ment to injection for modulating bulk and contact properties. Transient and transport effects associated with extraction can be used for measuring minority carrier drift mobility and lifetime. A special feature of extraction is its usefulness in extending the temperature range of operation of diodes and transistors. This may be accomplished with an auxiliary, extraction electrode and sweep field, or more simply, if less efficiently, by utilizing a base contact which satisfies the condition for extraction. In the latter case, when reverse current at the collector is high enough to permit appreciable field in the base region, considerable minority carrier depletion, and consequent enhancement of reverse resistance of the collector can be observed. Thus an extraction base contact, not only suppresses undesirable excess minority-carrier injection, but it also depresses the minority-carrier current which would normally be present.

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Effect of Shape Anisotropy on the Coercive Force of Elongated Single-Magnetic-Domain Iron Particles

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Elongated single-magnetic-domain iron particles, 150 angstrom units in diameter, have been prepared with properties that definitely confirm the existence of a shape anisotropy effect on coercive force. This conclusion is based upon four observations: (1) Torque curve analysis shows the predominating anisotropy effect to be uniaxial. (2) With increasing particle elongation, the temperature coefficient of coercive force departs from the temperature coefficient of crystal anisotropy and approaches the temperature coefficient of saturation induction. (3) Coercive forces greater than 2000 oersteds for iron have been measured. (4) A direct correlation is observed between particle coercive force and elongation.

I. INTRODUCTION

A BETTER understanding of the basic factors which determine the properties of high-coercive-force magnetic materials is emerging from studies of submicroscopic ferromagnetic particles, too small to contain magnetic domain boundaries. These "single-domain particles" cannot change their magnetization in response to an externally applied field by the relatively easy process of domain boundary movement, in the manner of soft magnetic materials, but respond to a field by the more difficult process of rotating their magnetization vectors. The magnetic anisotropy effects, opposing domain rotation, thus determine the coercive force of these particles.[1] Although the sources of magnetic anisotropy are not completely understood, four effects have been suggested: magnetocrystalline anisotropy,[2] strain anisotropy,[3,4] shape anisotropy,[4] and surface anisotropy.[5] The existence of these proposed anisotropy effects has not been experimentally confirmed, with the exception of crystal anisotropy, which was conclusively demonstrated in an investigation of the coercive force of fine particles of manganese-bismuth by Guillaud.[2] Crystal anisotropy has also been studied in iron by Néel[6] and in barium-iron oxide and related compounds by Went *et al.*[7]

It is now eight years since Stoner and Wohlfarth,[4] Néel,[8] and Guillaud[3] first suggested that the shape anisotropy of an elongated single-domain particle of iron should be more than ten times as great as its crystal anisotropy. Although the existence of shape anisotropy has not been confirmed experimentally during this time, Weil,[9,10] Galt,[11] and Meiklejohn[12] have attributed discrepancies between observed and calculated coercive force values to a possible shape-anisotropy effect arising from statistical fluctuations in particle dimensions, and Nesbitt[13,14] and Kronenberg[15] have established the presence of an elongated precipitate

[1] C. Kittel, Phys. Rev. **70**, 965 (1946); see also Revs. Modern Phys. **21**, 541 (1949).
[2] C. Guillaud, thesis, Strasbourg, 1943 (unpublished).
[3] C. Guillaud, J. phys. radium **8**, 347 (1947).
[4] E. Stoner and E. Wohlfarth, Trans. Roy. Soc. (London) **A240**, 599 (1948).
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[6] L. Néel, Compt. rend. **224**, 1488 (1947).
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[10] L. Weil, International Powder Metallurgy Day, Graz, July, 1948, No. 17 (unpublished).
[11] J. Galt, Phys. Rev. **77**, 845 (1950).
[12] W. Meiklejohn, Revs. Modern Phys. **25**, 302 (1953).
[13] Nesbitt, Williams, and Bozorth, J. Appl. Phys. **25**, 1014 (1954).
[14] E. Nesbitt and P. Heindenreich, Elec. Eng. **71**, No. 6, 530 (1952).
[15] K. J. Kronenberg, Z. Metallkunde **45**, 440 (1954).

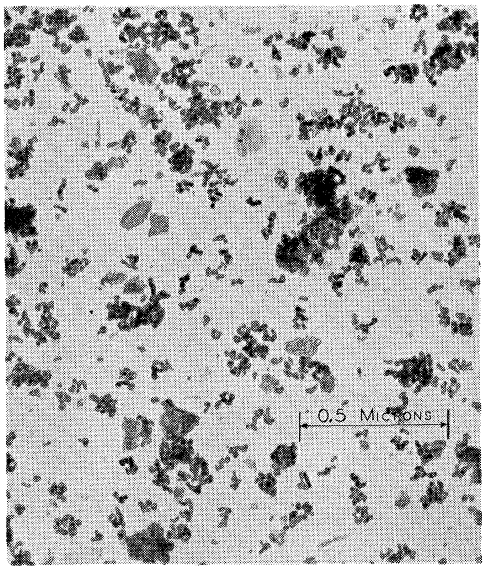

FIG. 1. Fine particle iron A. Median elongation 1.3; coercive force 1090 oersteds.

possessing shape anisotropy in the permanent-magnet alloy Alnico V.

It is the purpose of this paper to report on recent work at this laboratory which has resulted in the production of substantially elongated single-domain iron particles of high coercive force with properties that definitely confirm the existence of the shape-anisotropy effect.

II. DESCRIPTION OF THE PARTICLES

The preparation and observation of elongated iron particles with diameters between 100 and 1000 angstrom units present experimental difficulties which have prevented previous confirmation of the shape anisotropy effect. The particles described in this paper were produced by electrodepositing iron into a molten metal cathode. This venerable technique was employed by Herschel[16] over a century ago, and has since been used by Nagaoka,[17] Antik,[18] Dean,[19] Pawlek,[20] Mayer,[21] and Meiklejohn[12] to produce single-domain iron particles. By modifying this process in certain essential details, it was discovered that substantially elongated iron particles could be produced.

FIG. 2. Fine particle iron B. Median elongation 2.7; coercive force 1360 oersteds.

Figures 1 through 4 are electron micrographs of these particles at 50 000× magnification made by dispersing the particles on a thin film for direct observation with a high resolution electron microscope.[22] This technique successfully achieved resolutions down to 20 angstrom units, and permitted a direct measurement of particle size and shape. The diameter and length of each of the several hundred particles that could be resolved in a 100 000× electron micrograph were measured to the nearest quarter of a millimeter (corresponding to 25 angstrom units actual size), and distribution curves prepared for each sample. Typical curves are shown in Fig. 5. The diameter distribution was essentially Gaussian, with a standard deviation on the order of 35 angstrom units for most samples. The length-to-

FIG. 3. Fine particle iron C. Median elongation 3.0; coercive force 1600 oersteds.

[16] J. Herschel, Trans. Roy. Soc. (London) **114**, 183 (1824).
[17] H. Nagaoka, Ann. Physik. (*3*) **59**, 66 (1896).
[18] I. Antik and T. Kubyschkina, Wiss. Ber. Univ. Mosk. **11**, 143 (1934).
[19] R. Dean and C. Davis, U. S. Patent 2,239,144 April 22, 1941.
[20] F. Pawlek, Z. Metallkunde **42**, 451 (1950).
[21] A. Mayer and E. Vogt, Z. Naturforsch. **7a**, 334 (1952).
[22] M. Schuster and E. Fullam, Ind. Eng. Chem., Anal. Ed. **18**, 653 (1946). The authors are deeply indebted to E. F. Fullam of E. F. Fullam, Inc., for his beautifully detailed electron micrographs which have contributed so greatly to this work.

diameter ratio of the particles showed a logarithmic rather than a linear Gaussian distribution.

Figure 1 shows the almost spherical particles of sample *A*. The authors have prepared similar particles by the low-temperature decomposition of iron salts as described by Honda[23] and others.[24–28] Particles from sample *B* with twice this elongation, but characterized by an irregular, roughened surface, are shown in Fig. 2. Even greater elongations with a somewhat different structure are shown in Figs. 3, 4, and 6. These views of samples *C*, *D*, and *E* reveal the presence of dendritic branches on many of the particles. Samples *A* through *D* have mean particle diameters between 140 and 150 angstrom units; sample *E* has a larger mean particle diameter of 175 angstrom units. These diameters refer to the main body of the particles without any correction for the dendritic branches.

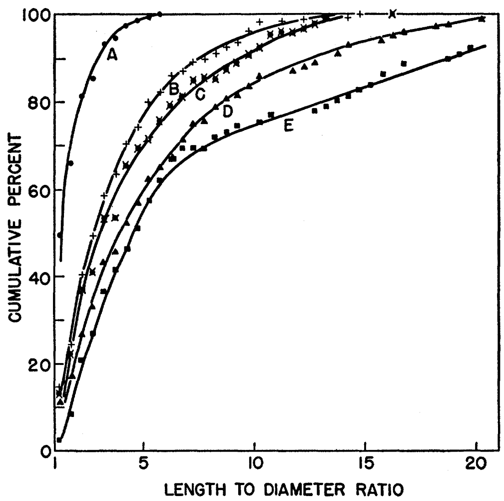

FIG. 5. Distribution of particle elongations for samples *A*, *B*, *C*, *D*, and *E*.

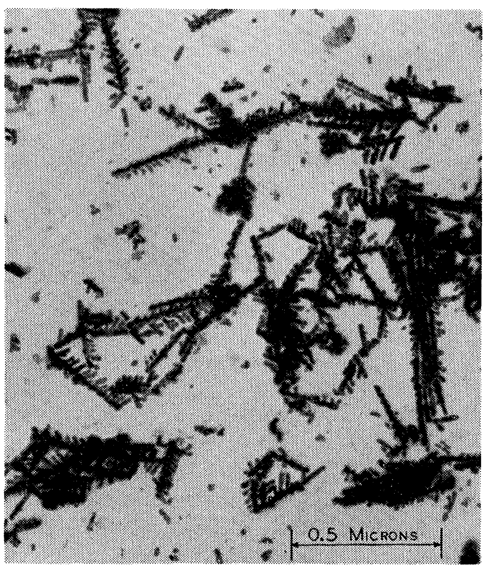

FIG. 4. Fine particle iron *D*. Median elongation 4.0; coercive force 1600 oersteds

It is interesting to note that the median length-to-diameter ratio of the particles in sample *E* is 4.6 and that 25% of this sample consists of particles with an elongation ratio greater than 10, with a few as high as 40. Stereoscopic electron micrographs have shown that the dispersion technique used causes most of the particles to lie flat on the film, minimizing distortion due to third-dimension alignment.

III. MAGNETIC MEASUREMENTS

To determine the intrinsic coercive force of each sample, the particles were dispersed in a liquid to a packing density below 5%, and then frozen in liquid nitrogen. The sample was then magnetized, and the reverse field required to reduce its intrinsic induction to zero determined at −197°C. Zero induction was detected by a sensitive galvanometer connected to a search coil fixed in the demagnetizing field. Coercive force values given are reproducible to 2%, with an overall accuracy well within 5%. More precise magnetic permeameter measurements of the complete hysteresis loops were made on bars prepared by dispersing the particles in a lead-tin-bismuth low-melting alloy. The intrinsic coercive force measurements were confirmed by the permeameter, which is accurate to within 2%. The particles dispersed in the low-melting alloy were

FIG. 6. Fine particle iron *E*. Median elongation 4.6; coercive force 1850 oersteds.

[23] K. Honda, Nippon Kinzoku Gakkai-Shi No. 1, 3 and 19 (1937).
[24] British Patent 590,392, April 7, 1942.
[25] F. Bertaut, Compt. rend. **229**, 417 (1949).
[26] F. Lihl, Acta Phys. Austriaca **4**, 360 (1951).
[27] B. Kopelman, Elec. Eng. **71**, No. 5, 447 (1952).
[28] Stewart, Conard, and Libsch, J. Metals **7**, 152 (1955).

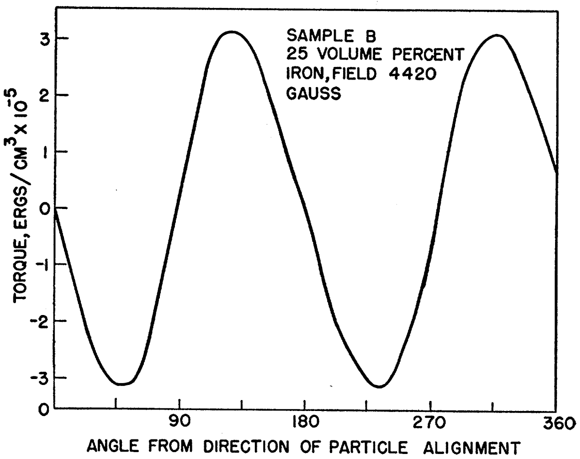

FIG. 7. Torque magnetometer curve.

suitable for precise measurements over the temperature range from −197°C to +25°C, which allowed the temperature coefficients of induction and coercive force to be established.

To provide further information on the nature of the anisotropy responsible for the observed magnetic properties, samples were prepared suitable for torque magnetometer studies. These one-inch diameter disks, 24 mils thick, contained 25% iron by volume, and were directionalized by applying a 5000 gauss field along the diameter during the solidification of the low-melting alloy matrix. The measurements were made by R. D. Robinson using the recording torque magnetometer at the General Electric Research Laboratory.

DISCUSSION

The electron micrographs clearly reveal the elongation of the particles, and the magnetic properties observed are all consistent with the concept of single-domain particles of iron with a high coercive force derived from shape anisotropy. Each of the observed magnetic properties will be considered in turn.

A. Torque Magnetometer Curves

The typical torque magnetometer curve shown in Fig. 7 indicates that the magnetic anisotropy of the sample is uniaxial rather than cubic. If any crystalline anisotropy is present, it was either not aligned by the directionalizing field, or was too small to be detected. No torque was measurable on the round particle samples. Electron microscope work to be published elsewhere reveals that the long axis of each particle is aligned by the directionalizing field. This, in conjunction with the observed uniaxial anisotropy, eliminates crystal anisotropy as the predominating effect.

B. Temperature Coefficient of Coercive Force

The coercive force due to crystal anisotropy should be proportional to K/I_s, while that due to shape anisotropy is predicted to be proportional to I_s, where K is the crystal-anisotropy constant, and I_s the saturation induction.[1] By comparing the observed temperature coefficient of coercive force for the elongated iron particles with the temperature coefficients of K/I_s and I_s measured for bulk iron, it is possible to discriminate between crystal- and shape-anisotropy effects.

The measurements reported in Table I show a clear correlation between particle elongation and temperature coefficient of coercive force. Round particles have the expected large temperature coefficient of coercive force proportional to the temperature coefficient of K/I_s, but with increasing particle elongation the temperature coefficient of coercive force is observed to approach the smaller temperature coefficient of I_s. These results demonstrate that crystal anisotropy determines the coercive force of the round iron particles produced by the low-temperature reduction of iron salts, but with increasing particle elongation shape anisotropy becomes the predominating effect.

C. High Coercive Force

To a first approximation the predicted coercive force of a round single-domain particle due to crystal anisotropy is:

$$H_{ci}=2K/I_s \quad \text{for favorable orientation;} \qquad (1)$$

$$H_{ci}=0.64K/I_s \quad \text{for random orientation;} \qquad (2)$$

where K is the cubic crystal anisotropy constant (4.2×10^5 ergs/cm³ for iron) and I_s is the saturation magnetization (1700 gauss for iron). This predicts a coercive force of 490 oersteds for favorably-oriented iron particles, and 160 oersteds for random orientation.[1] In view of the approximate nature of these calculations, it is not surprising that the experimentally-observed values for round iron particles have run as high as 1000 oersteds.[10–12,21] In addition, discrepancies may arise from the difficulty of producing ideal crystals, free of strains or elongation.

A length-to-diameter ratio as low as 1.3 might account for the reported coercive force of iron particles, according to the calculations by Stoner and Wohlfarth.[4] They proposed that the coercive force of a randomly-oriented elongated particle should be

$$H_{ci}=0.479(N_d-N_l)I_s, \qquad (3)$$

TABLE I. Correlation between median particle elongation and temperature coefficient of coercive force.

	−200°C to +25°C temperature coefficient %/°C
Predicted for crystal anisotropy (K/I_s)	97×10^{-3}
Round iron from formate reduction	85×10^{-3}
Sample A, elongation ratio 1.3	58×10^{-3}
Sample B, elongation ratio 2.7	28×10^{-3}
Predicted for shape anisotropy (I_s)	7×10^{-3}

where N_d and N_l represent the demagnetizing factors of the particle along the diameter and length, respectively. For particles with a length-to-diameter ratio of 1.3, a coercive force of 1000 oersteds is predicted. This increases to 4800 oersteds for particles with an elongation of 10.

The coercive force values as high as 2100 oersteds observed in the course of this work are much greater than crystal anisotropy could reasonably explain, and are strong evidence for the existence of the shape-anisotropy effect.

D. Correlation between Particle Elongation and Coercive Force

Table II summarizes the results of the elongation and coercive-force measurements. Figure 8 compares these results with Stoner and Wohlfarth's predictions for single-domain prolate ellipsoids. It is assumed that the intrinsic coercive force of a sample made up of single-domain particles represents the condition of zero induction caused by the reversal of 50% of the particles, and that the coercive force of the sample will therefore be related to the median elongation.

There are a number of reasons why the observed coercive forces might be substantially less than predicted. The irregularities and dendritic branches of the actual particles are far from the ideal prolate ellipsoids assumed by Stoner and Wohlfarth. The particle diameters are less than optimum, so the smaller particles may lose coercive force by the thermal reversal mechanism described by Néel,[29] Bertaut,[25] and Meiklejohn.[12] The inevitable agglomeration of these magnetic particles will certainly decrease the coercive force of the samples[1]; infinite dilution was assumed in the calculations. Any omission of small round particles in the counting would make the median elongation appear to be higher than actual. The coercive force of a sample containing a variety of particle shapes and diameters is not well understood, and may be less than the median.[30] It has been suggested by Bean and Jacobs that the uniform rotation of the magnetization vector assumed by Stoner and Wohlfarth may not take place, and instead these particles may reverse their magnetization by an easier nonuniform process.[31] Finally, the contribution of crystal anisotropy is not known, and may act to increase or decrease the coercive force of the particles depending upon the crystallographic orientation of the particle axis. Any of these factors may account for the discrepancies between the predicted and observed results. The measurements do not provide quantitative confirmation of Stoner and Wohlfarth's predictions, but the observed relation between elongation and coercive force confirms the existence of a shape anisotropy effect.

TABLE II. Measured properties of single-domain iron particles.

Sample	Mean diameter, angstroms	Median length-to-diameter ratio	Coercive force, oersteds
A	145	1.3	1090
B	150	2.7	1360
C[a]	140	3.0	1600
D[a]	140	4.0	1600
E[a]	175	4.6	1850

[a] Particles with dendritic structure.

[29] L. Néel, Compt. rend. **228**, 664 (1949).

[30] E. Wohlfarth, Research **7**, No. 3, S18, March, 1954.

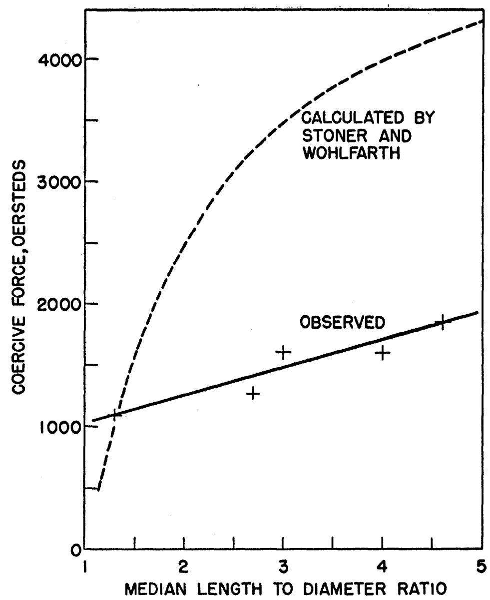

FIG. 8. Relation between median elongation and coercive force.

V. CONCLUSIONS

The uniaxial anisotropy indicated by torque magnetometer curves, the agreement between the temperature coefficients of coercive force and induction, the coercive force values of 2100 oersteds observed for pure iron, and the direct correlation between particle elongation and coercive force, all confirm the existence of a shape anisotropy effect on the coercive force of single magnetic domain particles.

ACKNOWLEDGMENTS

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[31] C. Bean and I. Jacobs (to be published).

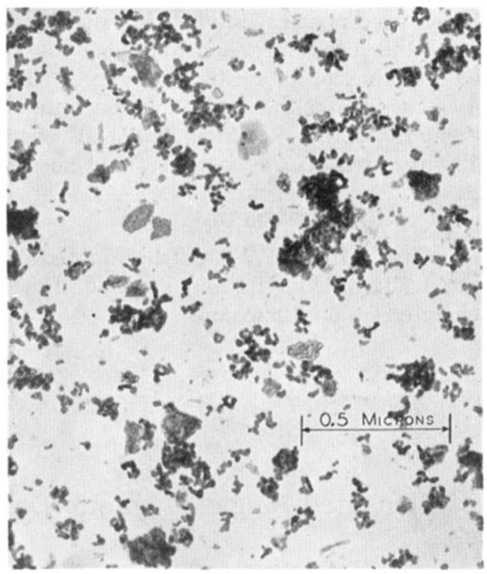

FIG. 1. Fine particle iron A. Median elongation 1.3; coercive force 1090 oersteds.

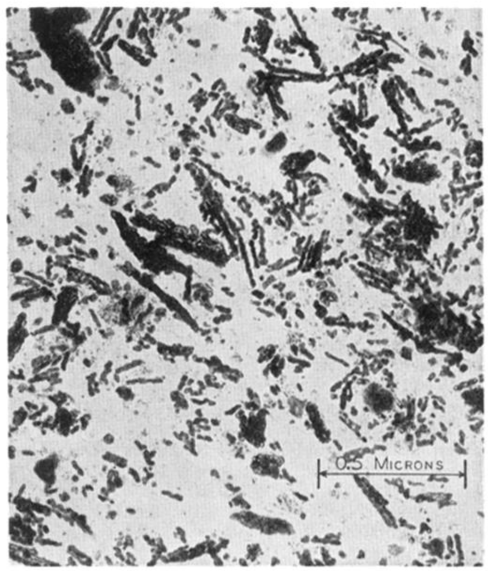

Fig. 2. Fine particle iron B. Median elongation 2.7; coercive force 1360 oersteds.

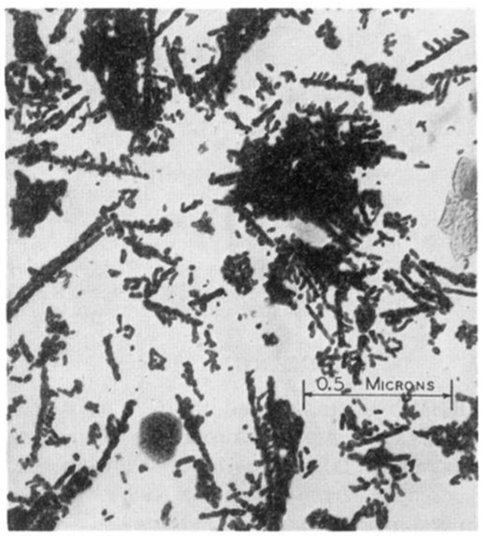

FIG. 3. Fine particle iron *C*. Median elongation 3.0; coercive force 1600 oersteds.

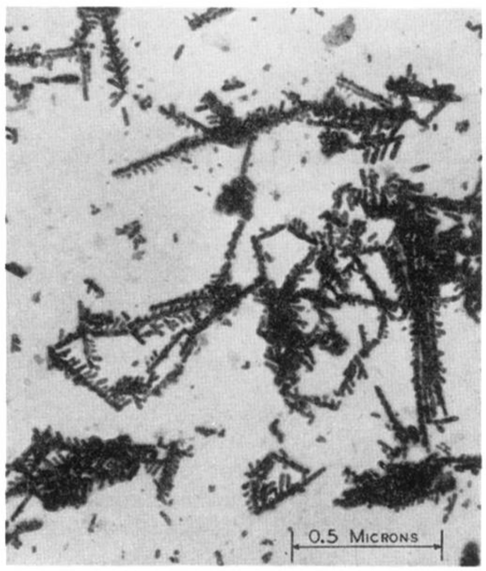

FIG. 4. Fine particle iron *D*. Median elongation 4.0; coercive force 1600 oersteds

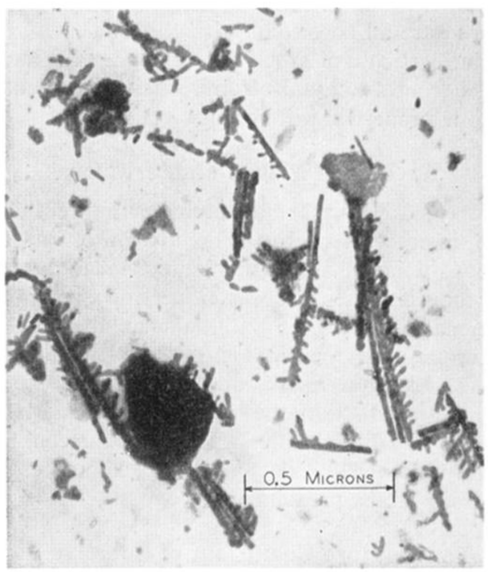

FIG. 6. Fine particle iron *E*. Median elongation 4.6; coercive force 1850 oersteds.