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The magnetic anisotropy of cobalt

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A modified form of the magnetic balance previously designed by one of us, is described. In this apparatus the gradient is made independent of the magnetizing field. With such an apparatus measurements have been made on the variation of the intensity of magnetization with magnetic field for single-crystal specimens cut along appropriate crystal axes, both for the hexagonal close-packed and face-centred cubic cobalt. Such measurements enable the magnetic anisotropy constants to be determined.

The nature of the phase change from close-packed hexagonal to face-centred cubic occurring at about 400° C is such that single crystals can be cut at room temperature, which will transform to give single crystals of known orientation in the face-centred cubic phase.

The values of the magnetic anisotropy constants for the hexagonal phase for various temperatures are compared with those of earlier determinations and fair agreement is found.

Measurements on the face-centred cubic phase were made every 50° C in the temperature range 500 to 1000° C; at the latter temperature the material became magnetically isotropic.

For face-centred cubic cobalt it was found that the crystal directions in order of increasing difficulty of magnetization are [111], [110] and [100], as is the case for nickel. Moreover, the value of the anisotropy constant k_1 obeys the same empirical law, giving the variation with temperature, as nickel. The similarity in the magnetic behaviour of these two ferromagnetics having the same crystal structure is thus evident.

INTRODUCTION

While many determinations of the magnetic anisotropy of iron, nickel and various alloys have been made, cobalt has received little attention probably because of the combined difficulties of growing the single crystals and of making the magnetic measurements. The only measurements for cobalt are those of Kaya (1938) at room temperature and those of Honda & Masumoto (1931), who, using the same specimens, made measurements on the close-packed hexagonal phase in the temperature range -190 to 390° C. There is a lack of satisfactory agreement between the room-temperature values. Since then the nature of the phase change from close-packed hexagonal to face-centred cubic at about 450° C has become clarified by the work of Nishiyama (1936). These facts encouraged the belief that a complete determination of the anisotropy of cobalt over the whole temperature range, i.e. both hexagonal and face-centred, was practicable. Furthermore, all the ferromagnetic elements at room temperature have different crystal structures, and though cobalt above the phase change has a face-centred cubic structure, the same as that of nickel, no determination has been carried out previously on this phase. These considerations add considerably to the necessity for such an investigation.

The previous results obtained for the hexagonal phase show that the basal plane is almost uniformly difficult to magnetize, whilst the c -axis is the direction of easy magnetization.

Complete measurements of the anisotropy of cobalt therefore present the difficulty of requiring accurate measurements both in the lowest fields, i.e. up to 500 Oe, as in the case of other cubic crystals, but also up to the 15 000 Oe which is

required to approach saturation along the difficult direction of magnetization in the hexagonal phase. The wide range of temperatures for which measurements are required, up to about 1000°C , discourages the use of a ballistic method. It appears feasible to modify the balance devised by one of us so as to meet all the requirements of this problem.

THE BALANCE TECHNIQUE

The balance technique has in recent years been successfully applied in a number of ways to problems which involve the measurement of magnetic saturation intensities at different temperatures. In this method a small displacement, linearly proportional to the force exerted on a small ferromagnetic specimen in the non-uniform field of an electromagnet, is measured. The electromagnet poles are shaped

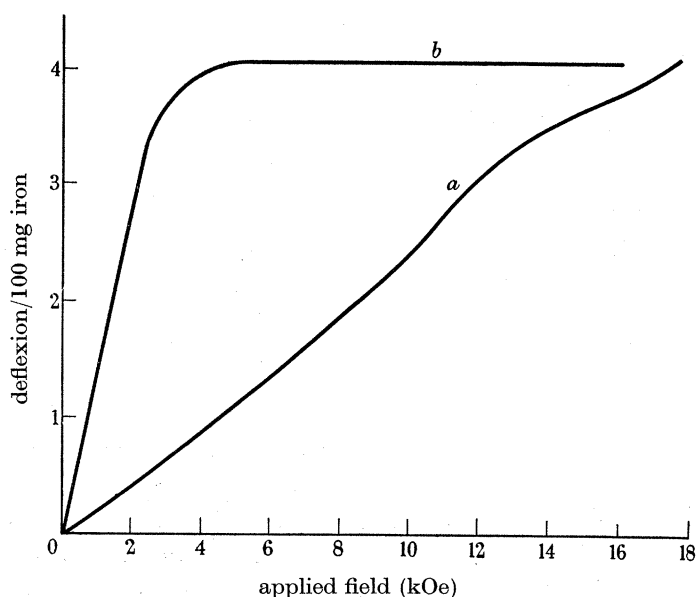


FIGURE 1. Variation of deflexion per 100 mg iron with applied field, showing the variation of the gradient with the magnetizing field for (a) the former ferromagnetic balance, (b) the present pattern.

with a 'step' to produce an adequate magnetic field with a suitable gradient. This gradient is a complex function of the magnetizing field and its variation does not admit of control. The field can be accurately controlled from 2000 to 20000 Oe, while the gradient rises to a value of about 500 Oe/cm. Calibration is effected by a direct comparison in the same magnetizing field with a standard material, i.e. iron, whose behaviour is known from other determinations. The variation of deflexion with magnetizing field is given in figure 1, graph (a). The great importance of saturation measurements in ferromagnetism has justified its wide use, and it is evident that could a suitable field gradient be separated and accurately controlled, the method could be used for this particular problem. At the same time, the possibility of extending the range of field measurements down to the lowest values was envisaged. Such an apparatus, with adequate accuracy in low

as well as high fields, as required for the determination of the anisotropy of cobalt and applicable throughout the whole temperature range of ferromagnetism, has been devised and a summary of the method has been given by Sucksmith, Clark, Oliver & Thompson (1953). In the improved method the magnetizing field is made uniform by the usual method of truncated conical poles without any step, while the field gradient is now produced by two parallel conductors carrying current in the same direction and near the pole faces. It is evident that such an arrangement gives a much reduced gradient, and there must be some sacrifice in robustness of the suspended system, but it should be noted that this gradient is independent

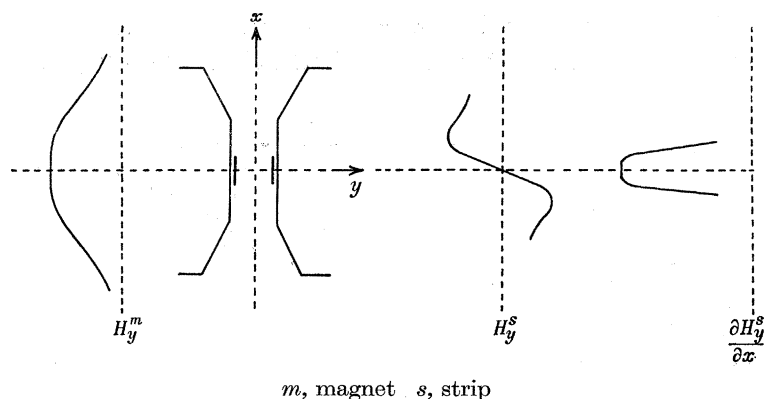


FIGURE 2. Diagram to illustrate the general principle of the present method.

of the magnetizing field, so that at the lower field values there is little loss of sensitivity. At the high fields, the decrease in the magnitude of the force from that used in the earlier balance can be easily overcome by decreasing the thickness of the material used for the ring and spirals, so that the balance is similar in these respects to the original paramagnetic balance. The substitution of strips for wires of circular cross-section carries with it advantages; heating of the conductor is appreciably decreased, whilst firm anchorage of the strips against the large mechanical forces due to the interaction between strip current and magnetizing field is facilitated. There is also the advantage that the strips produce a region of more uniform gradient at the centre of the system, even though this is achieved at the expense of a small reduction in the maximum value of the gradient. Figure 2 shows the general principle of the method.

THE APPARATUS

The electromagnet (pole diameter 10 cm) employed for the high field measurements between about 2000 and 14000 Oe is fitted with vertical adjustment by means of levelling screws, and a horizontal traverse in a direction parallel to the pole faces. This direction is also that of the current-carrying strips, which pass across the pole faces and continue horizontally between two multi-layer coaxial coils which carry current for the production of magnetic fields up to about 2000 Oe. With this arrangement either the low field coils or the magnet can be moved to

act upon the specimen and balance, thus allowing the complete range of magnetic fields to be utilized without disturbing the moving system. The strips pass through the electromagnet mounted on a rigid brass framework so that each may be adjusted relative to the electromagnet, since calibration was effected by comparison with iron* whose intensity per gram was taken to be 217.7 at 20° C between 10 000 and 17 000 Oe (Weiss & Forrer 1929). Thus no image corrections were necessary.

Confirmation of the validity of this view lies in the fact that for a constant gradient the deflexion per unit mass for an iron specimen in high fields should be constant, irrespective of the size or shape of the specimen. This point was carefully tested and satisfactory results obtained.

The advantage of a constant field gradient is illustrated by figures 1 (*a*) and (*b*), which show the variation of the deflexion with the magnetizing field for both magnetic balances. The gradient current of up to 100 A is conveniently obtained from a standard car battery. Since the deflexion is directly proportional to the gradient current, the latter must be measured accurately and consequently the standard potentiometer method is employed.

It is obvious that for the only deflecting force acting on the specimen to be that given by the current through the strips, then the magnetic field must itself possess an exceedingly high degree of uniformity, such that its variation is negligible compared with the strip gradient producing the deflexion. This limits the amount of reduction in the pole-face area, which in our case was found to be that corresponding to 5 cm diameter. Even with this limitation and maximum care in machining accurately parallel pole faces it was not possible to reduce this magnetizing field gradient to a negligible amount. However, by reversing the strip current, a double deflexion was obtained which completely eliminates the effects of this gradient. The theory outlined previously can be rigorously tested, since the deflexion for a specimen in a constant magnetizing field should vary directly with the gradient current. This was found to be accurate to within 1 part in 500 for deflexions ranging up to 3000 divisions.

THE IMAGE EFFECT

A serious source of error in ballistic measurements of induction is that due to the magnetic images of the specimen formed in the poles of the electromagnet. These images are analogous to the more familiar electrostatic images and have corresponding effects. Thus the flux through the search coil due to these images, directed similarly to the magnetization of the original specimen, may add considerably to the parent flux. Moreover, the magnitude of the correction for these images depends upon the permeability of the pole-face material (the image produced in an infinite mass with plane face and of permeability μ is of magnitude $M(\mu - 1)/(\mu + 1)$, where M is the magnetic moment of the specimen) and therefore upon the magnetizing field, and also upon the geometry of the search coil system.

* We take the opportunity of expressing our thanks to the British Iron and Steel Research Association for the iron (reference AHN) of purity 99.96 to 99.97 %.

For example, in one investigation, Weiss & Forrer (1926) needed to apply a correction of up to about 5 %, while in later work (1929) their image correction reached as much as 50 %.

With the new apparatus two distinct sets of images arise, those formed by the specimen and those by the gradient strips. The former are present in the early balance, but it was shown by Sucksmith (1939) that no image correction was necessary since any image effect is automatically eliminated by the method of calibration. With the step removed, any force exerted by the images must of necessity be perpendicular to the measured force and therefore can cause no complications. The images of the strips formed in the pole faces, however, give rise to a gradient of comparable magnitude to that given by the strips themselves. The variation of this image gradient with applied field was investigated by obtaining the deflexions for various magnetizing fields for an iron specimen. With the present apparatus these deflexions were found to be constant to within 1 part in 2000 for field values above about 5000 Oe (see figure 1(b)), and hence any correction for image variation must be less than this. Attempts to increase the magnetizing field by decreasing the pole-face diameter below 5 cm not only caused a reduction in the region of uniformity to a point where accuracy of setting became difficult, but also produced a diminution in the deflexion with increasing field. This is caused by a decrease in the permeability of the material of the pole-tips, thus leading to a reduction in the magnitude of the images. Measurements were thus limited to an upper limit of 14 000 Oe for the magnetizing field. Thus the presence of the strip images caused no complications within the above range.

For various constructional reasons it would have been extremely difficult to mount the copper gradient strips through the electromagnet gap and between air-core coils at exactly the same distance apart. This, coupled with the fact that there is an image effect for the former but not for the latter, means that the deflexions for a specimen in the same magnetizing field and gradient current differ in the two cases. It is thus evident that the relationship between these values must be accurately known. For this purpose, measurements were made on a specimen of nickel in a field (around 2000 Oe) which could be obtained by both the air-core and electromagnet. The conditions being the same, the factor of convertibility could be obtained accurately, since at this field the chosen specimen of nickel was technically saturated and errors are thereby reduced to a minimum.

The demagnetizing factor for a specimen can be measured using the air-core coils, and this is of importance when the specimen is not of simple shape, as, for example, etched single-crystal specimens. The initial slope of the curve of intensity against applied field has, for a material of sufficiently high permeability, a value of $1/N$ where N is the demagnetizing coefficient. This provides a means of verifying the technique by using the low-field coils and so accurately made ellipsoidal specimens of different sizes but similar axial ratios were made. In all cases the value of the experimentally determined demagnetizing factor agreed with the theoretical demagnetizing factor (Stoner 1945; Bozorth & Chapin 1942) within $\frac{1}{2}$ %, which was the error possible from the uncertainties in the shape and dimensions. Figure 1(b) also illustrates this point.

For low-temperature measurements a specially constructed Dewar flask was used. It was found sufficient to obtain results at only two temperatures below room temperature, these being obtained by using liquid nitrogen, and a mixture of solid carbon dioxide and ethyl alcohol respectively.

The high temperatures were obtained by using a furnace similar to that previously described by Myers & Sucksmith (1951). The overall external diameter was 1.75 cm, a size which enabled horizontal traverse of the electromagnet and the air-core coils without risk of fouling the gradient strips.

The thermocouple was mounted so that the junction was in a slot close by the side of the specimen box and was of gold-40 % palladium/platinum-10 % iridium for measurements below about 600° C, and platinum/platinum-13 % rhodium above this value. Calibration and checks were carried out according to standard practice.

PREPARATION OF SINGLE-CRYSTAL SPECIMENS

The mode of preparation of large single-crystal specimens of cobalt using a hydrogen furnace and controlled cooling conditions, and of the smaller single-crystal balance specimens has been adequately described by Myers & Sucksmith (1951). Three ellipsoidal specimens (total impurity content 0.1 %) were used, one cut along each of the three crystallographic directions [0001], $[10\bar{1}0]$ and $[11\bar{2}0]$. Each was carefully prepared and etched to remove any strained material. During the preparation a number of back-reflexion X-ray photographs were taken to ensure that the alinement was correct and that no strain was being introduced. The reflexions were quite sharp, with no indication of distortion. Further evidence of the perfection of the crystals was obtained from optical goniometry on the etched specimen which gave sharp and clear reflexions from the various planes. It was noticed after a deep etch that the etching solution had attacked preferentially on the $(11\bar{2}0)$ and in the case of the *c*-axis specimen signs of six sides developed whose intersecting edges ran into points which coincided with the long axis, indicative of the accuracy of alinement of the axis of the ellipsoid with the *c*-axis.

The magnetic results and *I-H* curves obtained for the hexagonal phase are similar to those of Honda & Masumoto and would require an excessive space for reproduction in their entirety. Moreover, the chief interest lies in the values of the anisotropy constants that may be obtained from them, rather than the actual curves. For these reasons, detailed results are omitted.

On comparing the curves obtained with those of Honda & Masumoto, the shape of the curves and the values obtained agree fairly well. On examining the curves it can be seen that the magnetization curves for the lower temperatures show three portions, of which the middle portion is sensibly linear. Similar behaviour is found in other ferromagnetics, which suggests that even in cobalt where the field necessary to produce saturation is so much greater, the mechanisms operative are similar to those of iron and nickel, differing only in the magnitude of the forces involved.

THE DETERMINATION OF THE ANISOTROPY CONSTANTS FOR HEXAGONAL PHASE

The anisotropy of cobalt has been expressed in a number of ways. By adding or subtracting constants, including functions of constant angles, various alternative expressions are possible, in which the constants have different numerical values.

Stoner (1950) uses an expression for the part of the free energy E_c , dependent on the direction of magnetization,

$$E_c = k'_2 \sin^2 \psi + k'_4 \sin^4 \psi, \quad (1)$$

where ψ is the angle between the c -axis and the magnetization, and k'_2 , k'_4 are the anisotropy constants. This assumes isotropy in the basal plane which experimentally is found to be very nearly so. It is evident that the energy difference between the magnetization along and normal to the c -axis is given by the sum k'_2 and k'_4 , i.e. $E_{[10\bar{1}0]} - E_{[0001]} = k'_2 + k'_4$, and can be obtained from the experimental results by evaluating the area between the curves and the I -axis. Such evaluations have been carried out by McKeehan (1934) and Bozorth (1937) on the results of Honda & Masumoto.

The magnetization curve for cobalt in a direction perpendicular to the hexagonal axis at low temperatures is given by an expression readily derived from equation (1):

$$4k'_4 \left(\frac{I}{I_s} \right)^3 + 2k'_2 \left(\frac{I}{I_s} \right) = I_s H, \quad (2)$$

where I_s is the saturation intensity at a given temperature and H is the effective field. The determination of the two constants separately has been carried out by Gans & Czerlinski (1932), and by a suitable choice of the constants a curve very similar to the experimental curve was obtained. Their values of the anisotropy constants can be converted into the form used here by a simple transformation and columns (8), (9) and (10), table 1, show such transformed values. Stoner (1950) and Kittel (1949) have also given values in graphical form.

However, the values of the constants can be found more conveniently by using the following method.

Equation (2) can be rearranged in the form

$$4k'_4 \frac{I^2}{I_s^4} + \frac{2k'_2}{I_s^2} = \frac{H}{I}, \quad (3)$$

from which it can be seen that the anisotropy constants can be evaluated by plotting a graph of I^2 and H/I , the slope being $4k'_4/I_s^4$ and the intercept $2k'_2/I_s^2$. This method has not been used previously, and so it is applied to the results of Honda & Masumoto so that comparisons can be made. These values are given in columns (5), (6) and (7) of table 1. Figure 3(a) shows the graph of I^2 against H/I , while columns (5), (6) and (7) of table 1 give the resulting anisotropy constants. At high temperatures the direction of easy magnetization is in a plane perpendicular to the hexagonal axis and an expression

$$4k'_4 \frac{I^2}{I_s^4} - \frac{2(k'_2 + 2k'_4)}{I_s^2} = \frac{H}{I} \quad (4)$$

TABLE I. COMPARISON OF VALUES OF THE ANISOTROPY CONSTANTS OF THE HEXAGONAL PHASE

temperature (° C)	(1) $10^{-6} k_2$	(2) $10^{-6} k'_4$	(3) $10^{-6} (k'_2 + k'_4)$	(4) $10^{-6} (k'_2 + k'_4)$	(5) $10^{-6} k'_2$	(6) $10^{-6} k'_4$	(7) $10^{-6} (k'_2 + k'_4)$	(8) $10^{-6} k'_2$	(9) $10^{-6} k'_4$	(10) $10^{-6} (k'_2 + k'_4)$	(11) $10^{-6} (k'_2 + k'_4)$
-176	7.90	1.04	8.94	9.3	6.8	2.4	9.2	6.2	3.1	9.3	9.2
-64	6.44	0.97	7.41	7.7	5.2	2.2	7.4	4.4	2.6	7.0	7.8
20	5.28	0.95	6.23	6.2	4.2	1.9	6.1	3.3	2.2	5.5	6.0
59	4.44	0.93	5.37	5.4	3.3	1.6	4.9	3.0	1.6	4.6	4.9
95	3.65	0.88	4.53	4.5	2.4	1.3	3.7	2.0	1.4	3.4	3.9
116	3.19	0.80	3.99	4.0	1.8	1.2	3.0	1.6	1.3	2.9	3.3
155	2.30	0.71	3.01	2.9	1.1	1.0	2.1	0.8	1.1	1.9	2.2
220	0.77	0.65	1.42	1.26	-0.06	0.73	0.67	-0.06	0.73	0.67	0.9
294	-0.68	0.59	-0.09	-0.17	-0.98	0.54	-0.44	-0.88	0.49	-0.39	-0.35
318	-1.17	0.58	-0.59	-0.62	-1.24	0.47	-0.77	-1.10	0.40	-0.70	-0.70
342	-1.55	0.52	-1.03	-1.05	-1.47	0.43	-1.04	-1.29	0.34	-0.95	-1.00
392	-2.06	0.40	-1.66	-1.60	-2.1	0.40	-1.7	-1.9	0.3	-1.6	—

Columns: (1), (2), (3), values obtained from I^2 and H/I graphs by using new results.

(4), values obtained from new results by the area method.

(5), (6), (7), re-evaluation of the Honda & Masumoto results using the straight-line method.

(8), (9), (10), interpolated values at specific temperatures from the values quoted by Gans & Czerlinski.

(11), interpolated values from the Bozorth graph.

is applicable, which enables the constants to be evaluated for temperatures of 300°C and upwards. The results of the various determinations carried out are given in table 1. The values obtained by applying this method to the new experimental results are given in columns (1) and (2), while the sums of these constants, column (3), can be compared with those obtained by the method previously employed,

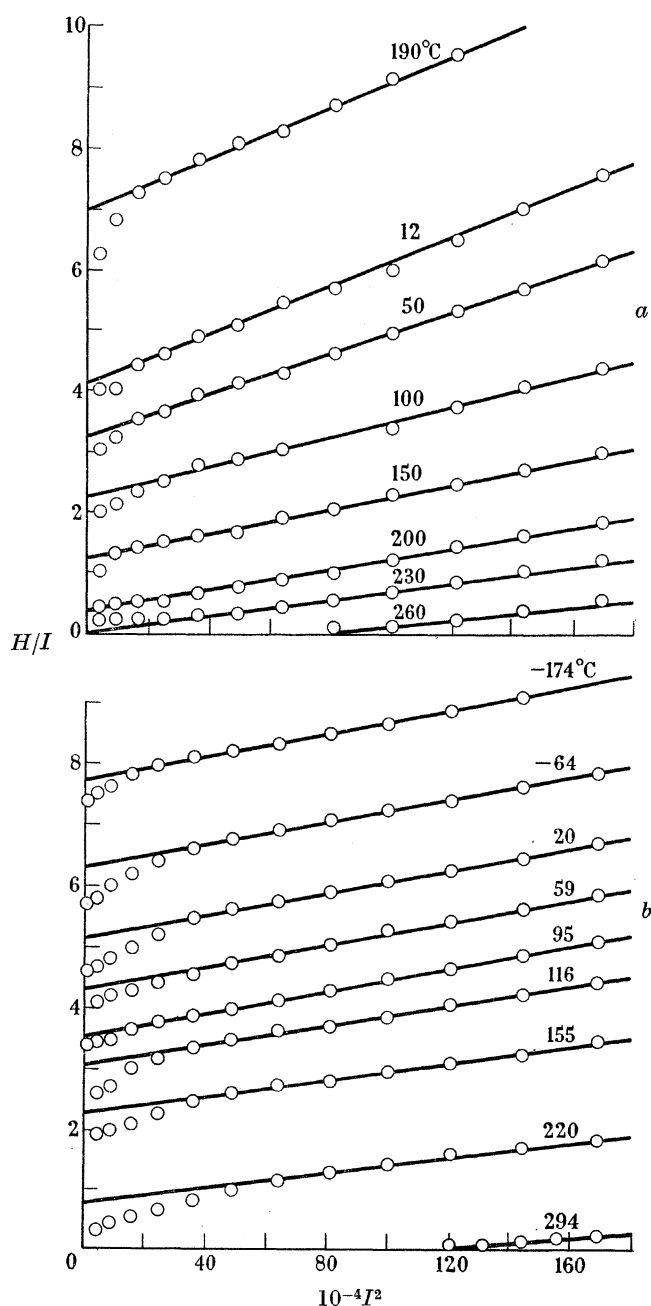


FIGURE 3. The variation of I^2 with H/I (a) for the results of Honda & Masumoto, (b) for the new results.

column (4). It will be seen that the agreement between the values obtained from the two methods is close. Interpolated values from the data given by Gans & Czerlinski for the constants are given in (8), (9) and (10); values which compare well with those obtained by the straight-line method applied to the Honda & Masumoto results shown in (5), (6) and (7). The values given in (1) are taken from a graph of Bozorth, interpolation being used, since the two series of results are not for identical temperatures.

Summarizing, it can be seen that all the values for the sum of the two constants as found by various methods from the two independent sets of experimental results agree fairly well, though the agreement between the individual constants is not so good. The differences, however, are of the same magnitude as those given by various investigations for the other ferromagnetics.

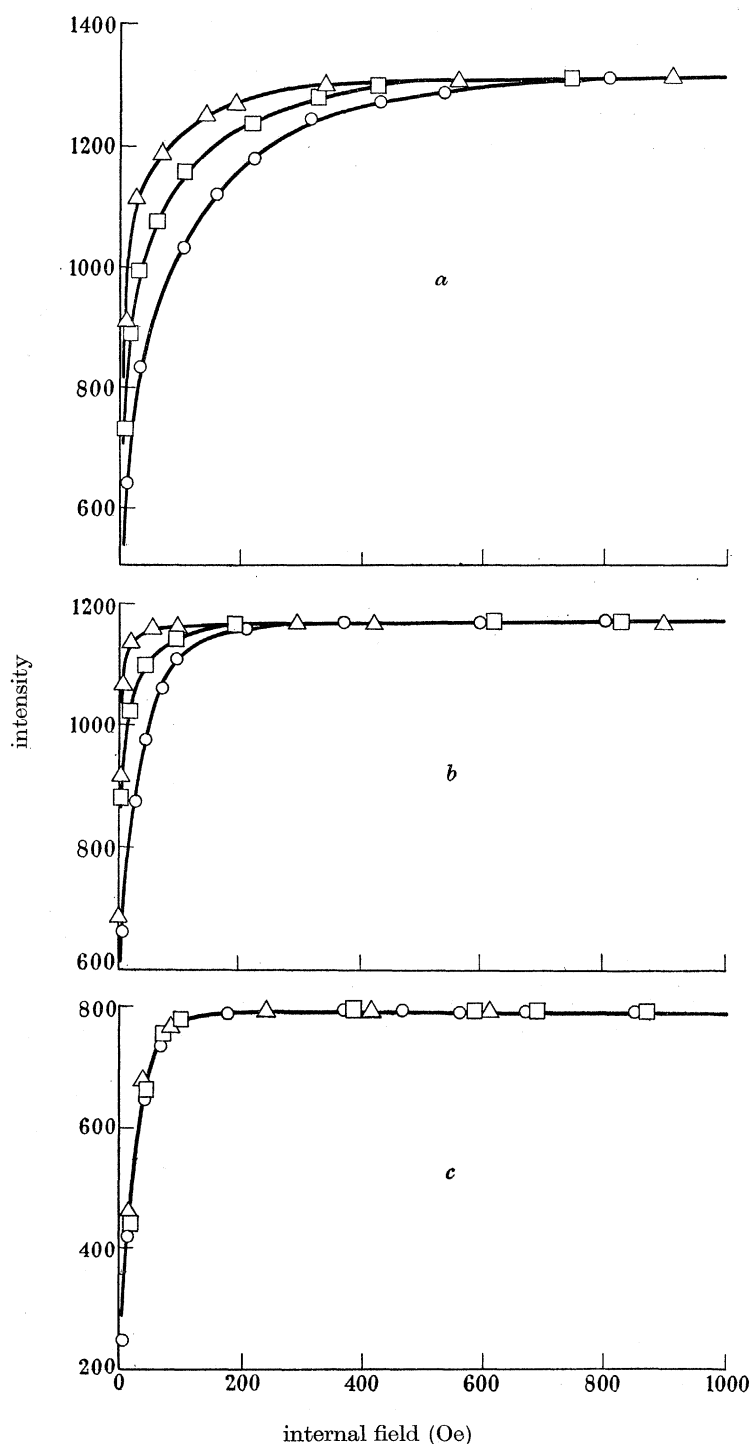
THE PHASE CHANGE

Before considering the face-centred cubic phase, it is necessary to review the nature of the phase change. The mechanism of the crystallographic change was investigated by Nishiyama (1936) and others, and can be summarized by stating that the face-centred cubic (111) plane is parallel to the close-packed hexagonal (0001) plane, and the direction $[1\bar{1}0]$ parallel to the $[11\bar{2}0]$ direction. The transformation takes place by a relative displacement of neighbouring (111) planes in a $[11\bar{2}]$, the magnitude of the displacement being $a/\sqrt{6}$, planes parallel to the shear plane being locked together in pairs. The hexagonal crystal on transforming can give rise to a face-centred cubic crystal of only one orientation, but the cubic crystal on reverting to the hexagonal phase can give rise to a hexagonal crystal (or crystals) oriented in one of four ways. It was concluded by Nishiyama from the experimental results that although the cubic crystal can give rise to four differently oriented hexagonal crystals, on the inverse transformation all these are brought back to the cubic crystal of the original orientation, as if the original cubic single crystal had reappeared. Support for this theory has been obtained by later workers, the most recent being Kehrner & Leidheiser (1953).

This means that crystals can be cut in the hexagonal phase to give rise to face-centred cubic crystals of known orientation, crystals whose magnetic properties in the face-centred cubic phase should not be modified by repeated heatings through the phase change. Accordingly, crystals were cut which would on transformation give rise to the cubic directions $[111]$, $[110]$ and $[100]$.

Since the transformation takes place by a slip mechanism, it was decided* to transform the crystal from hexagonal to cubic by taking it quickly over the phase change, and to cool slowly for the reverse change. Using this technique, the magnetization curves above the phase change were found to be repeatable; the balance deflexions for a given applied field agreeing within 2 parts in about 2000, the estimated experimental error. These results are in complete agreement with the nature of the phase change outlined above.

* We are indebted to Dr J. W. Christian for advice on this point.



FIGURES 4*a*, *b*, *c*. The variation of intensity with the internal field for the three crystallographic directions: Δ , [111]; \square , [110]; \circ , [100]. *a*, 550° C; *b*, 750° C; *c*, 1000° C.

An interesting point emerges from the room-temperature data obtained before and after the heat treatment. The agreement between these measurements was excellent. This indicates that although the cubic phase may give rise to a crystal or crystals oriented in one of four non-equivalent directions, by using this particular means of crossing the phase boundary, the specimen reverts to the original hexagonal crystal. Any part of the crystal which did not revert to the original orientation would give rise to regions whose basal planes were directed along the [0001] and even a very small fraction of the crystal doing so would cause a measurable difference in the magnetization curves.

THE MAGNETIZATION CURVES FOR FACE-CENTRED CUBIC COBALT

The furnace used for the highest temperature measurements was a continuously evacuated, molybdenum-wound furnace which differed only in detail from a similar one previously described by Myers & Sucksmith (1951). The thermocouple used for these measurements was platinum/platinum-13 % rhodium, and a series of measurements were made on iron to check that the recorded temperature was that of the specimen. The Curie point so obtained differed from that quoted by Potter (1934) by only 3° C, which was considered to be satisfactory agreement.

The magnetization curves for the [111], [110] and [100] directions in cubic cobalt were obtained every 50° C from 500 to 1000° C; at the last-mentioned temperature the material became isotropic. These curves are similar to those of nickel in that the crystallographic directions in order of increasing difficulty of magnetization are [111], [110] and [100], and the fields required to produce saturation are only of the order of a few hundred oersteds. The high anisotropy of hexagonal cobalt is therefore associated with the hexagonal form of the lattice and not with the element itself. Since the aim is to determine the anisotropy constants, a complete reproduction of the magnetization curves is not essential, and so typical specimen curves are given for the three crystallographic directions. Figures 4*a*, *b* and *c* illustrate the manner in which the curves vary with increasing temperature.

THE ANISOTROPY CONSTANTS

The energy of magnetization may be written as

$$E = \int_0^{I_{\text{sat.}}} H dI,$$

and so the anisotropy constants may be found by evaluation of the area between the *I*-axis and the curve, since

$$k_0 = E_{[100]},$$

$$k_1 = 4(E_{[110]} - E_{[100]}),$$

and

$$k_2 = 27(E_{[111]} - E_{[100]}) - 36(E_{[110]} - E_{[100]}).$$

The variation of the two anisotropy constants k_1 and k_2 with temperature is shown in table 2.

TABLE 2. THE ANISOTROPY CONSTANTS FOR FACE-CENTRED CUBIC COBALT

temperature (° C)	$-10^{-5}k_1$	$-10^{-5}k_2$
500	2.30	4.31
550	1.60	3.80
600	1.09	3.21
650	0.80	2.50
700	0.60	1.91
750	0.41	1.35
800	0.23	1.03
850	0.15	0.76
900	0.09	0.57
950	0.09	0.36
1000	—	—

A comparison can be made with face-centred cubic nickel and the following observations may be made. The magnitude of k_1 for cobalt is similar to that of nickel, though both k_1 and k_2 are negative whereas for nickel k_1 is negative and k_2 has been found in general to be positive. For cobalt k_2 is larger than k_1 , though on plotting the values given here, there are indications from the more rapid increase of k_1 with decreasing temperature, that k_1 might be greater than k_2 for lower temperatures than those for which measurements could be made. For nickel k_1 is greater than k_2 . On the other hand, even a casual inspection of the magnetization curves of figure 4 and comparison with the corresponding data for nickel leaves little doubt as to the close agreement in all but detail. The variation of k_1 with temperature for both nickel and cobalt can be expressed by an empirical relationship $k_1 = k_{10} e^{-\alpha T^2}$, where k_{10} and α are constants and T is the absolute temperature. The work of Brückhatov & Kirensky (1937) supplemented by the work of Bozorth (1939) at low temperatures, shows that the anisotropy constant k_1 for nickel corresponds closely over the temperature range 20 to 273° K with such an expression, having a value of $k_{10} = -750\,000$. At the latter temperature the value of k_1 becomes zero. The values of k_1 for cubic cobalt given in this paper are in close accord with such a relationship over the whole temperature range for which measurements could be made, with a value of $k_{10} = -2\,540\,000$.

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The effect of drop size on flame propagation in liquid aerosols

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[Plates 8 and 9]

A method has been developed whereby suspensions of controlled uniform drop size can be prepared from pure liquids. Using tetralin as the fuel, it has thus been possible, within limits, to study the effect of the drop size on the combustion properties of a liquid-in-air suspension.

Through a study of limits of inflammability, nitrogen dilution limits and burning velocities, it has been shown that the mechanism of flame propagation is completely transformed within the drop-size range 7 to 55 μ .

Below 10 μ the suspension behaves like a vapour, but above 40 μ the drops burn individually, in their own air envelope, and one burning drop ignites adjacent ones, thus spreading combustion. At intermediate sizes, behaviour is transitional.

A practical consequence of this transformation is that the lower concentration limit of inflammability is reduced and the rate of burning increased for the larger drops.

INTRODUCTION

Little fundamental work on flame propagation in liquid aerosols has been published, and it is concerned exclusively with those of a polydisperse character with very small drops. Haber & Wolff (1923), Burgoyne & Richardson (1949) and Burgoyne, Newitt & Thomas (1954) measured lower limits of inflammability and to some extent burning velocities, using liquids of low volatility. It was shown that the aerosols behaved generally as though the corresponding fuel vapour were concerned. Wolfhard & Parker (1949) showed that with a very fine spray of kerosene in air a continuous flame-front, like that of a pre-mixed gas, is formed and the droplets seem to be completely vaporized in the pre-heating zone of the flames.

Investigations of the combustion of single drops of liquid, exemplified by the work of Godsave (1953), Spalding (1950-1) and others, are relevant to the behaviour of coarser sprays.