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Magnetic Annealing Effect in Iron-Aluminum Single Crystals

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Magnetic anisotropy induced by magnetic annealing was measured for spherical single crystal specimens of 17.5, 20, 23, 25 and 29.5 atomic per cent aluminum iron alloys. The alloys with composition 23 to 29.5 per cent do not respond to magnetic annealing because of a rapid formation of the superlattice Fe_3Al. The uniaxial anisotropy constant, K_u, reaches its maximum value, 5×10^3 erg/cc, at 17.5 atomic per cent aluminum and decreases in proportion to the number of Al-Al pairs as the composition approaches Fe_3Al. Fourth order anisotropy was also observed to be induced at 20 atomic per cent aluminum.

1. Introduction

Magnetic annealing of iron-aluminum alloys has been studied by many investigators[1)-8)]. Some of them[1)2)] used the alloy nearby Fe_3Al and found no effect of magnetic annealing. Suzuki[3)] found that his specimen did respond to magnetic annealing and also observed a non-zero value of induced anisotropy for <100> magnetic annealing, in contrast to the prediction of the Néel-Taniguchi theory[4),5)]. Sugihara[6)] measured the effect of magnetic annealing on initial and maximum permeability over a wide range of composition. He found that the effect is maximum at 19.0 at % Al and is very small for more than 21.2 at % Al. Biorci, Ferro and Montalenti[7)] observed internal friction due to a rotation of atom pairs which is similar to the mechanism of magnetic annealing and found its logarithmic decrement changes with alloy composition almost as the change in the number of Al-Al pairs. Birkenbeil and Cahn[8)] measured the magnetic anisotropy induced by magnetic annealing and also by stress annealing from 9.6 to 24.8 at % Al, using polycrystalline specimens. Recently Gengnagel and Wagner[9)] reported the measurement of magnetically induced anisotropy for single crystal disks of 18.9, 21.5 and 25.1 at % Al and, for 21.5 % Al-Fe, observed the dependence of the induced anisotropy constant upon the crystallographic orientation of the annealing field.

Suzuki[10)] also found that a fourth-order anisotropy is induced for a slow rate of cooling (1°C/min) and that its magnitude depends strongly upon the crystallographic direction of annealing field. He also found that the axis of the fourth order anisotropy does not necessarily coincide with the principal axes of the crystal. Birkenbeil and Cahn[8)] and Gengnagel and Wagner[9)] also reported the presence of such a fourth order anisotropy.

2. Experiment

Single crystals were grown by Bridgeman method and ground to spherical shape by a method similar to that of Durand[11),12)]. The average size of the specimen spheres is about 7 mm in diameter and all diameter are equal within±2 microns (Fig. 1). A specimen is set into a high temperature torque magnetometer which is equipped with a air-flow bearing with 0.02 mm air-gap, heated up to a high temperature and cooled down to room temperature at a controlled rate in a magnetic field applied parallel to a certain crystallographic direction. Sometimes we annealed a specimen at 300°C in a magnetic field to see how the induced anisotropy depends upon the formation of the superlattice Fe_3Al.

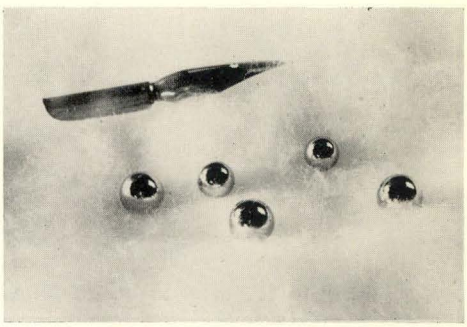

Fig. 1. Single crystal specimens of Fe-Al alloys,

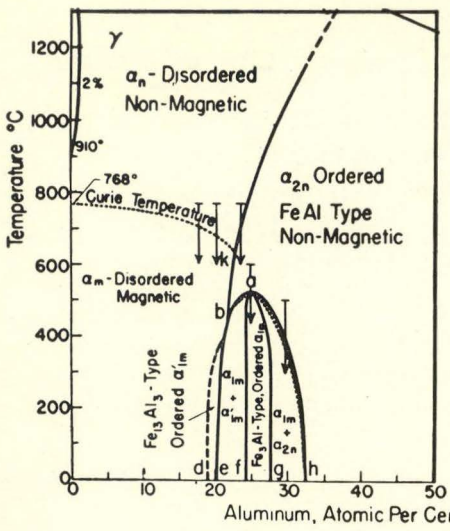

Fig. 2. Phase diagram of Fe-Al system as determined by Taylor and Jones[13]. Arrows indicate the compositions of the present specimens and temperatures from which the specimens were cooled in a magnetic field.

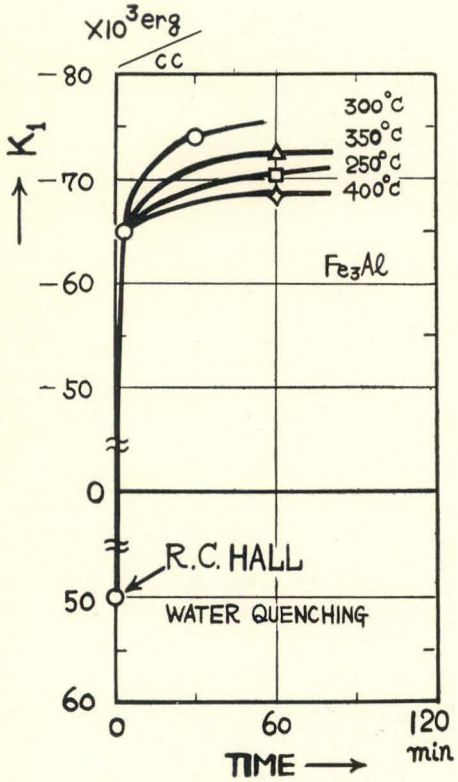

Fig. 3. Change of the magnetocrystalline anisotropy constant K_1 caused by a duration of annealing at various temperatures.

3. Results and Discussions

First we confirmed that the alloys with compositions 23%, 25% and 29.5% do not respond to magnetic annealing. The reason for this, is thought to be due to the rapid formation of the Fe_3Al superlattice, because all three compositions are in the range of Fe_3Al ordering (Fig. 2). Fig. 3 shows the variation of K_1 measured at room temperature as a function of duration of annealing at various temperatures. From this graph we deduce that the superlattice will be almost complete after a few minutes of annealing. We observed that the alloy with 17.5% Al-Fe does respond to the magnetic annealing. The torque curves were observed

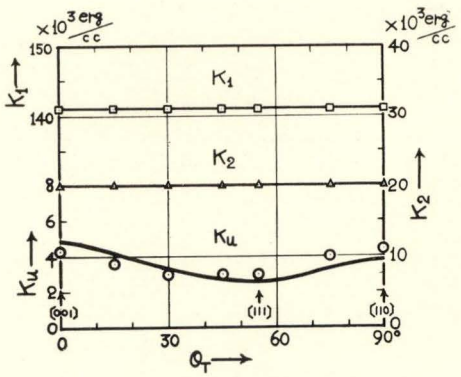

Fig. 4. Dependence of anisotropy constants K_1, K_2 and K_u upon crystallographic direction of the annealing field (17.5 at. % Al-Fe). Circles indicate the experimental results for (110), and the solid line for K_u was drawn by using $F=4.9\times10^3$ erg/cc and $G=5.0\times10^3$ erg/cc, both values of which were determined by the experiment for (001).

for different directions of annealing field and by subtracting a torque curve for non-magnetically annealed one from them the induced anisotropies were estimated. The coefficient of K_u thus determined was plotted in Fig. 4 as a function of crystallographic orientation of the annealing field together with K_1 and K_2. The values of K_1 and K_2 stay at constant values, while values of K_u, or the induced uniaxial anisotropy, depends upon the crystallographic orientation of the annealing field. This dependence is well expressed by the phenomenological formula

$$E_u=-F\sum_i\alpha_i^2\beta_i^2-G\sum_{i>j}\alpha_i\alpha_j\beta_i\beta_j, \qquad (1)$$

given by the Néel-Taniguchi theory, where the α_i's and β_i,s are the direction cosines of intrinsic magnetization and of annealing field. From the comparison between the experiment and theory, we can determine the value of F and G, which are plotted in Fig. 5 as a function of alloy composition. The hatched triangle and circle are the values observed by Gengnagel and Wagner,[9] and the solid triangle and circle are those obtained by Suzuki[3]. The non-zero values

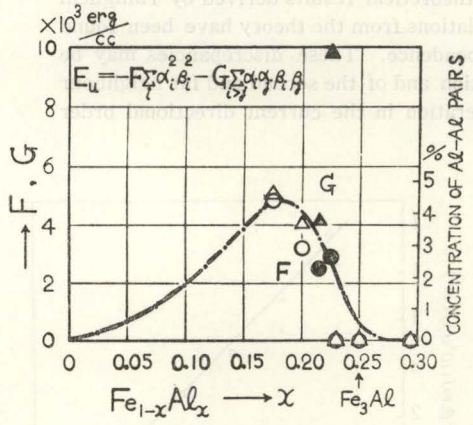

Fig. 5. Dependence of the two coefficients F (circles) and G (triangulars) upon the alloy composition of Fe-Al system. Solid marks and hatched marks are due to Suzuki[3] and Gengnagel and Wagner[9] respectively. The broken line indicates the number of Al-Al pairs as determined by Biorci, Ferro and Montalenti[5] by using the x-ray data of Bradley and Jay[10].

of F should be interpreted in terms of second nearest neighbor interactions. The chain line represents the number of Al-Al pairs as estimated by Biorci, Ferro and Montalenti[7] by using the x-ray data of Bradley and Jay[14]. Experimental points are in fair agreement with this curve, which means that the experiment can be explained in terms of directional order between iron and aluminum atoms. There is also some tendency for the coefficient G to decrease more slowly than the coefficient F decreases as the composition appoaches Fe_3Al. We interpret this behavior in terms of directional ordering between two kinds of iron atoms with different magnetic moments, which have previously been found to exist in ordered Fe_3Al according to the neutron diffraction results of Nathans et al[15].

It was also observed that when the alloy of the composition 20% Al-Fe was cooled at 2.5°/min from 700°C, the induced anisotropy contained two-, four- and six-fold anisotropy. This fact can be interpreted phenomenologically in terms of a quadrupole-quadrupole interaction and also a higher order interaction between neighboring atoms. However, the reason why such higher order anisotropies are induced only in a small composition range and also in this particular alloy system is still uncertain.

References

1 R. C. Hall: J. Appl. Phys. **28** (1957) 1212.
2 Ya. S. Shur and A. A. Glazer: Fizika metallov i Metalloveniya **5** (1957) 355.
3 K. Suzuki: J. Phys. Soc. Japan **13** (1958) 756.
4 L. Néel: Compt. Rend. **237** (1953) 1613; J. Phys. et Rad. **15** (1954) 225.
5 S. Taniguchi and M. Yamamoto: Sci. Rep. Inst. Tohoku Univ. **A6** (1954) 330; S. Taniguchi: Sci. Rep. Res. Inst. Tohoku Univ. **A7** (1955) 269.
6 M. Sugihara: J. Phys. Soc. Japan **15** (1960) 1456.
7 Gi Biorci, A. Ferro and G. Montalenti: Tech. Note Inst. Galileo Ferraris 4a (1960).
8 H. J. Birkenbeil and R. W. Cahn: J. Appl. Phys. **32** (1961) 362S.
9 H. Gengnagel and H. Wagner: Z. f. ang. Phys. **13** (1961) 174.
10 K. Suzuki: Reported at annual meeting of the Physical Society of Japan, October (1958).
11 J. Durand: Rev. Sci. Instr. **30** (1959) 840.
12 T. Wakiyama: Bull. Kobayashi Inst. Phys. Res. **10** (1960) 127.
13 A. Taylor and R. M. Jonse: J. Phys. Chem. Solids **6** (1958) 16.
14 A. J. Bradley and A. H. Jay: Proc. Roy Soc. **A136** (1932) 210.
15 R. Nathans, M. T. Pigott and C. G. Shull: J. Phys. Chem. Solids **6** (1958) 38.