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LETTER TO THE EDITOR

The influence of plastic deformation on the magnetic properties in Fe–Al alloys

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Abstract. The magnetisation was measured in plastically deformed 34.0 and 36.2 at.% Al–Fe alloys and superlattice dislocations were observed by electron microscopy. At 34.0 at.% Al content, the spontaneous magnetisation increases considerably as a result of a slight plastic strain and has a broad maximum at about 200 K. At 36.2 at.% Al content, the magnetic susceptibility increases remarkably with plastic deformation and at the same time a spontaneous magnetisation appears and increases rapidly with decreasing temperature. The spontaneous magnetisation is discussed considering the atomic rearrangement due to superlattice dislocations. The change of magnetic properties is difficult to explain by local environment effects only.

The magnetic moment distribution in Fe–Al alloys has been studied from the viewpoint of local atomic environment effects by many investigators (Arrott and Sato 1959, Beck 1971, Besnus *et al* 1975). The transition between paramagnetism and ferromagnetism near 33 at.% Al content was explained by the number of nearest neighbour (NN) Al atoms around a host Fe atom, n_{Al} (Kouvel 1969). The magnetic moment of an individual Fe atom is fairly constant at 2.2 μ_B when n_{Al} is small and decreases with increasing n_{Al}; the magnetic moment is 1.46 μ_B at $n_{\mathrm{Al}} = 4$ and finally reaches zero at $n_{\mathrm{Al}} \simeq 8$.

The magnetic transition is also observed in heavily cold-worked alloys at above 33 at.% Al content. The change of atomic configuration due to cold-work produces the magnetic transition from a paramagnetic to a ferromagnetic phase. The number of host Fe atoms with different atomic configuration can be calculated as a function of dislocation density and the experimental results of Taylor and Jones (1958) have been qualitatively explained by one of the present authors (Takahashi 1986). The experimental study using specimens with various plastic strains should be pursued in order to have a more quantitative discussion. In the present study, magnetisation curves are measured for plastically deformed alloys with compositions of 34.0 at.% and 36.2 at.% Al. A few unexpected phenomena have been found: at 34.0 at.% Al content the spontaneous magnetisation, M_s, increases remarkably with a slight plastic strain and has a broad maximum at about 200 K, and at 36.2 at.% Al content the magnetic susceptibility, χ, increases considerably with strains of only a few per cent.

Rectangular prisms (50 × 2.5 × 2.5 mm^3) were cut out from single-crystal rods of 34.0 and 36.2 at.% Al–Fe alloys and then annealed at 1273 K in vacuum for one day. They were cooled very slowly at 30 K/day from 973 K to 673 K to obtain a high degree

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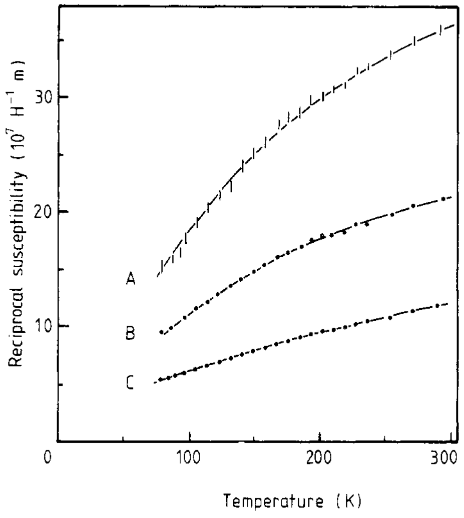

Figure 1. The variation of reciprocal susceptibility with temperature for the alloy containing 36.2 at.% Al. Curves A, B and C represent before plastic deformation and after 2.0 and 5.0% plastic deformation, respectively.

of B2-type long-range-ordered state. They were tested under tension at room temperature by an Instron-type machine. Magnetic measurements were made on a balance suitable for measuring the susceptibility of paramagnetic specimens. Thin-foil specimens for electron microscopy were cut out first from deformed specimens by spark machining and finally thinned by the electro-chemical polishing method. The thin foils were examined in a H-800 electron microscope operating at 200 kV.

In the 36.2 at.% Al–Fe alloy, magnetic measurements were made in a range of magnetic field strength between 0.84×10^5 to 9.8×10^5 A m^{-1} at temperatures from 77 K to room temperature. No significant variation of χ with magnetic field was detected in the undeformed specimen, implying that no ferromagnetism was present. The value of χ was determined by a least-squares fit to the isothermal magnetic data. The reciprocal susceptibility, $1/\chi(T)$ does not follow the Curie–Weiss law as shown in figure 1.

A plastic strain of 2.0% makes χ increase remarkably, and a weak ferromagnetism is also observed in the magnetisation curves. M_s and χ are obtained from the linear part above 4.2×10^5 A m^{-1} by a least-squares fit to the isothermal magnetic data and $1/\chi(T)$ and is also shown in figure 1. χ increases with plastic strain and attains a value three times as large as that before plastic deformation in the 5% strained specimen. By extrapolating the $1/\chi(T)$ curves one obtains a negative Curie temperature. The antiferromagnetic Curie temperature clearly remains unchanged under plastic deformation. M_s appears even under slight strain and increases with increasing plastic strain. Figure 2 shows the temperature dependence of M_s in the specimens deformed by 1.5, 5.0 and 5.5% strains. The value of M_s decreases rapidly with increasing temperature and disappears at temperature T_C. T_C increases with increasing plastic strain and attains a value higher than room temperature at above 6% plastic strain. In 8.5% strained specimens, a large value of M_s (33×10^{-4} Wb m^{-2}) was observed even at room temperature.

In the 34.0 at.% Al content alloy a ferromagnetic magnetisation process is observed before plastic deformation. The applied magnetic field is not enough to make the magnetisation curve completely saturated at a strength of 10^6 A m^{-1}. M_s and χ are obtained by the usual method of extrapolation back to zero-field of the linear parts above 5.6×10^5 A m^{-1}. The value of χ does not change under plastic deformation within the

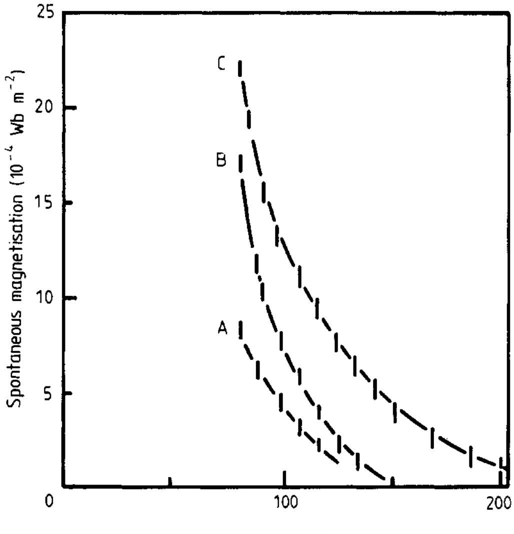

Figure 2. The variation with temperature of the spontaneous magnetisation due to plastic deformation at 36.2 at.% Al. Curves A, B and C represent plastically strained samples of 2.0, 5.0 and 5.5%, respectively.

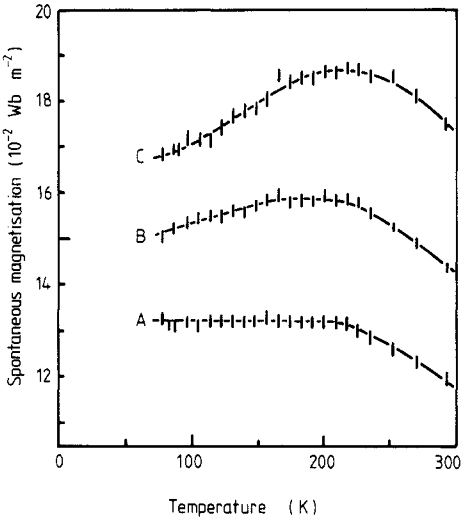

Figure 3. The values of spontaneous magnetisation with temperature before (curve A) and after plastic deformation (B: 4.0%, C: 7.5%) at 34.0 at.% Al content.

limit achievable by quantitative comparison. M_s is shown versus the test temperature in figure 3. The value of M_s in the 7.5% strained specimen is also shown in figure 3. The increase of M_s due to plastic deformation is very large and reaches ≃30% of the value of the undeformed specimen. M_s in the deformed specimen has a broad maximum at about 200 K. An M_s–temperature peak becomes notable with increasing plastic strain.

The slip system of both alloys was determined to be $\{110\}\langle 111\rangle$ by slip trace analysis. The $\langle 111\rangle$ superlattice dislocation is separated into two $(\frac{1}{2})\langle 111\rangle$ superpartials connected by an antiphase boundary (APB). The separation width was about 35 nm. The dislocation density is estimated by counting the number of intersections between dislocation lines and straight lines drawn at random on the photographic films. It is seen from electron diffraction observations that the specimens used in the present study have only B2-type superlattice characteristics even after plastic deformation.

In the B2-type structure of $Fe_{(1+c)}Al_{(1-c)}$ with $0 \leqslant c \leqslant 0.5$ there are two different sites; the α-sites (corner sites) are occupied only by Fe atoms and the β-sites (body centred sites) are by Al and Fe atoms (in a stoichiometric Fe–Al ordered alloy, β-sites are occupied only by Al atoms). The leading superpartial dislocation in atomically ordered alloys creates an APB on the $\{110\}$ glide plane after it has slipped. Near the APB, the arrangement of Fe and Al atoms is different from that in the ordered state. The atomic arrangement of α-site Fe atoms near the APB on the $\{110\}$ plane should play an important role in the magnetic transition. Near the APB, the α-site Fe atoms are arranged in a chain with their 1st NN (Takahashi 1986).

In the B2-type structure, the number of α- and β-site Fe atoms per unit volume near the APB having a different environment from the ordered state in their neighbours are given by

$$n_\alpha = r\rho/(\sqrt{2}a^2) \qquad n_\beta = cr\rho/(\sqrt{2}a^2)$$

where a is a lattice constant, ρ is the dislocation density and r is the spacing between two superpartial dislocations, which depends on the types of superlattice dislocations involved. (When a superpartial dislocation moves independently free from another superpartial, r is $2/\sqrt{\rho}$.)

Then, M_s at 0 K would be expressed as a simple function of the dislocation density if Fe atoms nears the APB behave ferromagnetically. The increase of M_s at 34.0 at.% Al would also be explained if Fe atoms at α- and β-sites have magnetic moments near the APB of 2.2 μ_B and 1.46 μ_B, respectively.

The experimental value of M_s at 77 K is about twice as much as the calculated one at 36.2 at.% Al content. At 34.0 at.% Al, however, the experimental value is about 35 times as large as the calculated one. In order to explain this large difference, a theory could be introduced where the ferromagnetic Fe atoms on the APB have a long-range magnetic influence on their neighbouring Fe atoms and induce a ferromagnetic change in them. This long-range magnetic influence would extend to 3 nm and would be possible in the delicate composition. The same idea has also been applied to the explanation of M_s in Pt_3Fe (Takahashi and Umakoshi 1988).

The value of χ at 36.2 at.% Al changes considerably as a result of plastic deformation. The ferromagnetic clusters, which occupy an area of at least 10^2 nm, would cause the long-range influence on the paramagnetic interaction to extend over the whole crystal. However, even above T_C where M_s disappears, the value of χ does not return to the initial one before plastic deformation. Thus, in conclusion, the long-range influence effect remains at above T_C. The influence seems difficult to explain by the local environment model (Besnus *et al* 1975).

The value of χ of the undeformed Fe–36.2 at.% Al alloy does not follow the Curie–Weiss law and has a different value from that of Arrott and Sato (1959). The value measured by them is larger than the present result and is comparable to the value of our 5.5% strained specimen. Since χ is very sensitive to plastic strain (as shown in the present study) and the variation of the reciprocal susceptibility with temperature becomes linear as the plastic strain increases, therefore it would seem that their specimens would have contained a slight plastic strain.

The Curie temperature becomes high with increasing strain as shown in figure 2. The ferromagnetic clusters distribute themselves over the glide plane, making a strip along the dislocation. These magnetic clusters have their own Curie temperature. As the size of each strip is independent of plastic strain at the initial deformation stage, the Curie temperature of each ferromagnetic cluster would be the same. If there is no magnetic interaction between the ferromagnetic clusters, the Curie temperature should be independent of plastic strain, but the experimental evidence is against this supposition. Experimental evidence would indicate that there exists some magnetic interaction between these clusters, which depends on the distance between the clusters and decides the Curie temperature. This interaction seems to support the long-range influence in χ.

M_s has a maximum at about 200 K in the 34.0 at.% Al–Fe alloy with plastic deformation. A similar phenomenon was discovered by Danan and Gengnagel (1968); in the magnetisation of the undeformed specimens with 29 to 33 at.% Al contents, a broad maximum was found at about 200 K. It is not possible to find a reasonable explanation for the occurrence of the maximum of M_s at about 200 K but these two broad maxima near 200 K must be caused by the same effect.

The detailed mechanism of these interesting phenomena including the broad maximum has not yet been determined. Further study is now in progress.

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