. Fe, Ni, Cr and Cd were not detected in the alloys. The samples for resistance measurements were in the form of coils, the current and potential leads were of the same composition as the alloy wires. Electrical resistivity measurements were carried out at liquid nitrogen temperature with a Leeds and Northrup precision Kelvin bridge. By suitably adjusting the length of the wires forming the specimen it was possible to detect changes in resistivity of 10^{-10} Ωcm. The experimental details are reported elsewhere [3].

The samples were heated to 620° C and quenched in a bath of calcium chloride solution at −2° C. Isochronal annealing was carried out in the temperature range 0 to 500° C for two annealing times of 5 and 15 min. The difference in the resistivity of the sample immediately after quenching (ρ_Q) and after annealing at a particular temperature, T (ρ_T) is plotted against temperature in Figs. 1 and 2 for the 0.35% and 1.0% alloys respectively.

The following features are observed in the annealing curves. (1) the first recovery stage occurs in the temperature range 0 to 40° C in both the alloys. (2) The second stage is observed in the temperature range 120 to 200° C in both the alloys; the resistivity recovery in this stage is about 18% of the total quenched-in resistivity. (3) A peak is observed in the Al–1% Mn alloy only at about 290° C. (4) The peak in the concentrated alloy is followed by an annealing stage showing a marked fall in resistivity. The effect of the longer annealing time is essentially to shift the annealing stages to lower temperatures.

The first two stages have also been observed in pure Al and a number of Al alloys [4]. For example, quenching of 99.995% pure Al from 600° C gives rise to the first stage at −50 to 0° C, while the second stage corresponding to a resistivity recovery of about 20% of the total quenched-in resistivity occurs in the range 100 to 200° C. Alloying elements shift these stages to slightly higher temperatures; this is also observed in the present investigation. Consequently the first stage of the Al–Mn alloys correspond to the annealing of vacancies to permanent sinks and the formation of secondary sinks like Frank and prismatic dislocation loops. The second stage is associated with the annealing of the dislocation loops.

A resistivity peak corresponding to the third stage in the Al–1% Mn alloy has been observed in quenched Al–Cu and Al–Zn alloys at temperatures of about 0° C, particularly when the solute content exceeds 1% [4]. These peaks are associated with the formation of clusters and have widths of the order of a few hundred nΩcm. However, the peak in the 1% Mn alloy is rather

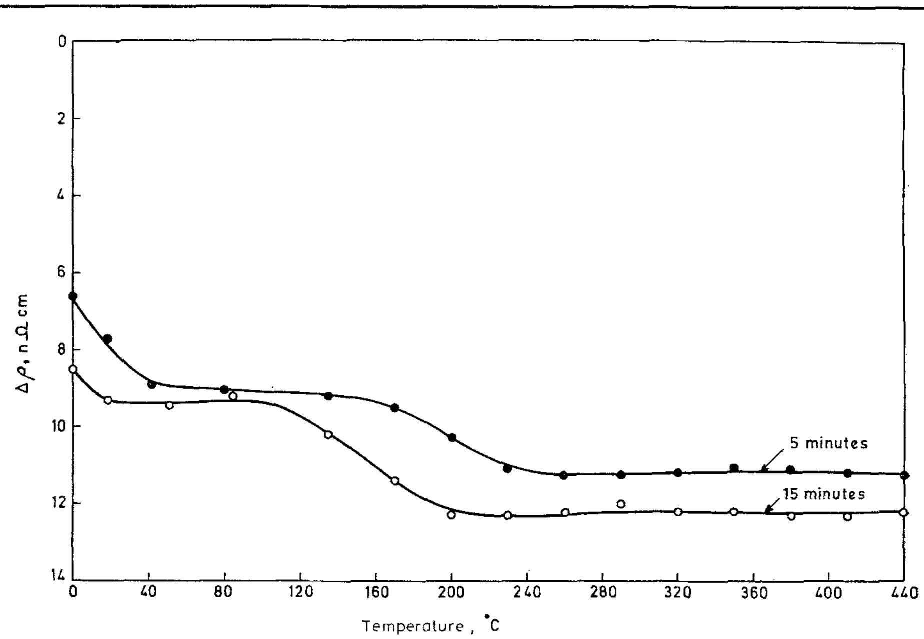

Figure 1 Isochronal annealing of quenched Al–0.35 wt % Mn alloy.

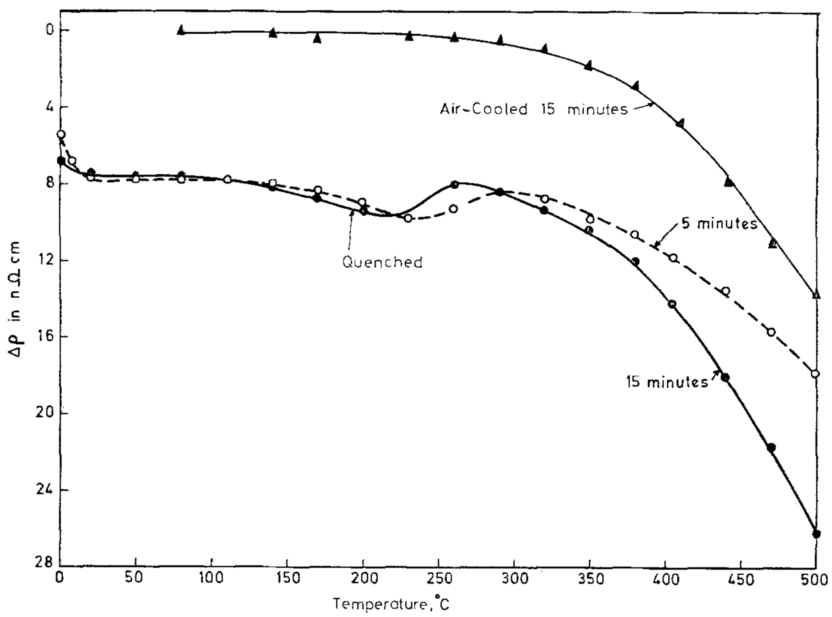

Figure 2 Isochronal annealing of quenched and air-cooled Al–1.0 wt % Mn alloy.

narrow. It is possible that there is clustering setting in at this stage but this requires more careful examination.

The fourth stage is associated with considerable decrease in resistivity and it corresponds to the only stage observed in the splat-cooled alloy. It is therefore associated with precipitation. To check the effect of cooling rate on the process of decomposition, a sample air-cooled from 620° C was isochronally annealed between 80 and 500° C for 15 min at each temperature. The results are shown in Fig. 2 where $\Delta\rho$ is the resistivity of the sample relative to that annealed for 15 min at 80° C. There is only one stage, occurring beyond $\sim$ 260° C. A comparison of the fall in resistivity for the air-cooled and quenched alloys shows that quenching has no significant effect on precipitation occurring in this stage. This is in contrast to the behaviour in Al–Si alloys where air-cooling drastically reduces the precipitation of Si [5].

References

1. M. HANSEN and K. ANDERKO, "Constitution of Binary Alloys" (McGraw-Hill, New York, 1958) p. 110.
2. S. P. BHAT, T. R. RAMACHANDRAN and A. K. JENA, *J. Mater. Sci.* 9 (1974) 1759.
3. D. P. LAHIRI, T. R. RAMACHANDRAN and A. K. JENA, *Trans. Ind. Inst. Metals*, 27 (1974) 360.
4. T. FEDERIGHI, in "Lattice Defects in Quenched Metals" (Academic Press, New York, 1965) p. 217.
5. H. S. ROSENBAUM and D. TURNBULL, *Acta Met.* 6 (1958) 653; 7 (1959) 664.

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Temperature dependence of magnetic anisotropy

The magnetic anisotropy of most ferromagnetics is a rapidly varying function of temperature. A number of workers [1, 2] have theoretically shown it to be related to the magnetization by

$$\frac{K_1(T)}{K_1(0)} = \left[\frac{M(T)}{M(0)}\right]^n$$

where $K_1(T)$, $K_1(0)$, $M(T)$ and $M(0)$ are the anisotropy constants and magnetization at temperatures T and 0 K respectively, and $n = 10$.

Charap and Weiss [3] showed that this tenth power law should hold for all ferromagnetics with cubic lattices. However, these theories have not been substantiated by experiment. Iron gave a third or fourth power law at low temperature changing to a ninth at higher temperatures [4], while nickel followed a much modified tenth power type relation [5]. An alloy of 3% Si–Fe gave a third or fourth power changing to a ninth power at higher temperatures [6].

The different methods used in the theoretical calculations all involve basic assumptions of the coupling between neighbouring electron spins. In the limit of complete correlation between spins theory gives a tenth power law, while for the limit of no correlation a sixth power has been predicted [7, 8]. This spin correlation has been described as extending over a region containing an atom and several shells of nearest neighbours [9], and evidence of spin ordering in regions of this size has been obtained by neutron diffraction [10].

It is well known that Ni–Fe alloys of approximately 75 at.% Ni undergo an atomic order-disorder transformation when given an appropriate heat-treatment. This transformation has a marked effect on most magnetic properties. In particular, the development of atomic order increases the Curie temperature and the saturation magnetization [11]. Because of the dependence of these parameters on spin-order it has been proposed that atomic order and spin order are inter-related [12]. In particular, changes in short range atomic order should alter the amount of spin order in the regions described in [9]. In this investigation specimens were obtained in

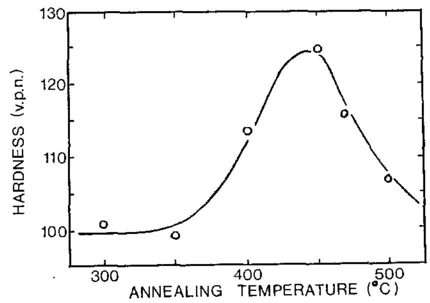

Figure 1 Relation between hardness and annealing temperature (5 h at each temperature).

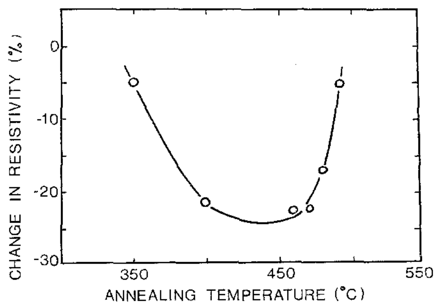

Figure 2 Relation between change in resistivity and annealing temperature (100 h at each temperature).