Letters to the Editor

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The Origin of High Permeability in Permalloy

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IT is well known that alloys of the composition near Ni_3Fe have unusual magnetic properties sensitive to heat treatment: (a) when cooled rapidly from 600°C, they develop extremely high initial and maximum permeabilities (μ_a and μ_{max}); (b) when cooled slowly or annealed in a magnetic field, they exhibit high μ_{max} only in the direction parallel to the field applied during the heat treatment. The author has investigated these properties in connection with the formation of the superlattice at 490°C, and explained (b) in terms of "directional order."[1]

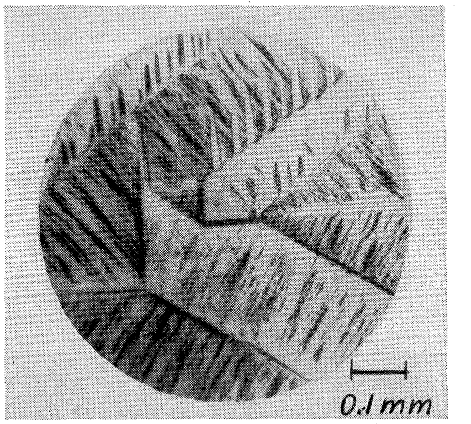

FIG. 1. Domain pattern observed on (110) surface of Ni_3Fe crystal. Nearly perfect order. $K_1 = -28\times10^3$ ergs/cc.

The principal points are as follows: The fractional contraction $\delta l/l$ observed[1] during the superlattice formation at 490°C was -4.4×10^{-4}. This is considered to correspond to the fractional difference of pair-lengths between like and unlike atom-pairs, because the ordering process means an increase of the unlike atom-pairs. If, therefore, the fractional numbers of unlike atom-pairs, or the degrees of order, are different in different bond directions, the lattice should deform spontaneously to the order of 4.4×10^{-4}. Such an arrangement of atoms, the directional order (d.o.), will be promoted by the ordering process under the influence of the magnetostrictive force, which usually, being counterbalanced by the elastic force, gives rise to but a small amount of strain. As soon as the alloy is cooled and the d.o. frozen, the spontaneous magnetization becomes stable in the same direction as it was during annealing, on account of the interaction between magnetostrictive force and the strain of d.o. The magnitude of strain necessary to explain the observed anisotropy in the case (b) was 1.7×10^{-4}, which is a reasonable value for the strain of d.o.

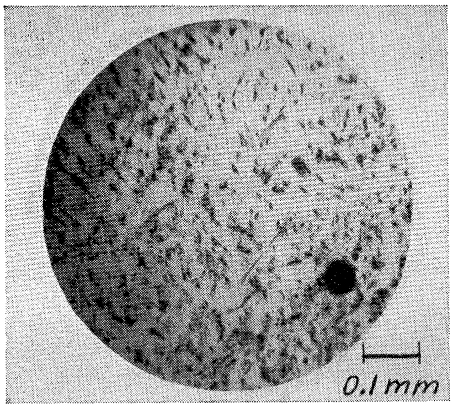

FIG. 2. Domain pattern observed on (110) surface of Ni_3Fe crystal. Partially disordered. $K_1 = -2\times10^3$ ergs/cc.

The origin of the unusually high μ_a in case (a), however, remains in question. In this respect, the author investigated the variation of domain structure during the disordering process by means of powder pattern technique.[2] A large single crystal (*ca* 2 cc) of the alloy Ni_3Fe[3] was prepared by sudden solidification after supercooling *ca* 100° below the mp to prevent segregation. Two specimens, one for the domain pattern observation and the other for the torquemeter measurement, were cut along a (110) plane. Perfect order was attained by annealing for one week at 490°C and several days below this temperature. The disordering process was carried out by raising the temperature from 490° stepwise to 610°C, the procedure being interrupted several times by quenching for observations. Both specimens were always treated together.

The crystal anisotropy constant K_1 decreased from -29×10^3 ergs/cc to zero during the disordering process, as has been reported by Grabbe.[4] At first the domain patterns showed a structure having 180°, 109°, and 71° boundaries, which was to be expected for a crystal having the easiest magnetization along the $\langle 111\rangle$ direction (Fig. 1). No essential changes were observed until K_1 decreased to -7×10^3, except some slight deformation of linear boundaries which appeared in the later stages. Further disordering baking (at 550°C), however, made the figure rather irregular, in which 180° boundaries were broken and deformed and numerous crooked boundaries appeared (Fig. 2). At this transition K_1 was -2×10^3. When quenched from 610°C, fine crooked and dotted line-like boundaries appeared at a distance of *ca* 0.01 mm (Fig. 3). The irregular movement of these boundaries under

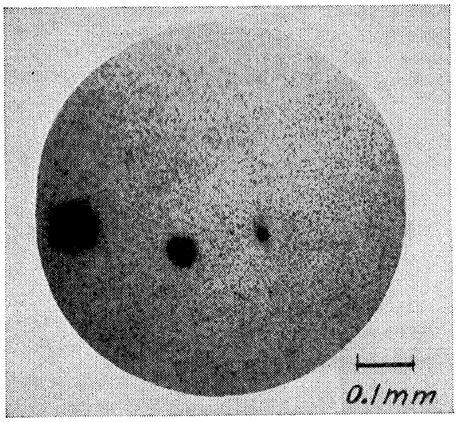

FIG. 3. Domain pattern observed on (110) surface of Ni_3Fe crystal. Nearly perfect disorder. $|K_1| < 0.4\times10^3$ ergs/cc.

the influence of an applied field could be observed only when the size of the colloid particles was adequate.

The fine division of domains thus observed is to be attributed to the random distribution of strains under the condition that $K_1<(3/2)\lambda E\epsilon$, where λ means the saturation value of magnetostriction, E the Young's modulus and ϵ the strain. There is evidence that the strain is caused by the random generation of d.o. For, if we substitute into the above expression $\lambda=5\times 10^{-6}$, $E=2\times 10^{12}$ dyne/cm² and $\epsilon=1.7\times 10^{-4}$, the strain of d.o., we get 2.5×10^3 ergs/cc, which is nearly equal to the actual value of K_1 when the transition of patterns took place.

The fine domain structure described above might, under proper conditions, give rise to high μ, as will be discussed along the following lines: (1) The crooked boundaries in this structure might continuously decrease their area in the process of magnetization, and the resulting decrease of exchange energy could play a role in promoting the magnetization. The exchange energy stored in the demagnetized state was estimated at *ca* 10^2 ergs/cc if we assume a distribution of spin-direction with a period of 0.01 mm. If, therefore, the d.o. were destroyed so much by further disordering that $\lambda E\epsilon$ decreases to 10^2 ergs/cc, magnetization would take place without any external work. This means a high mobility of the boundaries. (2) The influence of inclusions or lattice defects would be nothing but a local one in this structure, without any essential effect on the magnetization as a whole. (3) The contribution to μ_a will be proportional to the total area of the boundaries, which seems to be very large in this structure as compared to usual domain structure.

Too severe disordering will destroy the fine domain structure so as to decrease the exchange energy, again decreasing μ_a. It is experimentally known that the maximum μ_a is attained by a proper rate of quenching for permalloy[5] and by proper prolonged annealing for Mo-permalloy.[6] These treatments are interpreted as means of attaining proper values of the strain.

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[1] S. Chikazumi, J. Phys. Soc. (Japan) **5**, 327 (1950).

[2] Williams, Bozorth, and Shockley, Phys. Rev. **75**, 155 (1949).

[3] 25.2 weight percent Fe, 74.8 percent Ni, 0.02 percent Mn, as the result of chemical analysis.

[4] E. M. Grabbe, Phys. Rev. **57**, 728 (1940).

[5] G. W. Elmen, J. Franklin Inst. **207**, 583 (1929).

[6] R. M. Bozorth, *Ferromagnetism* (D. Van Nostrand Company, Inc., New York, 1951), p. 140, and K. Yasukochi, unpublished.

Activation of LiI Crystal Phosphors*

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LITHIUM iodide crystals have been grown[1,2] with different activators and tested for pulse height and resolution with thermal neutrons from the BNL reactor. A collimated beam ⅛ in. in diameter was used for exploring different parts of the crystals. A ⅞ in. diameter uniform beam was available for testing over-all response. The crystals, wet with Nujol, were placed on a 5819 photomultiplier inside a 1/32 in. thick diffuse reflector made from titanium oxide in lucite. The electronics used were essentially the same as described previously.[3] The pulse height has been measured in terms of the gamma-ray energy necessary to produce a photoelectric line at the same pulse height in a standard[3] NaI(Tl) crystal.

In general, single crystals ⅝-in. diameter and 2½ in. long were grown; then cleaved into one centimeter thick sections. These pieces were cleaved into small (2 mm) cubes if the pulse-height distribution was very nonuniform. Crystals grown at 4 in. per day with an excess of TlI activator (0.5 percent by weight) were clear and colorless with a thin layer of thallous iodide around the outside of the crystal. Spectroscopic analysis[4] of a typical piece from the tip of the crystal gave 0.008 percent by weight of TlI; at the top 0.013 percent was found. The pulse heights from these pieces were in the ratio of 1:2. Two regions of pulse height were favored, 120 to 180 kev, and 300 to 450 kev, NaI(Tl) equivalent. In general pieces of the order of 2 mm³ gave the resolution found for the equivalent pulse height in NaI. However, larger pieces had either two peaks or a very broad distribution in pulse height (Fig. 1). Exploration with the collimated neutron beam showed that the transition between the two regions occurs within less than ⅛ inch. Attempts to grow uniformly activated crystals by using growing speeds from 1.7 in. to 7 in. per day were unsuccessful.

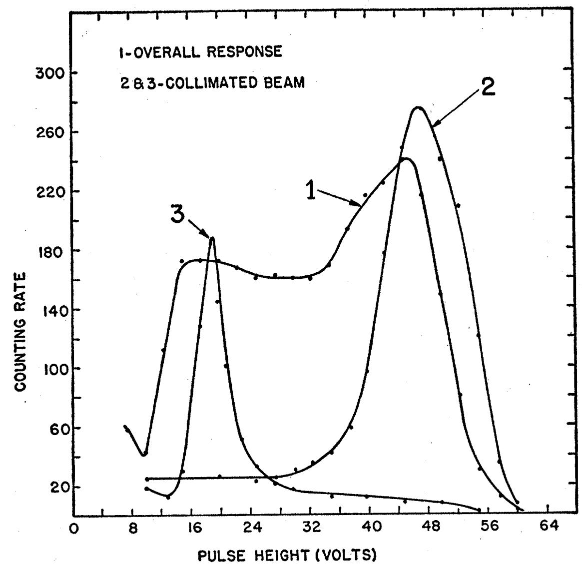


FIG. 1. LiI(Tl) ¾ in. × ½ in. × ⅛ in. crystal irradiated with thermal neutrons. (1) Response of whole crystal in uniform beam. (2 and 3) ⅛ in. beam at characteristic spots in crystal.

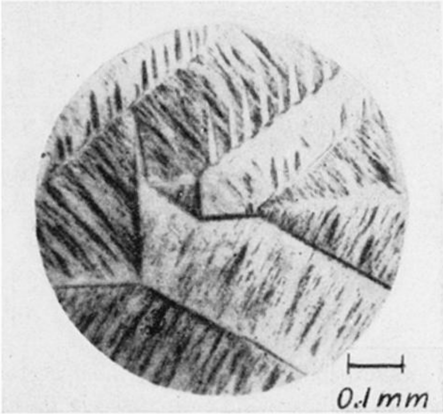
From the above it is evident that the pulse height is a function of thallium concentration. Similar variations in thallium concentration were also found by Harshaw[5] in NaI(Tl) crystals (0.1 to 0.5 percent). However, in that case the pulse height was not affected. It seems that the amount of thallium entering the LiI lattice is insufficient for complete activation. A search is being made for other activators which can enter the crystal in sufficient amounts. So far, indium, tin, and silver have been tried. Reagent grade chemicals were used, but small impurities may have an unexpected effect.

LiI(In) behaved very much like LiI(Tl); most of the activator was expelled from the lattice. On neutron irradiation two peaks were found corresponding to 45 and 80 kev. The fluorescence band is a whitish orange and does not match the 5819 spectral response.

A crystal grown with 0.15 percent by weight $SnCl_2\cdot 2H_2O$ activator was transparent yellow at the tip, becoming more and more opaque yellow toward the top. All but the most opaque part gave a uniform pulse height of 197 kev, and the resolution found with NaI(Tl) for that pulse height (14.5 percent). The decay time is almost the same as that of LiI(Tl). The fluorescence band is in the green.

A crystal grown with 0.3 percent AgI activator was colorless and transparent at the tip, gradually becoming cloudy toward the top. All the activator went into the crystal, since no AgI was found on the surface. The pulse height was the equivalent of 210 kev. Different sections of the crystal showed a pulse-height variation of 20 percent. The fluorescence band is greenish yellow.

The results with the tin activator looked sufficiently promising to grow a larger crystal. A 1½ in. ampule was used and 0.05 percent by weight $SnCl_2\cdot 2H_2O$ was added. Five parallel crystals starting at the tip grew from this melt. The tip was transparent and slightly yellow; the top was cloudy. Pieces approximately 1 × ¾ × ⅜ inches gave a resolution between 13.7 percent and 16.5 percent, and a pulse height equivalent to 250 kev (Fig. 2). The



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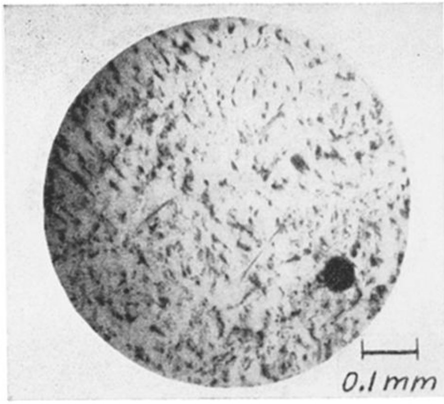

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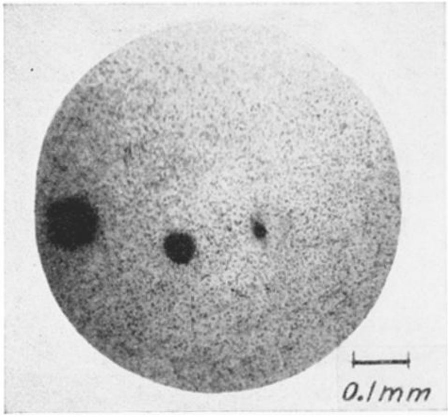

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