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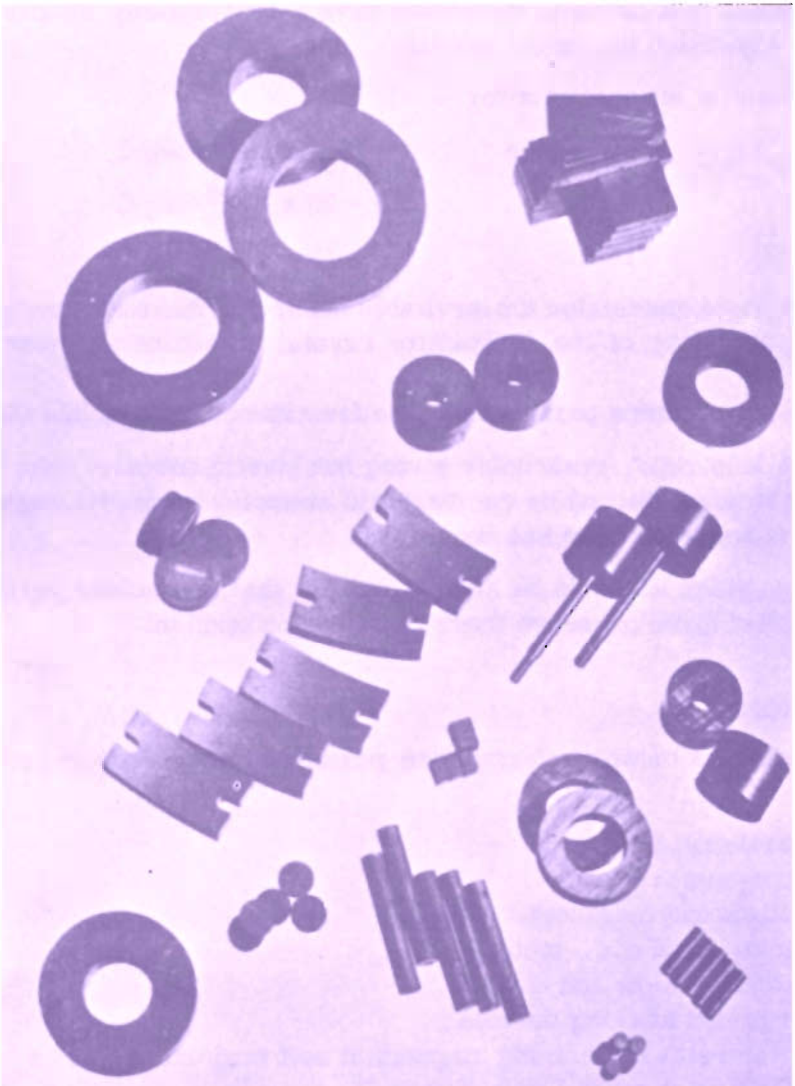
Permanent Magnet Materials



Permanent magnet materials

Cast alloys

RECO
"TICONAL"

Sintered ceramic materials

Plastic ceramic materials

FERROXDURE

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FOREWORD

The place of permanent magnets in modern life is so evident that their importance cannot be overlooked. Every home contains at least a few of these devices, and it is hard to imagine present day technology without the aid of the modern permanent magnet. Examples are found in

Communication,
Power distribution,
Timing devices,
Vehicles,
Traffic control etc.

Modern permanent magnets are available in cast alloys ranging in size from large castings to tiny cubes, and available also in ceramic material in any geometric form.

The excellent properties of the modern materials allow permanent magnets to be made with very small dimensions and exceptional stability. They are ideal for use in

electrotechnical and
mechanical equipment and for
applied physics.

In these applications, permanent magnets offer considerable economic advantages over electrically energised systems, not only in initial outlay but also during operation because power supplies - with their attendant costs and complications - are eliminated.

INTRODUCTION

Permanent magnets - either isotropic* or anisotropic* - can be classified as being basically either

metallic alloy
ceramic material or
plastic bonded ceramic material

The table shows the class to which each of our materials belongs.

	metallic alloy	ceramic material	plastic bonded ceramic material
isotropic *	reco	ferroxdure	ferroxdure
anisotropic *	"Ticonal" **	ferroxdure	-

The most obvious differences between the groups are that the ferroxdure magnets are characterised by exceptionally high values of coercive force and resistivity while "Ticonal" magnets possess higher values of remanent magnetism and energy product.

Ferroxdure is therefore most suitable for applications in which demagnetising influences (either from external sources or resulting from the use of short magnets) are large and also in high frequency applications.

"Ticonal" is particularly suitable for applications in which high values of magnetic energy are required from small volumes of magnetic material.

The isotropic materials in general are inferior in magnetic properties to the anisotropic ones but are particularly suitable for applications in which multipolar magnets are to be used or where less expensive magnets are necessary giving a reasonable performance.

The plastic bonded ferroxdure magnets combine the characteristic magnetic properties of isotropic ferroxdure (however on a lower level) with the mechanical properties of the plastic material used. These magnets open a new field of applications, especially where the price is of prime importance.

Each of the permanent magnet materials is manufactured in a variety of grades possessing different properties that result from differences in composition and treatment.

The grades are distinguished by the addition of numbers to the name of the material. The numbers are approximately relative to the nominal energy product of the grade.

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* Isotropic materials can be magnetised equally well in any direction. Anisotropic materials have optimal magnetic properties in one direction only.

** "Ticonal" is a registered trade name.

SURVEY OF PERMANENT MAGNET MATERIALS

MAIN MAGNETIC PROPERTIES

The survey on the following pages shows data on some of the principal magnetic properties for the complete range of permanent magnet materials.

Demagnetising curves are given after the tables.

The meaning of the survey is to facilitate the selection of the permanent magnet materials for the proper use. The designer can focus his interest for permanent magnets on materials yielding :

a. high performance magnets with either
   1) high values of coercivity (H_{cb}) and intrinsic coersive field strength (H_{ci}).

or

   2) high values of remanence (B_r)

or on

b. cheaper magnets.

The typical magnetic values are indicated for good comparison of the different grades, while the minimum values quoted are guaranteed for test pieces or for minimum-flux standard magnets only.

Notes

The minimum values of B_r and H_{cb} never occur simultaneously. Generally the minimum value of B_r will coincide with a value of H_{cb} well above the quoted average, whereas the minimum value of H_{cb} is coupled with a high value of B_r.

(M) stands for Pb, Sr or Ba etc.

permanent magnet material typical chemical composition	max. energy product $(BH)_{max}$. in megagaussoersteds		occurs at		remanence B_r in gausses		coercivity H_{cb} in oersteds		intrinsic coercive field strength H_{ci} in oersteds	
	min.	typ.	B_d gausses	H_d oersteds	min.	typ.	min.	typ.	min.	typ.
ISOTROPIC PLASTIC-BONDED FERROXDURE Ferroxdure P30, P40 and SP50 magnets are extruded, injection moulded and punched, D55 magnets are pressed and machined.										
Ferroxdure P30 KPN-K-992 85% ferroxdure powder $(M)Fe_{12}O_{19}$ 15% thermoplastic material	0.3	0.35	700	500	1150	1250	1050	1100	2500	2700
Ferroxdure P40 KPN-K-989 90% ferroxdure powder $(M)Fe_{12}O_{19}$ 10% thermoplastic material	0.4	0.45	800	550	1350	1450	1150	1200	2300	2500
Ferroxdure SP50 KPN-K-7028 93% ferroxdure powder $(M)Fe_{12}O_{19}$ 7% thermoplastic material	0.5	0.55	800	690	1550	1600	1225	1275	2300	2400
Ferroxdure D55 KPN-V-815 95% ferroxdure powder $(M)Fe_{12}O_{19}$ 5% thermosetting material	0.55	0.60	850	700	1650	1700	1300	1400	2500	2750

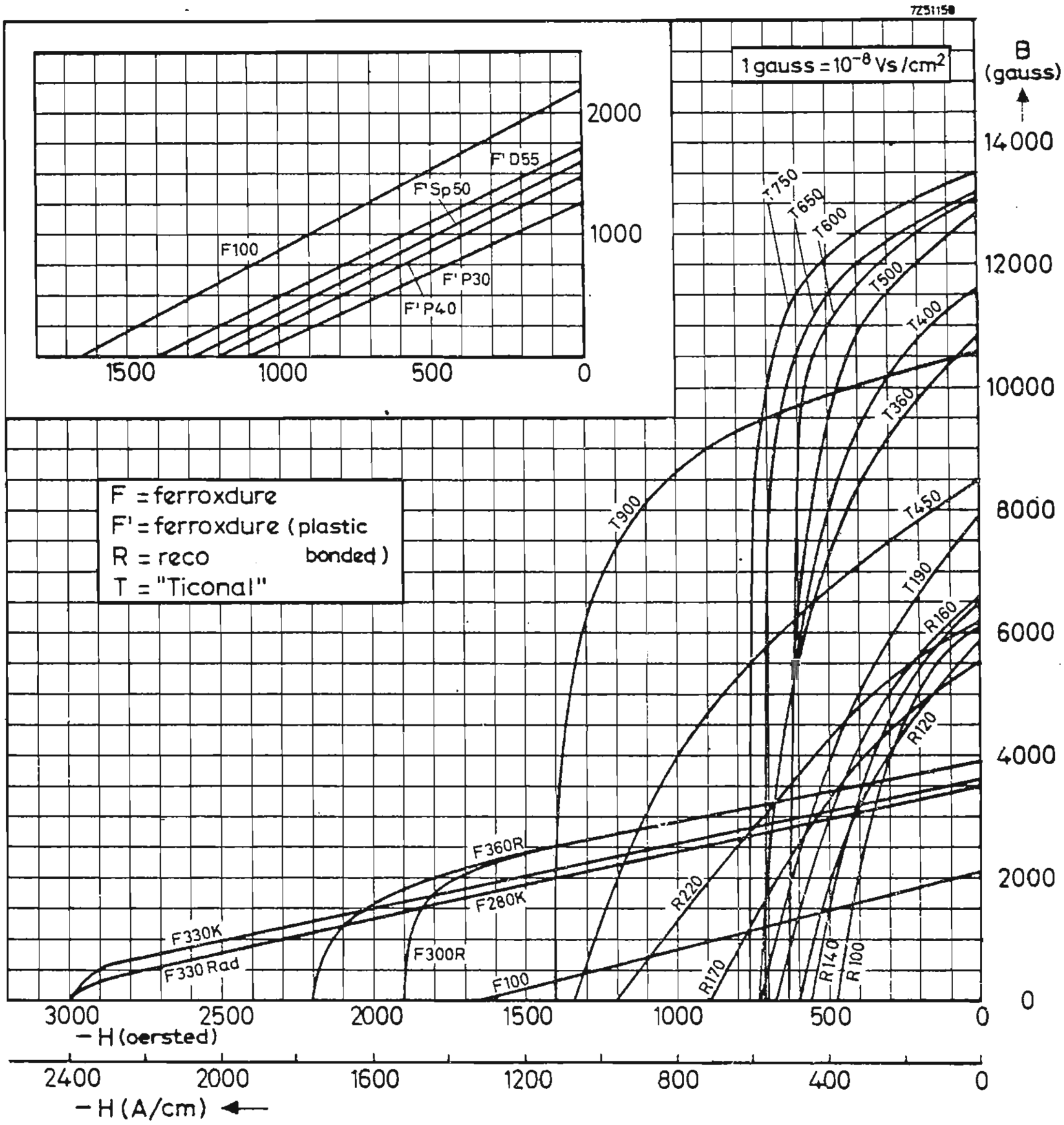
permanent magnet material typical chemical composition	max. energy product (BH)max. in megagaussoersteds		occurs at		remanence B_r in gausses		coercivity H_{cb} in oersteds		intrinsic coercive field strength H_{ci} in oersteds	
	min.	typ.	B_d gausses	H_d oersteds	min.	typ.	min.	typ.	min.	typ.
ISOTROPIC FERROXDURE All magnets are pressed, sintered and ground.										
Ferroxdure 100 KPN-K-359 100% ferroxdure powder $(M)Fe_{12}O_{19}$	0.9	0.95	1200	800	2100	2200	1600	1650	2600	2700
ISOTROPIC ALLOYS-RECO All magnets are cast and can be ground only.										
Reco 100 24% Ni, 14% Al, bal. Fe	1.00	1.20	4000	300	5800	6200	460	480	480	530
Reco 120 1% Ti, 4% Co, 26% Ni, 13% Al, 3% Cu, bal. Fe	1.10	1.30	3100	400	5300	5900	500	600	550	650
Reco 140 0.8% Ti, 5% Co, 25% Ni, 10% Al, 7% Cu, bal. Fe	1.30	1.40	3500	400	6200	6500	530	565	550	600
Reco 160 1.9% Ti, 13% Co, 18.5% Ni, 10% Al, 7.5% Cu, bal. Fe	1.50	1.65	4150	400	6000	6600	600	680	650	750
Reco 170 5% Ti, 10% Co, 24% Ni, 9.5% Al, 6% Cu, bal. Fe	1.50	1.65	3300	500	5200	5600	830	890	900	1000
Reco 220 7% Ti, 26% Co, 15% Ni, 7% Al, 5% Cu, bal. Fe	2.00	2.30	3750	600	5600	6300	1100	1200	1200	1300

permanent magnet material typical chemical composition	max. energy product $(BH)_{max.}$ in megagaussoersteds		occurs at		remanence B_r in gausses		coercivity H_{cb} in oersteds		intrinsic coercive field strength H_{ci} in oersteds	
	min.	typ.	B_d gausses	H_d oersteds	min.	typ.	min.	typ.	min.	typ.
ANISOTROPIC FERROXDURE All magnets are pressed, sintered and can be ground only.										
Ferroxdure 280K KBN-K-435 100% ferroxdure powder $(M)Fe_{12}O_{19}$	2.60	2.80	1800	1600	3400	3550	2800	3000	3000	2700
Ferroxdure 300R KBN-K-434 100% ferroxdure powder $(M)Fe_{12}O_{19}$	3.10	3.30	2000	1650	3800	3900	1600	1900	1700	2000
Ferroxdure 330 (Rad) KBN- 100% ferroxdure powder $(M)Fe_{12}O_{19}$	2.7	2.9	1800	1600	3400	3500	2800	3000	3000	-
Ferroxdure 330K KBN-V-252 100% ferroxdure powder $(M)Fe_{12}O_{19}$	3.20	3.40	1900	1700	3600	3700	2800	3000	2900	3300
Ferroxdure 360R KBN-V-254 100% ferroxdure powder $(M)Fe_{12}O_{19}$	3.40	3.60	2000	1800	3800	3900	2000	2200	2100	2400

permanent magnet material typical chemical composition	max. energy product (BH)max. in megagaussoersteds		occurs at		remanence B_r in gausses		coercivity H_{cb} in oersteds		intrinsic coercive field strength H_{ci} in oersteds	
	min.	typ.	B_d gausses	H_d oersteds	min.	typ.	min.	typ.	min.	typ.
ANISOTROPIC ALLOYS - TICONAL All magnets are cast and can be ground only.										
Ticonal 190 14% Co, 21% Ni, Al, 3% Cu, balance Fe	1.80	2.10	5000	400	7400	8000	650	730	670	800
Ticonal 360 1.5% Ti, 24% Co, 15% Ni, 8.5% Al, 3% Cu, bal. Fe	3.20	3.60	7200	500	10500	10700	680	710	700	760
Ticonal 400 0.8% Ti, 24% Co, 14% Ni, 8.5% Al, 3% Cu, bal. Fe	3.80	4.00	8000	500	11200	11600	610	640	620	680
Ticonal 450 5% Ti, 34% Co, 14.5% Ni, 7.5% Al, 4.5% Cu, bal. Fe	4.00	4.25	5300	800	8000	8500	1200	1335	1300	1500
Ticonal 500 24% Co, 14% Ni, 8.5% Al, 3% Cu, balance Fe	4.50	4.80	9600	500	12300	12800	600	630	610	650
Ticonal 600 24% Co, 14% Ni, 8.5% Al, 3% Cu, balance Fe	5.50	5.77	10500	550	13000	13100	630	645	640	680
Ticonal 650 24% Co, 14% Ni, 8.5% Al, 3% Cu, balance Fe	6.20	6.50	11000	565	12800	13000	640	700	650	780
Ticonal 750 1) 24% Co, 14% Ni, 8.5% Al, 3% Cu, balance Fe	7.00	7.50	11500	650	13200	13400	720	760	730	780
Ticonal 900 2) 5% Ti, 34% Co, 14.5% Ni, 7.5% Al, 4.5% Cu, bal. Fe	7.50	9.00	8000	1100	10000	10600	1300	1400	1350	1500

1) Only for circular cross-sections, from 10 to 23 mm diameter. 2) Only for rectangular and tiny magnets.

Demagnetisation curves



Conversion table for Giorgi units.

1 gauss = 10^{-4} weber/sq.metre

1 oersted = $\frac{10^3}{4\pi}$ = 79.6 amperes/metre

1 gauss oersted = 8×10^{-3} VA sec/m^3 = 8×10^{-3} joule/m^3

OTHER MAGNETIC AND PHYSICAL PROPERTIES

Grade		required magnetising force Hsat (Oe)	L/D ratio for open circuits	permeance -B/H at (BH)max. (Gs/Oe)	recoil permeability μ_{rec} (Gs/Oe)	density (gr/cm^3)	specific electrical resistivity ($\Omega\ mm^2/m$)	temperature coefficient of remanence (%/deg C)	Curie temperature (°C)	coefficient of thermal expansion (10^{-6}/deg C)
Ferroxdure	P30	12000	0.5	1.4	1.10	3.2	10^{13}	-0.2	-	-
	P40	12000	0.5	1.5	1.15	3.6	10^{11}	-0.2	-	-
	Sp50	12000	0.5	1.2	1.19	4.05	10^{10}	-0.2	-	-
	D55	12000	0.5	1.2	1.15	4.10	10^{10}	-0.2	-	-
Ferroxdure	100	12000	0.5	1.5	1.112-1.118	4.9	10^{10}	-0.2	450	8.5
Reco	100	2500	3.0	13	4.0-6.5	6.9	0.7	-0.015	730	12.5
	120	2500	3.0	8	4.4-5.0	6.9	-	-0.015	700	12.5
	140	2500	3.0	9	5.0-6.0	7.0	0.75	-0.015	770	11.5
	160	2500	3.0	11	4.0-5.0	7.0	0.65	-0.015	810	11.5
	170	3000	2.2	7	3.4-4.0	7.0	0.60	-0.015	790	11.5
	220	5000	2.2	6	3.2-3.8	7.2	-	-0.015	750	11.5
Ferroxdure	280K	12000	0.5	1.2	1.08-1.15	4.8	10^{12}	-0.2	450	15.0
	300R	8000	1.0	1.25	1.08-1.15	5.0	10^{12}	-0.2	450	10.5
	300Rad	12000	0.3	1.1	1.08-1.15	4.8	10^{12}	-0.2	450	15.0
	330K	12000	0.5	1.1	1.08-1.15	4.9	10^{12}	-0.2	450	15.0
	360R	10000	1.0	1.1	1.08-1.15	5.0	10^{12}	-0.2	450	10.5
Ticonal	190	2500	3.0	13	3.8-5.0	7.0	-	-0.015	750	11.5
	360	2500	3.5	15	4.0-5.0	7.3	0.50	-0.015	860	10.8
	400	2500	4.5	16	4.0-5.0	7.3	0.50	-0.015	800	10.8
	450	5000	2.2	7	2.5-3.0	7.3	0.50	-0.015	850	10.8
	500	2500	4.5	20	4.0-5.0	7.3	0.45	-0.015	850	10.8
	600	2500	5.0	19	3.0-4.0	7.3	0.45	-0.015	850	10.8
	650	2500	4.5	20	3.0-4.0	7.3	0.45	-0.015	850	10.8
	750	2500	4.3	17	3.0-4.0	7.3	0.45	-0.015	850	10.8
	900	5000	2.2	7	1.7-2.5	7.3	0.50	-0.015	850	10.8

Conversion of electrical resistivity: $1\ \Omega\ mm^2/m = 10^{-4}\ \Omega cm = 10^{-6}\ \Omega m$.

MAGNETISING AND DEMAGNETISING RECOMMENDATIONS

MAGNETISATION

Efficient magnetic circuit design requires that a magnet should be magnetised after it has been assembled into its associated magnetic circuit. Failure to do this exposes the magnet to the maximum self-demagnetisation influences. Furthermore, adoption of this procedure also simplifies handling and assembly.

Design equations are usually based on an assumption of magnetisation to saturation, and the magnetising force required to produce this is proportional to the coercivity of the magnetic material. The recommended minimum values of magnetising field strength are given in the Table. It is extremely important that the magnetising field strength used is not less than the specified minimum, otherwise the maximum performance of the materials will not be achieved.

Table - Recommended Minimum Magnetising Force

Material	Magnetising Field Strength * (Ampere-turns per centimetre length of magnet)
Ferroxdure	9600
Ferroxdure	
300R	6400
360R	8000
Reco	2000
Reco 170	2400
220	4000
Ticonal	2000
Ticonal 450	4000
900	4000

* For unshielded magnet

If the magnet to be magnetised is assembled in a circuit which shields the magnet, then the required field strength will be greater than the minimum value stipulated in the Table by the amount required to saturate the shielding circuitry. For complicated magnetic circuits, advice should be sought.

The required magnetising current can be obtained from metal rectifiers, ignitron pulse circuits, storage accumulators, charged capacitors or motor generators. To obtain the maximum effect from the magnetising current, the magnetic circuit should be closed during magnetisation by a heavy iron yoke.

DEMAGNETISATION

Partial demagnetisation of permanent magnets may be necessary for stabilisation purposes and, provided that the magnets are relatively small - about 1 kg or less - satisfactory demagnetisation can usually be achieved using the normal 50 Hz power supply. The partial demagnetisation is usually achieved by a controlled alternating field. The magnet is usually placed in an open coil in which the alternating current is controlled by means of a variable transformer.

Complete demagnetisation is often undertaken to facilitate handling and assembly. The complete demagnetisation of ferroxdure is best produced by raising the temperature of the magnet beyond its Curie temperature (about 450 °C). This heating process will not in any way affect the magnetic properties of the ceramic material.

Complete demagnetisation of Ticonal is achieved in a similar way to partial demagnetisation, although considerably more power is required. It is generally more convenient to connect the supply directly to the coil and to move the magnet slowly through the coil.

Theoretically, alternating fields of about 2000 oersted per centimetre length of the magnet are sufficient to demagnetise Ticonal magnets, but the effectiveness of the field is reduced considerably by the screening provided by associated iron circuits. The exact extent of this screening is difficult to calculate, and in practice the quickest method of finding the actual field and current requirements is by experiment.

Under no circumstances should Ticonal be demagnetised by raising the temperature of the magnet above the Curie temperature (about 850 °C). Raising the temperature above only 600 °C will permanently ruin the magnetic performance.

Demagnetisation of very large magnets is a special problem, and advice should be sought in each case.

STANDARD TERMINOLOGY SPECIFYING AXIS AND DIRECTION OF MAGNETISATION

PRE-MAGNETISED MAGNETS

Permanent magnets made from materials such as isotropic ferroxdure and the anisotropic grades FXD 330K and FXD 330Rad - having a long straight-line range in their demagnetisation curves - can be demagnetised, in some cases even into the region around B = 0, without any appreciable shift of the working point after removal of the demagnetising force.

These magnets can therefore be ordered in the magnetised state.

Permanent magnets not made from these materials are generally magnetised only after being built into the magnetic circuit, since the shorter straight-line range of their demagnetisation curves may not permit them to be demagnetised to the same extent.

Within the straight-line range of the demagnetisation curve, magnets of ferroxdure are less sensitive to demagnetising forces than most of the reco and "Ticonal" magnets.

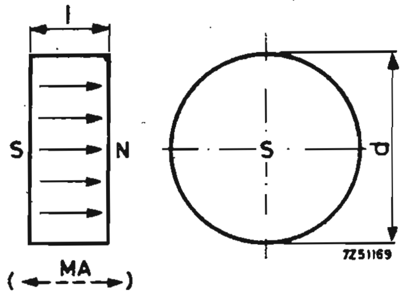
Where ready-magnetised magnets are required it is recommended that the direction of magnetisation be indicated on the drawing by means of standard terminology, to avoid misunderstanding.

STANDARD TERMINOLOGY

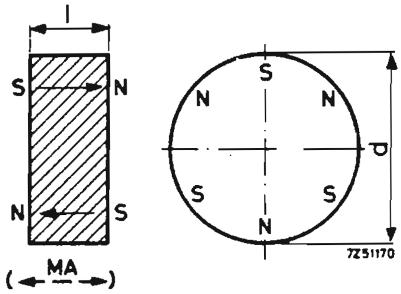
For anisotropic magnets the axes of magnetisation should also be indicated, even if magnetisation by the manufacturer is not required.
For the axis of orientation (unmagnetised magnets) the symbol $<\overset{MA}{\text{----}}>$ is used, and for the direction of magnetisation the symbol →N (or S→) is used with the standard terminology as indicated in the following examples.

For isotropic and anisotropic magnets

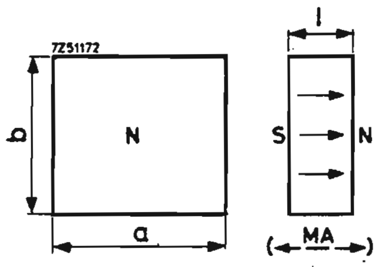
Magnetisation



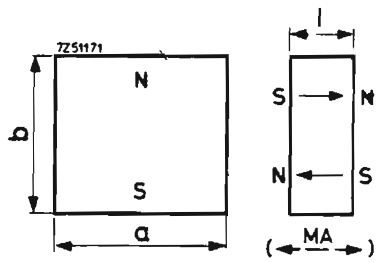
parallel to the length,
or axial.



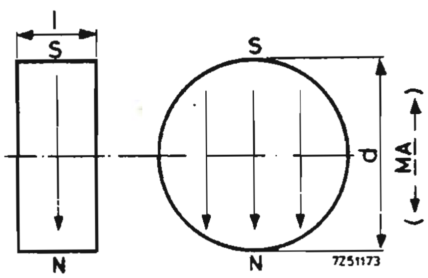
axial (n) poles
(in figure n = 6).



parallel to the side 1 or
normal to a x b.

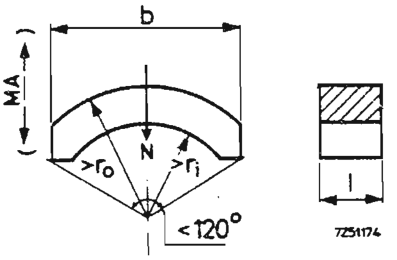


parallel to the side 1,
n poles.
(in figure n = 2).

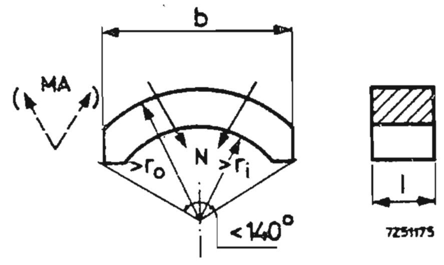


parallel to the diameter
or diametrical.

Magnetisation for segments



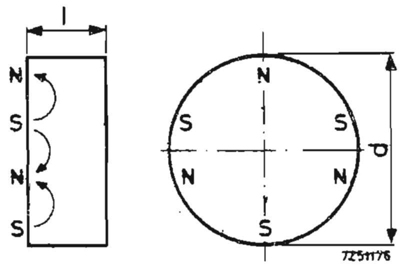
diametral



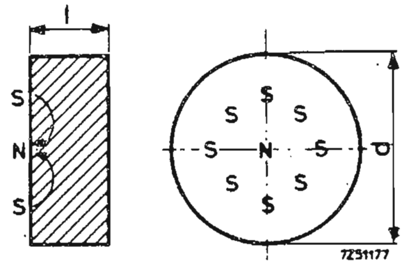
radial

For isotropic magnets only

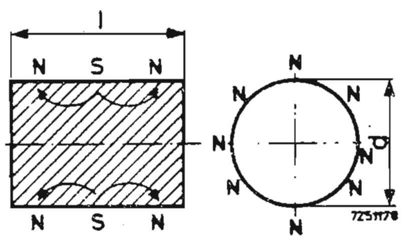
Magnetisation



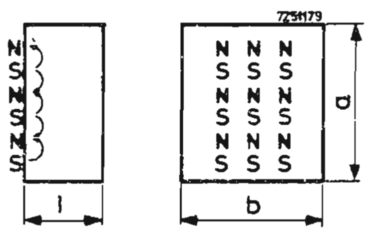
lateral,
n poles on one cross-sectional surface.
(in figure n = 6).



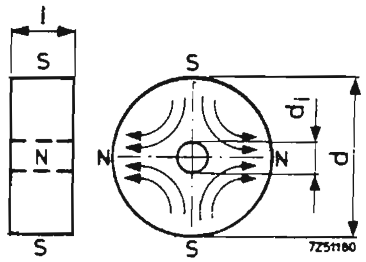
lateral,
2 poles on one cross-sectional surface with one pole in the centre.



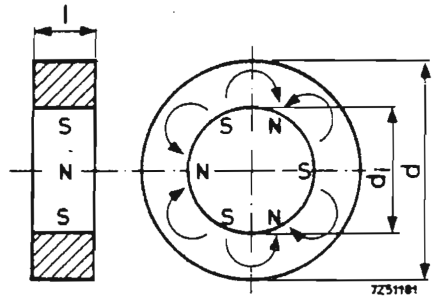
lateral,
n poles on circumference
(in figure n = 3).



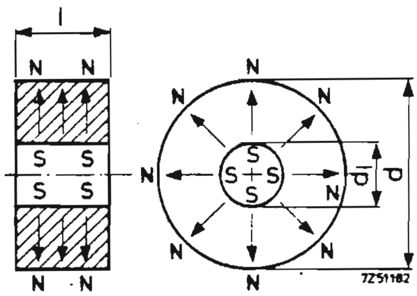
lateral,
n poles on the side a x b,
neutral zones parallel to side b.
(in figure n = 6).



lateral,
n poles on outer circumference.
(in figure n = 4).



lateral,
n poles on inner circumference.
(in figure n = 6).



radial,
N- or S- pole inside.
(in figure S-pole inside).

MARKING OF PERMANENT MAGNETS

When it is necessary to identify magnetised magnets of the same type but with different ways of magnetisation, a colour code is recommended.

The poles can then be marked by spots of paint or some other identification mark,

either south pole yellow
or north pole red
or neutral side white.

If the accuracy obtainable by spots of paint is not sufficient for the marking of the pole position, it is possible for example to use grooves, which must be indicated on the drawing.

For larger permanent magnets a marking by means of the article number can be used.

SHAPE INACCURACIES AND TOLERANCES

In the interests of rational and economical manufacture there should be as little restriction placed on the tolerances as possible in order to avoid additional processing operations.

FERROXDURE

Ferroxdure magnets are shaped during manufacture. The raw material is pressed under high pressure in dies or extruded through jets prior to sintering.

Preference should be given to simple designs, because changes in shape due to shrinkage after sintering are then less troublesome.

For the wet manufacturing process linear shrinkage is larger than for the dry process and thus somewhat greater tolerances are required.

Tolerances for "as sintered" products are approximately:

dimension	tolerance
5 mm	±0.3
5 - 10 mm	±0.4
10 - 25 mm	±0.5
above 25 mm	±2.5 %

If closer tolerances are required, however, grinding will then be necessary. This is often the case with parallel pole faces.

Ceramic parts in general may not only exhibit departures from linear dimensions but also slightly bent or warped surfaces.
Furthermore ellipticity, eccentricity and conicity lead to deviations in diameter and wall thickness.

Apart from the inaccuracies inherent in unmachined parts, errors may also occur during machining. For instance, rings ground on the outer periphery will run out-of-true if the ring is incorrectly clamped.

RECO AND "TICONAL"

Reco and "Ticonal" magnets may be sand cast, shell moulded or cast to the required shape by any other modern technique.

These permanent magnets being hard and brittle cannot be machined economically by conventional methods. Holes are cored with sand or graphite and the magnets are finished by grinding.

For smaller holes inserts can be used which can subsequently be drilled out.

For the high energy product materials, holes and inserts have to be avoided as they spoil the crystal orientation.

Tolerances for "as cast" products are approximately:

dimension	tolerance
$<$ 50 mm	$\pm$0.5 mm
50 - 100 mm	$\pm$0.8 mm
$>$ 100 mm	$\pm$1.0 mm

It is recommended to apply "as cast" tolerances in all dimensions and to restrict grinding to the pole faces only.

Tolerance between two ground parallel

surfaces is $\pm$0.05 mm

Tolerance perpendicularity

between one ground and one cast surface
is $\pm$1.5 degrees

between two ground surfaces
is $\pm$0.5 degree.

Tolerance parallelity

between two ground parallel surfaces, measured at opposite ends is 0.05 mm.

Magnets cut from bars have a diameter tolerance of

dimension	tolerance
ø10 - 18 mm	$\pm$0.05 mm
ø $>$ 18 mm	$\pm$0.15 mm

SYMBOLS FOR DIMENSIONAL DEVIATIONS

In general, shape inaccuracies are kept within the dimensional tolerances.
For special requirements of dimensional deviation it is recommended to use in the drawing the following symbols:

↗ Tolerance of eccentricity

— Tolerance of bending or curvature

▱ Tolerance of plainness

○ Tolerance of roundness

⌭ Tolerance of cylindricity

⌒ Tolerance of accuracy to shape

⌓ Tolerance of surface uniformity

// Tolerance of parallelity

⊥ Tolerance of perpendicularity

∠ Tolerance of angularity

⌖ Tolerance of position

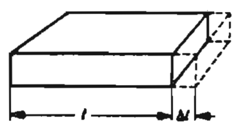
◎ Tolerance of concentricity

⌯ Tolerance of symmetry

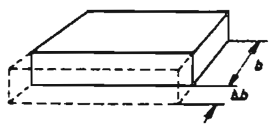
80√ Surface roughness in ru (1 ru = 40 μm)

DIMENSIONAL DEVIATIONS

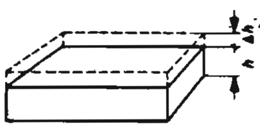
In the following table are given a few deviations of shape and dimensions consequent on the manufacturing techniques used.



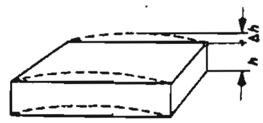
Δl length tolerance



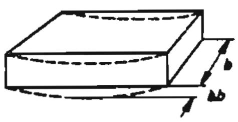
Δb width tolerance



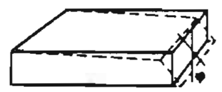
Δh height tolerance



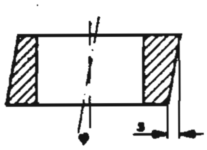
Δh curvature



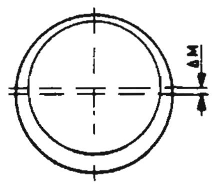
Δb curvature



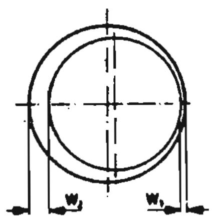
φ twisting with long rods



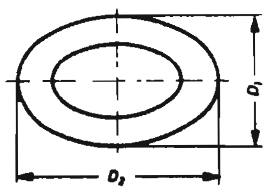
out of true running because of angular deviation in the case of grinding of outer circumference



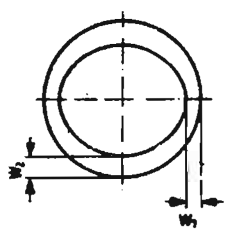
ΔM eccentricity in the case of grinding outer circumference



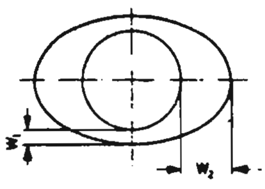
$\Delta W = W2 - W1$ difference in wall thickness on account of eccentricity with ground outer circumference



$\Delta D = \frac{D2 - D1}{2}$ deviation in diameter on account of ovality



$\Delta W = W2 - W1$ difference in wall thickness in the case of inner ovality, with outer circumference ground



$\Delta W = W2 - W1$ difference in wall thickness in the case of outer ovality, with inner circumference ground

STANDARDS FOR TESTING

VISUAL STANDARDS FOR FERROXDURE MAGNETS

Visual requirements are laid down by means of limit samples of which photographs have been made.

For each visual characteristic two limit samples have tobe determined of which one is marked X and the other is marked O.

In all cases it is to be understood that X means bad and is to be rejected
O means good and is acceptable.

MAGNETIC STANDARDS FOR PERMANENT MAGNETS

The best method of testing magnets is to measure their performance under actual working conditions. For this reason the test requirements for any type of magnet should be laid down in concert with the customer.

Often a simplified mo l of the magnetic circuit will suffice for measuring flux, voltage or force of attraction etc. according to the application.

For series and mass production of permanent magnets the testing of the material specifications on each magnet is impracticable. It has become common practice to test each magnet in comparison with a magnet of minimum guaranteed flux. Copies of these so-called minimum flux standard magnets are available on request.

The minimum guaranteed flux magnet standards are laid down in the following way:

A standard magnet is made out of a material having either

min. B_r value (min. flux standard) or
min. H_c value (min. coercive force standard)

and has the following dimensions:

Ring magnets: minimum dimensions perpendicular to pressing direction and nominal dimensions parallel to pressing direction.

Block and disk shaped magnets: ditto
Segmentary magnets : ditto

Ring magnets with diametrical magnetisation:
minimum wall thickness,
minimum length or height.

Cylinders and disk shaped magnets with diametrical magnetisation:
minimum cross section, minimum diameter.

SSS SYSTEM

Our Standard Sampling System is a non-destructive inspection system for products which are received or supplied in batches, and in respect of which it is economically justified to allow a (small) percentage of rejects.

The magnets are delivered on the condition that the amount of rejects
either mechanically
or visually
or magnetically
does not exceed the permissible quantity in accordance with the SSS system with a "point of control" $p_o = 2\%$.

"TICONAL" AND RECO

INTRODUCTION

One of the most important groups of industrial permanent magnet materials are the anisotropic Titanium, Cobalt, Nickel, Aluminium alloys known by the trade name "Ticonal".

The earliest group of permanent magnet materials of this composition and known as the isotropic reco alloys, are used today mainly in older designs which would not benefit from a replacement by stronger magnetic materials.

"Ticonal" and reco are precipitation-hardened alloys made by modern foundry techniques and specialised heat treatment. The available range of these high efficiency metallic permanent magnet materials gives a wide coverage of performance and characteristics.
The correct choice from this range enables magnetic circuits to be designed having efficiencies hitherto unattainable. The reduction in the size of magnets and the associated circuits usually results in a significant reduction in costs.

"Ticonal" and reco permanent magnets are manufactured from the purest materials, and every process of their production is subject to close laboratory control to ensure that the high standards of performance of these magnets are maintained.
These materials are melted in an induction furnace, which is essential for the close control required in the production of "Ticonal" and reco.

There have been marked advantages in the manufacturing of these precipitation hardened alloys since the first reco grades became available, and the few original grades have been expanded to today's standard range with grades in values of

coercive field strength from 400 to 2000 oersteds and
maximum energy products over 9×10^6 gauss-oersted.

"Ticonal"

190 The earlier "Ticonal" grades where achieved by applying a magnetic
360 field to the magnet during cooling.
400 The precipitate formed is aligned in the direction of the applied field,
450 resulting in stronger magnetic properties in this direction.
500

"Ticonal"

600 The newer "Ticonal" grades are achieved by orienting the crystal structure of the alloy in the desired direction of magnetic orientation. This is accomplished by casting the molten metal against steel plates, which chill the metal and cause rapid cooling and growth of long crys-

tals in the preferred direction, resulting in a higher value of the external energy product.
This technique can only be followed for straight sections and solid magnets.

"Ticonal"
650 750 The newest "Ticonal" grades show a further improvement in the magnetic properties which were achieved by complete directional crystal growth. This type of structure is achieved by a special casting process which is responsible for more complete directional crystal growth. Because the direction of magnetisation must correspond to the direction of crystal growth, the highest magnetic performances can only be developed in forms with a straight axis of magnetisation.

"Ticonal"
900 The "Ticonal" grade combining a high coercive fieldstrength with a high external magnetic energy product - one of the most recent grades - opens new fields for permanent magnets where larger demagnetising influences have to be withstood.

Due to the heat treatment the "Ticonal" and reco grades have a structure which is very stable, so that there are practically no changes of the magnetic properties in the course of time.

MECHANICAL PROPERTIES

The "Ticonal" and reco permanent magnets after heat treatment are very hard and brittle and cannot be machined other than by finish grinding.

The tolerances "as cast" - particularly with the highly automated casting process - can generally be kept within such narrow limits that only the surfaces through which the magnetic flux is passing need further processing.

Holes may be cored during the original casting, or alternatively, mild-steel inserts may be cast in. These inserts can then be drilled and tapped to give accurately located fixing holes.

For the "Ticonal" grades with crystal orientation, holes have to be avoided and inserts cannot be cast in.

The "Ticonal" and reco permanent magnets can be fixed by means of screws (only non-magnetic screws to be used in a direction parallel to the field lines and only if the magnet can be manufactured with a hole), adhesive or soft soldering. Hard soldering may lead to deterioration of the magnetic properties.

The "Ticonal" and reco permanent magnets should as far as possible, only be exposed to compressive loading.

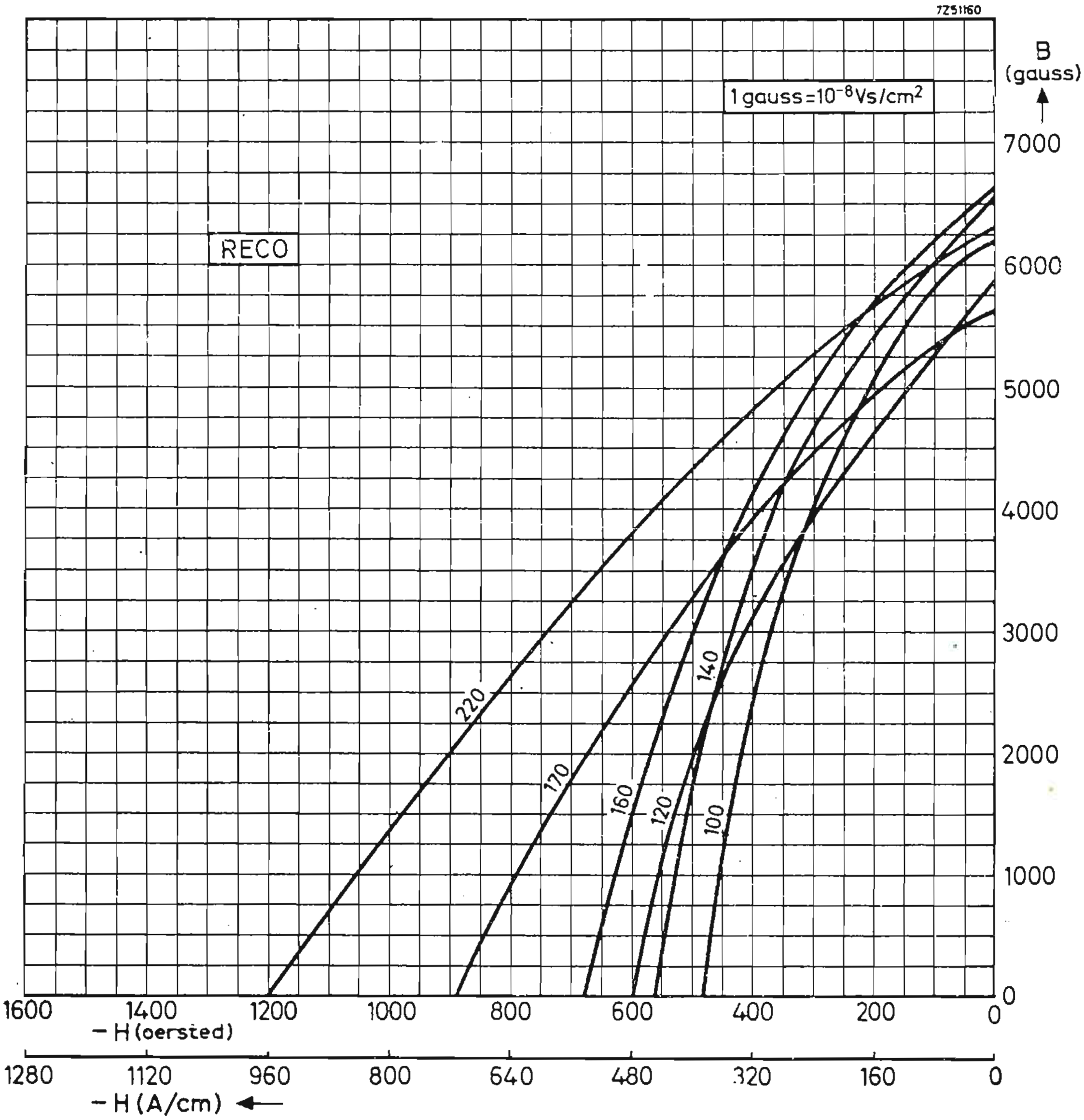
Great resistance of the "Ticonal" and reco magnets against corrosion and attack by acids is ensured by the high nickel content.

RECO

The reco permanent magnet materials are isotropic which means they have the same magnetic properties regardless of the direction of magnetisation.

The various grades show different external energy products as a result of different percentages of nickel, cobalt and titanium in the alloys.

Demagnetisation curves.



The types reco 170 and reco 220 are characterised by their higher values of coercive field strength.

Chemical composition in %

Material	Ni	Al	Co	Cu	Ti	Fe
Reco 100	24	14	–	–	–	bal.
Reco 120	26	13	4	3	1	bal.
Reco 140	24	10	5	7	0.8	bal.
Reco 160	18.5	10	13	7.5	1.9	bal.
Reco 170	24	9.5	10	6	5	bal.
Reco 220	15	7	26	5	7	bal.

Design data

See Survey of permanent magnet materials.

"TICONAL"

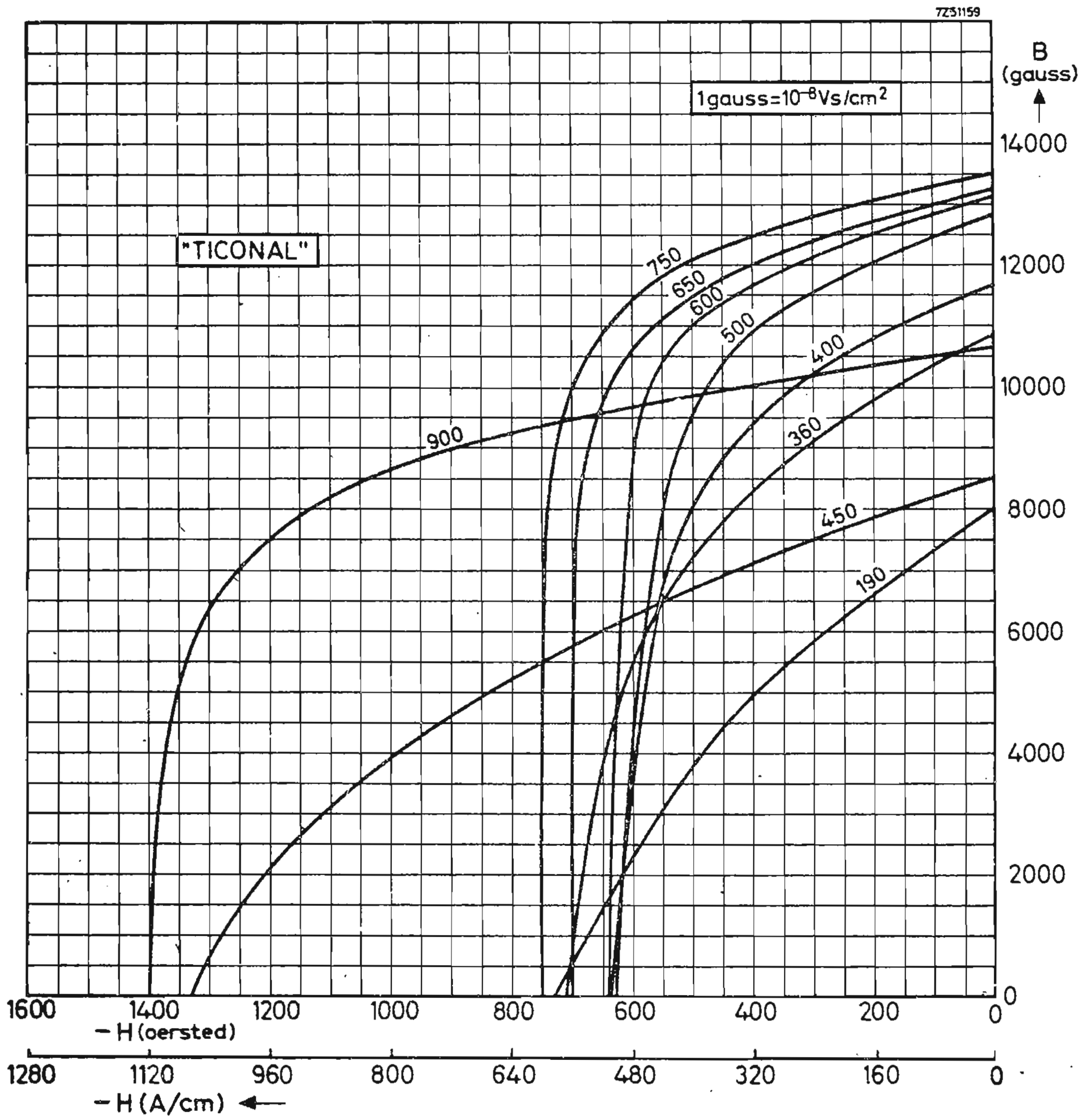
The "Ticonal" permanent magnet materials are anisotropic, which means that the high magnetic properties are achieved only if the magnets are magnetised in the direction of orientation - the magnetic axis.

An axial direction of orientation is most easily obtained in the casting and heat treatment process. For optimum magnetic properties therefore, the magnets to be produced should have a straight axis of magnetisation (coincident with the axial direction of orientation or magnetic axis).

This means that the only practical cross sections are circular, rectangular or prismatic. The manufacture of magnets with a complicated shape or with more than two poles is generally laborious and expensive.

The methods of production of the grades "Ticonal" 190 - 360 - 400 - 450 and 500 are similar. For "Ticonal" 600 chilling by means of steel plates is introduced to achieve crystal orientation.
"Ticonal" 750 compared with these types has a high degree of crystal orientation due to the continuous highly automated casting process. "Ticonal" 650 is somewhat lower in external energy product and is manufactured by multi-cavity hot moulding or by one of the other methods of manufacturing crystal oriented "Ticonal" magnets.

Demagnetisation curves



Grades of "Ticonal"

"Ticonal"

190
360
400
500

are the first anisotropic grades cast by normal foundry practice, which provide less restrictions to form and magnetisation than the production methods for the crystal oriented "Ticonal" grades.

The external energy products may be considered good, having values between 1.8 and 5 x 10^6 gauss-oersteds.

"Ticonal"
600 is a crystal oriented anisotropic permanent magnet material with excellent magnetic properties. It is advantageous when the dimensions perpendicular to the direction of orientation are greater than in the direction of orientation, since otherwise the crystal orientation might be incomplete.

"Ticonal"
750 is a crystal oriented anisotropic permanent magnet material with nearly ideal monocrystals. The extremely high energy product of this grade is the result of the highly automated casting process for long circular bars from which magnets of any length can be cut.

Preferrable diameters 10 to 22 mm.
The length of the magnet should be calculated according to the circuit and performance required.

Note: It should be remembered that the demagnetisation curve has a sharp knee just at the value (BH)max. Therefore the working line of a statically used magnetic circuit - without an external demagnetising field - should intersect the BH-curve in the (BH)max. point. Otherwise the optimum performance will not be achieved, and the use of "Ticonal" 750 would not lead to a higher performance or to a smaller system than obtainable with "Ticonal" 600 or even "Ticonal" 500.

"Ticonal"
650 is a crystal oriented anisotropic permanent magnet material with lower magnetic properties than "Ticonal" 750. The various manufacturing processes, of which multi-cavity hot moulding is the most common, have the advantage that magnet shapes are not limited to circular cross sections. Nevertheless holes should be avoided, because they degrade the magnetic values as a result of incomplete crystal orientation.

Note: The knee in the demagnetisation curve is less sharp than with the 750 grade.
For diameters smaller than 15 mm it is recommended that the diameter/length ratio be greater than unity.

"Ticonal"
450 has a very high coercive field strength due to its high cobalt and titanium content.

"Ticonal"
900 (previously Ticonal XX) has the highest energy product of permanent magnet materials combined with a high coercive field strength.

It is economically attractive for tiny cube shaped magnets. Owing to the great coercive field strength the optimum length of the magnet will usually be small.
The material is often used with success where previously platinum-cobalt was the only solution.

Chemical composition in %

Material	Ti	Co	Ni	Al	Cu	Fe
Ticonal 190	–	14	21	12	3	bal.
Ticonal 360	1.5	24	15	8.5	3	bal.
Ticonal 400	0.8	24	14	8.5	3	bal.
Ticonal 450	5	34	14.5	7.5	4.5	bal.
Ticonal 500, Ticonal 600, Ticonal 650, Ticonal 750	–	24	14	8.5	3	bal.
Ticonal 900	5	34	14.5	7.5	4.5	bal.

Design data

See "Survey of permanent magnet materials".

APPLICATIONS FOR RECO AND "TICONAL" PERMANENT MAGNETS

Reco magnets are used today mainly in older designs which would not benefit from a replacement by stronger magnetic materials.

"Ticonal" magnets having the highest external magnetic energy are used in all those applications requiring superior performance.

Also the need for small dimensions (watches),
high acoustic quality (loudspeakers),
sensitivity (microphones and telephones),
accuracy (meters),
ease of starting (magnetos),
high torque (motors),
cold stability

requires the use of "Ticonal" permanent magnets.

The crystal oriented "Ticonal" permanent magnets therefore find wide use in

- Pick-ups
- Microphones
- Loudspeakers
- Meters
- Magnetos
- Magnetrons
- Instrumentation such as
  - Watt-hour meters
  - Magnetic detectors
  - Ampere-, volt-, and lumen meters
  - Tachometers/Speedometers
  - Temperature control
  - Circuit breakers
- Timing devices in clocks and watches.

See also the general list of applications of permanent magnet materials.

FERROXDURE

INTRODUCTION

Another important group of industrial permanent magnet materials are the ferromagnetic oxides, one of which is a ceramic material known as ferroxdure.

Ferroxdure is a major development in permanent magnet materials and represents a complete departure from the conventional permanent magnet.

Ferroxdure, a ceramic material containing only non-critical raw materials, is distinguished by its high coercive field strength - up to more than 4000 oersteds - and such high electrical resistivity that it may be considered to be an insulator.

The high coercive field strength means that magnets with very short lengths can be used without excessive self-demagnetisation. The high electrical resistivity - some 10^{10} times that of iron-minimises eddy current losses and thus makes ferroxdure an ideal material for high frequency applications.
The relative low induction values require larger cross sections than for conventional permanent magnets.

These properties have led to new applications and new designs for existing applications.

Ferroxdure corresponds approximately to the chemical formula $(M)Fe_{12}O_{19}$ where M stands for Ba, Sr, Pb etc.

Ferroxdure being a true ceramic material is brittle, and close dimensional tolerances can only be achieved by grinding.

Ferroxdure has a low specific gravity which introduces a weight advantage over other permanent magnet materials.

Ferroxdure isotropic permanent magnets are manufactured from carefully selected raw materials which are milled to give an intimate mixture of powder. The powder - in some cases after pre-firing - is granulated and formed to the required shape in dies by high pressure pressing or extrusion. The fragile, compacted piece then undergoes an accurately controlled firing process in a special furnace from which it emerges with a ceramic structure and a black colour.

Ferroxdure anisotropic permanent magnets are produced by an extension of the above manufacturing process.

The isotropic ferroxdure material is remilled after firing to a very fine powder. The powder or slurry is then formed to the required shape by high pressure pressing in dies with simultaneous application of an intense homogeneous magnetic field. The pieces are now magnetically orientated.

After this magnetic treatment the orientated compacted pieces are again fired in the furnace in which atmosphere and temperature are accurately controlled, and from which the pieces emerge with a ceramic structure and a black colour.

Compared with isotropic ferroxdure, the orientated or anisotropic ferroxdure permanent magnets possess a very much improved performance in the direction of the magnetic field used during pressing.

Note: During sintering the compacts shrink to about 85% of the dimensions of the pressed form.

Specific gravity is about 4.8.
The higher the coercive field strength, the lower the specific gravity.

Ferroxdure plastic bonded, isotropic permanent magnets are manufactured starting from a mixture of isotropic ferroxdure powder with either thermoplastic or thermosetting materials as bonding agents. Familiar plastics-manufacturing techniques such as extrusion, injection moulding and pressing are used for the shaping of the magnets.

The plastic bonded isotropic ferroxdure magnets combine the magnetic properties of isotropic ferroxdure (but at a slightly lower level) with the mechanical properties of the plastics.

Thus they can be used to make magnets which

- can be bent and even cut with a knife or pair of scissors
- meet narrow size tolerances without being machined
- have complicated shapes
- can be machined with conventional tools.

PLASTIC BONDED ISOTROPIC FERROXDURE

Ferroxdure P30 (norm KPN - K - 992)

A soft, flexible and resilient permanent magnet material with 85 wt% ferroxdure powder (M)$Fe_{12}O_{19}$ and 15 wt% thermoplastic material, shaped by extrusion or injection moulding.

Ferroxdure P40 (norm KPN - K - 989)

A flexible permanent magnet material with 90 wt% ferroxdure powder (M)$Fe_{12}O_{19}$ and 10 wt% thermoplastic material, shaped by extrusion or injection moulding in bars, strips, rods and suchlike.

Ferroxdure Sp50 (norm KPN - K - 7028)

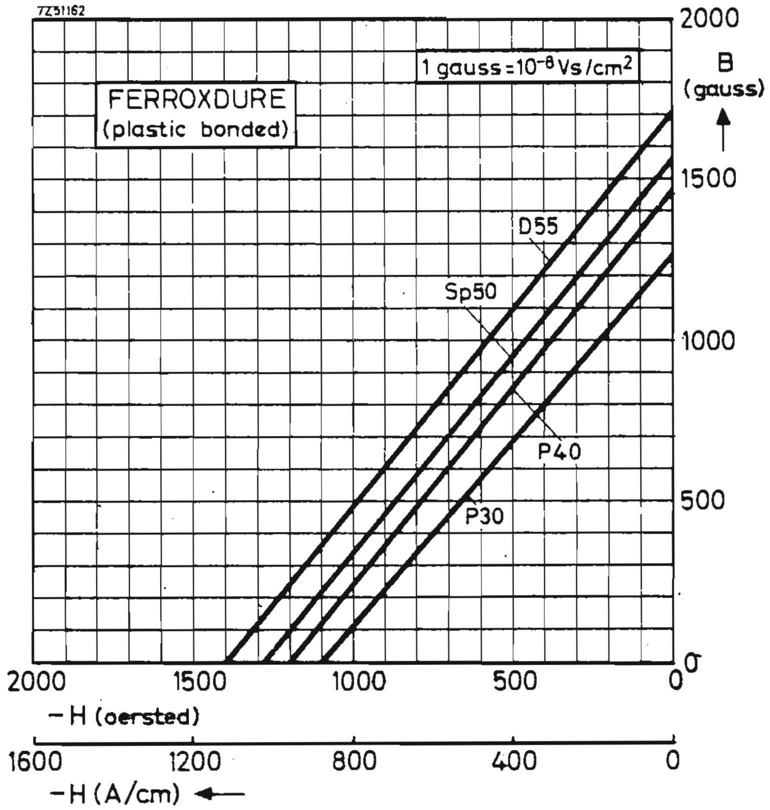
A relatively flexible permanent magnet material with 93 wt% ferroxdure powder (M)$Fe_{12}O_{19}$ and 7 wt% thermoplastic material, shaped by injection moulding to the required shapes.

Ferroxdure D55

A hard and rigid permanent magnet material with 95 wt% ferroxdure powder (M)$Fe_{12}O_{19}$ and 5 wt% of thermosetting material, shaped by pressing.

The plastic bonded isotropic ferroxdure magnets find use where magnets have been unsuitable till now for either technical or economical reasons.

Demagnetisation curves

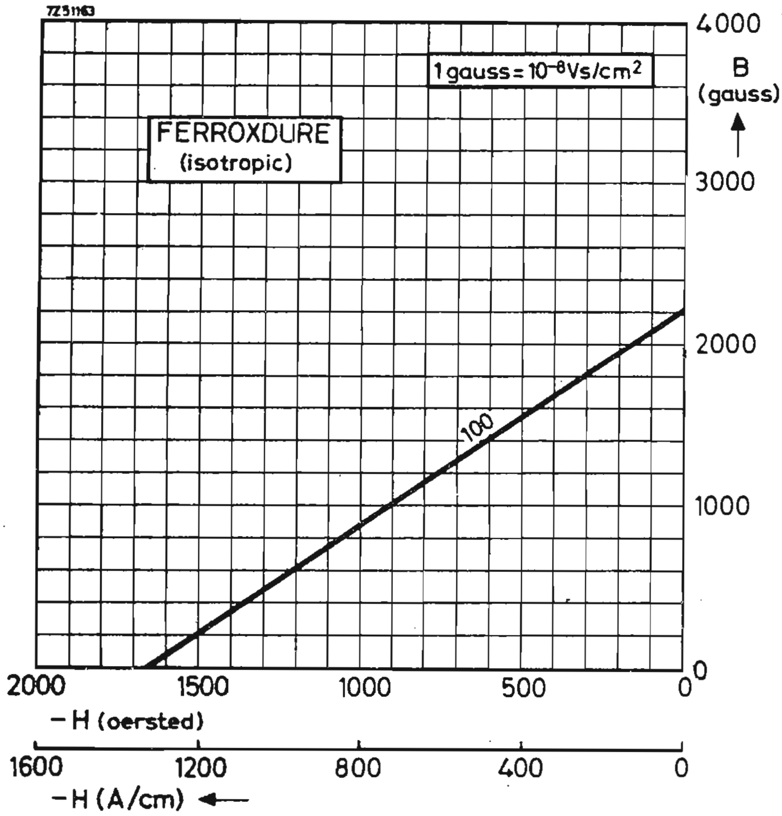


ISOTROPIC FERROXDURE

Ferroxdure 100 (KPN - K - 359)

The individual crystals have a random orientation and poles can therefore be induced wherever the application demands. The material is best suited either for applications where high magnetic values are not essential or else where the isotropic properties are required.

Demagnetisation curve



ANISOTROPIC FERROXDURE

Ferroxdure 280K and 330K (KBN - K - 435-252)

The materials have high values of coercive field strength and are therefore ideal for applications where strong demagnetising influences are encountered.

Note: Ferroxdure 280K is an improved grade of ferroxdure 250K.

Ferroxdure 330 Rad.

This material has a higher intrinsic coercive field strength and lower remanence compared with ferroxdure 330K, but has a radial orientation which is especially suitable for the manufacture of segmental magnets for use in d.c. motors.

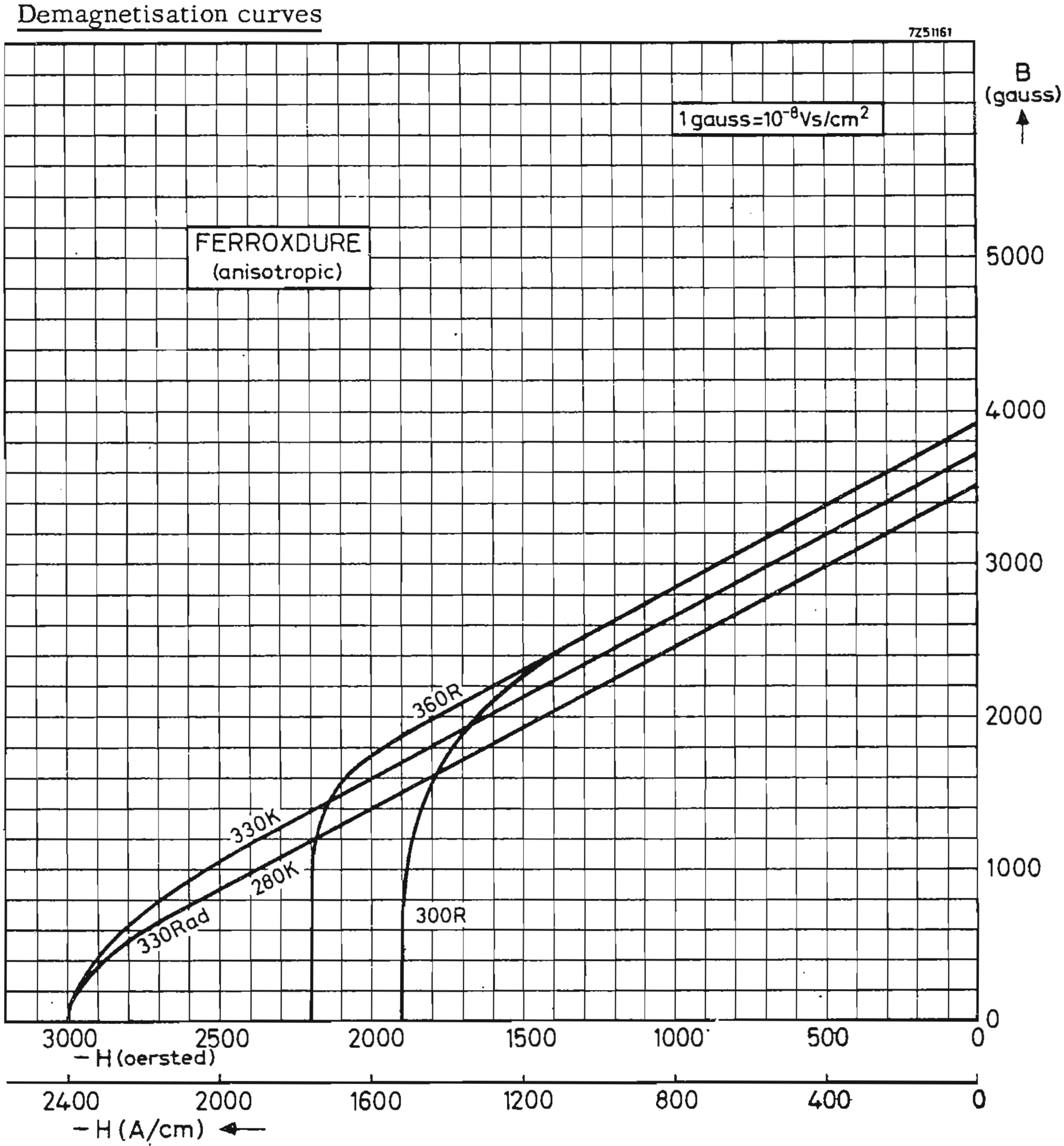
Ferroxdure 300R and 360R (KBN - K 434 - V-254)

The materials have the same high values of flux density but ferroxdure 360R has a higher coercive field strength (and a greater distance of the point (BH)max from the knee in the demagnetisation curve), which permits designs to operate at the maximum energy product of the material.

Both materials are particularly suitable for applications demanding high values of external energy product.

If dismounting requirements and/or highest flux requirements are imposed, it is recommended that the magnet be magnetised in its system.

Demagnetisation curves



DESIGN DATA

See "Survey of permanent magnet materials".

CHEMICAL COMPOSITION

The pure ceramic ferroxdure permanent magnet materials contain 100 wt% $(M)Fe_{12}O_{19}$.

CHEMICAL PROPERTIES of ferroxdure containing 100 wt% $(M)Fe_{12}O_{19}$.

Ferroxdure is chemically rather inert. Its chemical resistance is characterised as follows:

Ferroxdure is not attacked by: sodium chloride in a 30% solution;
a mixture of benzol-trichlorine ethylene in a 50% solution;
petrol;
nitric acid;
nitric acid in a 50% solution;
acetic acid;
cresol;
phenolic solutions;
sodium sulphate solution.

Ferroxdure is lightly attacked by: dilute sulphuric acid;
hydrochloric acid in a 50% solution.

Ferroxdure is subject to attack by: concentrated hydrochloric acid.

TEMPERATURE COEFFICIENT AND THE EFFECT IN MAGNETIC PERFORMANCE

With the isotropic ferroxdure grades the effect of variations in temperature on the induction is practically reversible. In other words, after temporarily heating or cooling, the starting point on the BH curve is regained within some percent without remagnetisation being necessary. Only after heating above the Curie point does permanent demagnetisation occur.

The same applies to anisotropic ferroxdure grades, but with these materials care should be taken that when cooling the magnets below room temperature (which gives an increase of B and a decrease of H) the working point of the magnets does not pass the knee of the demagnetisation curve. Otherwise a lower working point will be obtained after reheating to the original temperature.

In the sequence

ferroxdure 300R
360R
280K
330K
330Rad

the materials have a decreasing sensitivity, due to the higher coercive field strength values, resulting in a favourable shift of the knee.

GLUING OF FERROXDURE MAGNETS

For making very large magnets it is possible to glue individual ferroxdure parts to each other. Ferroxdure parts can also be glued to metal fittings. Here it should be noted that ceramic materials have a considerably smaller coefficient of thermal expansion than most metals.

The coefficient of expansion is for

ferroxdure	8.5×10^{-6}/deg C
steel	$11 - 20 \times 10^{-6}$/deg C
brass	18×10^{-6}/deg C

With a very rigid connection the inevitably occurring thermal stresses may easily lead to damaging of the ferroxdure crystal structure and may even cause fracture.
With some epoxy resins particularly, the formation of cracks has been observed.

Generally a less rigid, reasonably strong but elastic adhesive joint is adequate. Frequently it is reinforced by the magnetic clamping force. Experience with adhesives on a neoprene base has been good.

In the design stage it should be noted specially that ferroxdure permanent magnets can resist large pressure more readily than tension.

APPLICATIONS

Some applications in which ferroxdure permanent magnets are commonly used today are

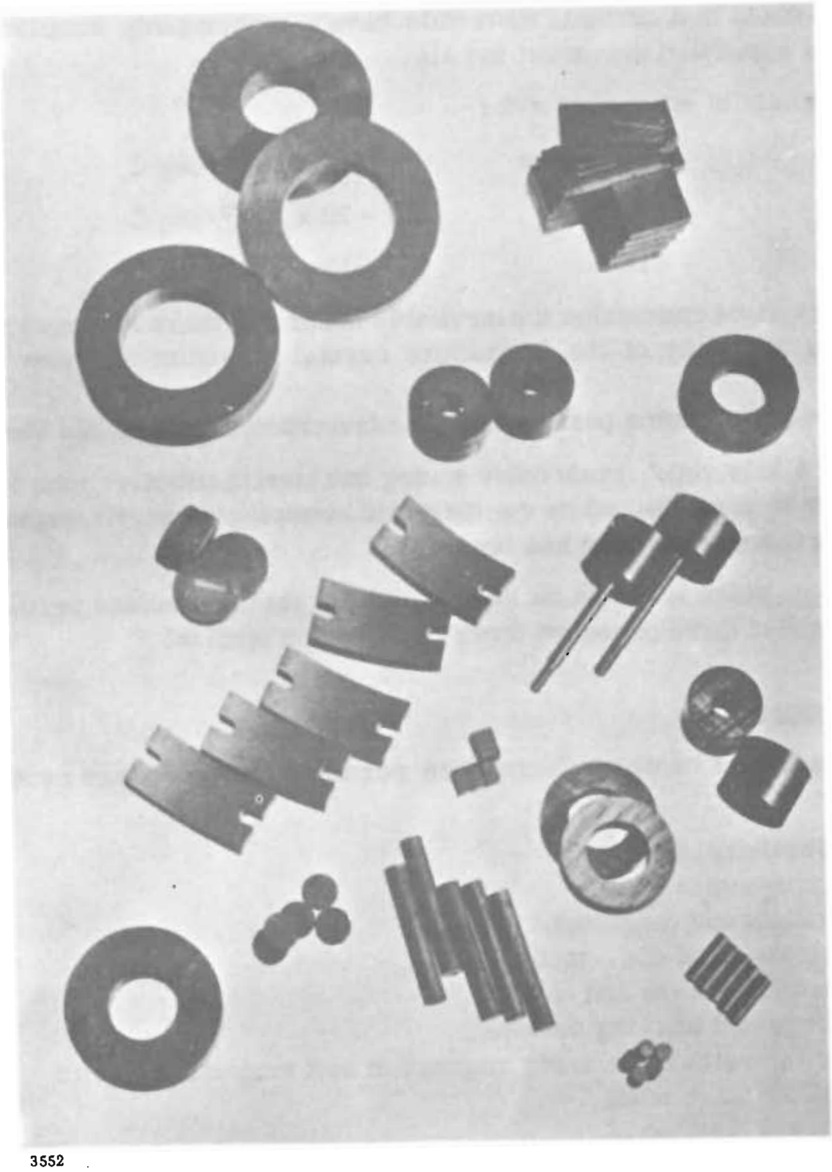
- Loudspeakers
- Bicycle dynamos
- Generators and magnetos
- Synchronous and d.c.-motors
- Separators, filters and chucks
- Couplings and sticking devices
- Deflection units and biasing magnets in soft magnetic circuits
- Travelling wave tubes
- Clocks and watches.

The radially orientated ferroxdure 330 Rad will no doubt further stimulate the use of segments in fractional horse power motors

a) for the automotive industry such as starter motors, screen wiper motors, ventilator motors, screen washer motors and all those motor-equipped devices which make car driving more comfortable.

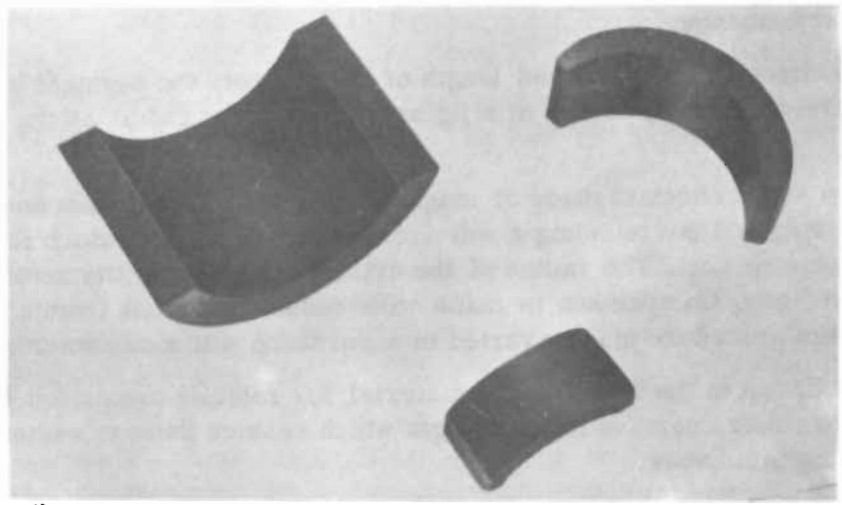
b) for the household appliances such as electric tooth brushes, mixers, coffee mills, knives, small vacuum cleaners, polishers, etc.

All the grades with nearly straight demagnetisation curves will expand the applications for permanent magnets in sandwich type devices and the more professional applications such as travelling wave tubes, watches, magnetos, alternators, generators, synchronous motors, filters and separators.



3552

ANISOTROPIC FERROXDURE SEGMENTS



3553

RZ 18440-2

Besides the already well known ferroxdure magnets in the form of rings, disks, cylinders, rods and blocks, a new and rather important form has been introduced: the ferroxdure magnet in the form of a segment with either diametrical or radial orientation.
Material for diametrical magnetisation: ferroxdure 330 K
for radial magnetisation : ferroxdure 330 Rad.

Segmentary permanent magnets are used in the magnetic circuit of e.g.

D.C. motors and
Fly-wheel magnetos.

These circuits are composed of a soft iron armature (with coils) and a soft iron ring with segmentary magnets.

The following data are of major consequence for both the circuit engineer and the manufacturer of the magnets.

A. The internal radius of the ring.
B. The external radius of the armature.
C. The min. acceptable air gap between rotor and magnet.
D. The angle of the segment: $< 120^{\circ}$ for diametrically orientated magnets; 120°-140° for radially orientated magnets.
E. The required flux from which the length of the segment is derived.

On enquiry, please give at least these data complete with tolerances. A check list is also available on request.

The radii of the segments should slightly exceed the radii of the ring and of the (armature + min. acceptable air gap). In this way, the segments will touch the ring at their edges and so the risk of breakage during mounting is reduced. Also, the varying air gap occurring between segments and armature will favourably influence the silent running of the device, without adversely affecting the magnetic performance.

Apart from checking the width and length of the magnet, the segment height and thickness are checked by means of a jig having the same radius as the soft iron ring.

Normally, a static check is made of magnetic flux with the segment enclosed by a soft iron ring and surrounding a soft iron cylinder, around which is a longitudinal measuring coil. The radius of the cylinder is equal to the armature radius plus air-gap. Comparison is made with results obtained from a standard segment. This procedure may be varied in accordance with a customer's wishes.

Attention is drawn to the fact that the material for radially orientated segments has a high intrinsic coercive field strength which enables them to withstand high demagnetising influences.

Special requirements for the values of intrinsic coercive field strength should be stated.

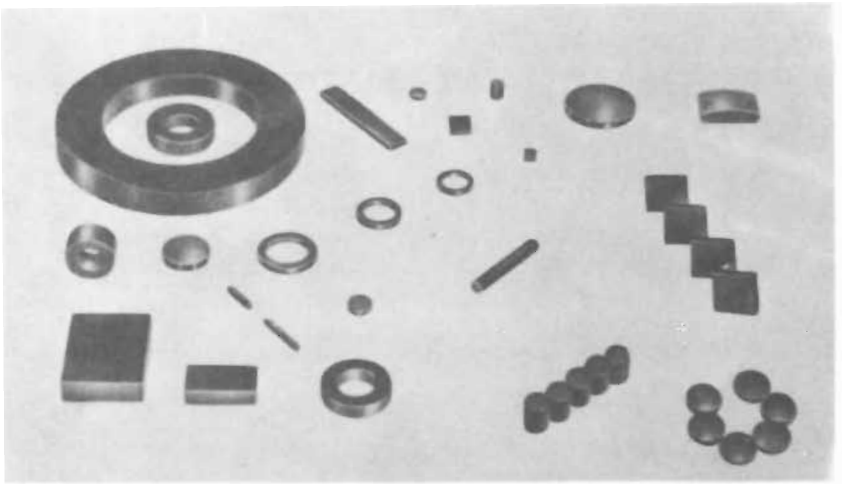
LIST OF PREFERRED PERMANENT MAGNETS

Permanent magnets may be

a. Ordered to your own design (within the limits of the materials and manufacturing techniques).

b. Selected from the list of preferred types. The list contains data on types for which the dies and moulding plates already exist. In a lot of cases stock is available for immediate dispatch to enable trials and small series production in short time.
   Choice of a preferred type eliminates the need for additional tools and development work at the factory. Please use catalog number for ordering.

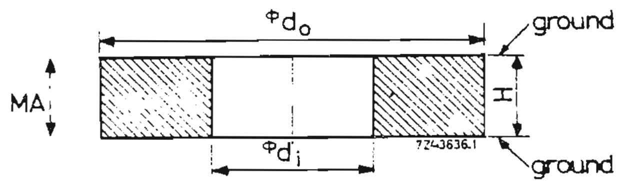
Our technical assistance on the design and application of permanent magnets is always at your disposal - see the section "Design advisory service".



3554

ANISOTROPIC FERROXDURE

Ring magnets for loudspeakers etc.

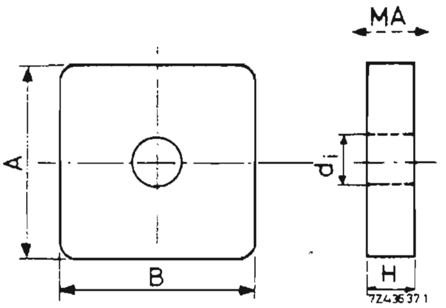


Material: Fxd 300R
Direction of magnetisation: axial
Version: unmagnetised

dimensions						type number	catalog number
outer diam.		inner diam.		H			
mm	tolerance	mm	tolerance	mm	tolerance		
36	±0.8	18	±0.5	8	±0.1	K6 150 71	4322 020 60071
38.5	±0.6	23	±0.5	9	−0.1	K6 154 81	60381
40	+1.3 −0.7	15	±0.4	7	±0.1	K6 152 61	60081
40	±0.9	22	±0.5	9	±0.1	K6 152 11	60091
45	±1	22	±0.6	8	±0.1	K6 153 01	60101
45	±1	22	±0.6	9	±0.1	K6 152 41	60111
45	±1	22	±0.6	10.5	±0.1	K6 150 51	60121
45	±1	24	±0.6	8.5	±0.1	K6 154 51	60411
45	±1	24	±0.6	9	±0.1	K6 154 21	60131
51	±1.2	24	±0.6	9	±0.1	K6 151 21	60151
51	±1.2	24	±0.6	10	±0.1		60031
55	±1.2	24	±0.6	8	±0.1	K6 150 81	60161
55	±1.2	24	±0.6	12	±0.1	K6 152 01	60171
60	±1.5	24	±0.6	8	±0.1	K6 153 11	60181
60	±1.5	24	±0.6	12	±0.1	K6 151 91	60191
60	±1.5	24	±0.6	13	±0.1	K6 150 61	60201
60	±1.5	30	±0.7	10	±0.1	K6 152 71	60211
68	±1.5	32	±0.7	13	±0.1	K6 151 51	60231
72	±1.5	32	±0.7	15	±0.1	K6 151 11	60241
73	±2.2	31	±0.9	10	±0.1	K6 153 21	60261
84	±1.8	32	±0.9	15	±0.1	K6 152 81	60271
90	±1.8	36	±0.9	17	±0.15	K6 152 51	60281
96	±2.4	40	±1	25	±0.15	K6 153 31	60291
102	±3	51	±1.5	10	±0.15	K6 153 61	60301
102	±3	51	±1.5	14	±0.15	K6 153 71	60311
121	±3.6	57	±1.7	12	±0.2	K6 153 91	60321
134	±4	57	±1.7	14	±0.2	K6 153 51	60331
134	±4	57	±1.7	14	±0.2	K6 154 01 [1]	60341
134	±4	57	±1.7	20	±0.2		60021
155	±4.5	57	±1.7	17.5	±0.15		60011
184	±5.5	73	±2.2	18.5	±0.2	K6 153 41	60351
184	±5.5	81.3	±2	18.5	±0.2		60001

[1] Outer diameter provided with 3 slots

Square magnets for loudspeakers

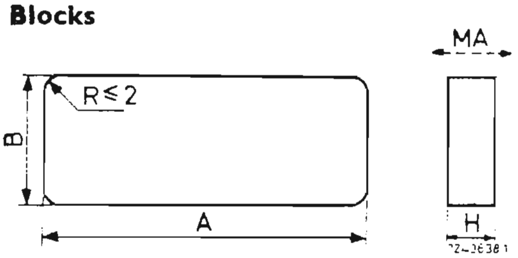


Material: Fxd 300
Direction of magnetisation: ⊥ A × B
Version: unmagnetised

dimensions A mm	A *tolerance*	B mm	B *tolerance*	H mm	H *tolerance*	diam. hole mm	diam. hole *tolerance*	*type number*	*catalog number*
30.6	±0.8	30.6	±0.8	5	±0.1	12.4	±0.4	K6 137 51	4322 020 63011
32	±0.8	26	±0.6	8	−0.1	15.5	+0.8	K6 176 51	63091
41	±1	41	±1	8	±0.1	15.5	+0.8	K6 137 61	63041
50	±1	50	±1	10	±0.1	26	±0.6	K6 175 65[1]	63021[1]
50	±1	50	±1	12	±0.1	26	±0.6		63001[1]

[1] Inner diameter provided with 2 slots.

Blocks

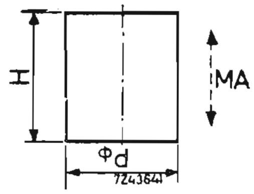


Material: see below
Direction of magnetisation: ⊥ A × B
Version: magnetised

dimensions A mm	A *tolerance*	B mm	B *tolerance*	H mm	H *tolerance*	*material*	*type number*	*catalog number*
7	±0.2	1.4	±0.1	0.8	±0.1	300R		4322 020 62161[2]
5	±0.2	5	±0.2	4	−0.2	300R	K6 175 90	62021
7	±0.3	7	±0.3	4.2	±0.05	250K		62001
15	±0.3	9	±0.5	5	±0.25	250K	K6 176 10	3122 104 92701
20	±0.5	10	±0.5	5	±0.1	250K	K6 176 30[2]	4322 020 62031[2]
20	±0.5	10	±0.5	5	±0.1	250K	K6 176 40	62041
30	±0.8	30	±0.8	15	±0.1	250K	K6 176 20[2]	62071[2]
40	±1	25	±0.75	10	±0.1	330K		62181
50	±1.3	19	±0.5	4.9	−0.25	250K	K6 175 30[2]	62091[2]
50	±1.3	19	±0.5	4.9	−0.25	250K	K6 175 50	62101
50	±1.3	19	±0.5	6.1	±0.1	250K	K6 175 70[2]	62111[2]
50	±1.3	19	±0.5	6.1	±0.1	250K	K6 175 80	62121
131	±3	51	±1.5	17.5	±0.2	330K		62141[2]

[2] Magnets are not magnetised.

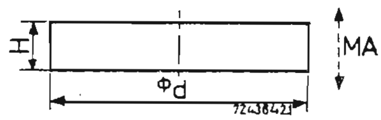
Slugs



Material: see below
Direction of magnetisation: axial
Version: magnetised

dimensions				material	type number	catalog number
d		H				
mm	tolerance	mm	tolerance			
10	±0.5	10	±0.2	250K	K6 038 00	4322 020 61021
10	±0.5	12	±0.2	250K	K6 038 10	61011
10	±0.5	15	±0.2	250K		61001

Discs

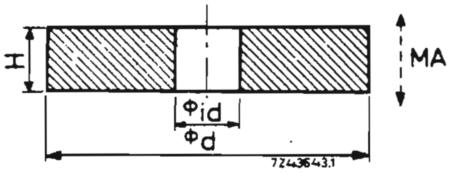


Material: see below
Direction of magnetisation: axial
Version: unmagnetised

dimensions				material	type number	catalog number
d		H				
mm	tolerance	mm	tolerance			
5.5	±0.05	1.8	±0.03	330K	—	4322 020 62591
10	±0.2	2	±0.05	330K	—	62502
10	±0.5	4.6	±0.1	250K	—	62581
12	±0.3	6	±0.25	300R	K6 112 75	62541 [3]
28.8	−0.3	12.5	±0.5	250K	—	62511
40.6	±1	9	±0.1	250K	K6 112 65	62551
45	±1.1	9	±0.1	250K	K6 075 00	62561

[3] Magnets are magnetised

Rings (other than for Loudspeakers)



Material: see below
Direction of magnetisation: axial
Version: unmagnetised

dimensions						material	type number	catalog number
outer diam.		*inner diam.*		*H*				
mm	*tolerance*	*mm*	*tolerance*	*mm*	*tolerance*			
20	±0.2	5.15	±0.15	4	±0.1	300R	K6 153 81	4322 020 60041
24	+0.08	10.2	±0.3	4.05	±0.1	250K	K6 154 11	60052
30	±0.6	12.7	±0.5	6.35	±0.05	250K	K6 152 20	60061
42	+2.3	10	−0.5	8	+1.6	250K	K6 152 30	60391

Segments

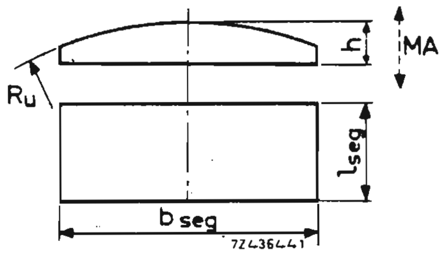
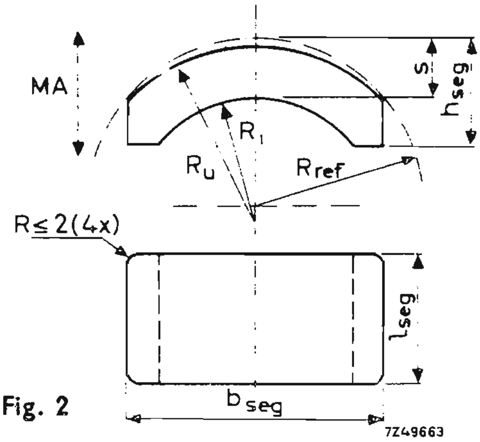


Fig. 1

Material: Fxd 300R
Direction of magnetisation: axial
Version: unmagnetised

dimensions							type number	catalog number
R_u		b_{seg}		l_{seg}		*h*		
mm	*tolerance*	*mm*	*tolerance*	*mm*	*tolerance*	*mm*		
49	+10	34	±0.9	23	±0.6	7.1	K6 200 10	4322 020 61541
55	+10	35	±0.9	23	±0.6	10.4	K6 200 05	61531

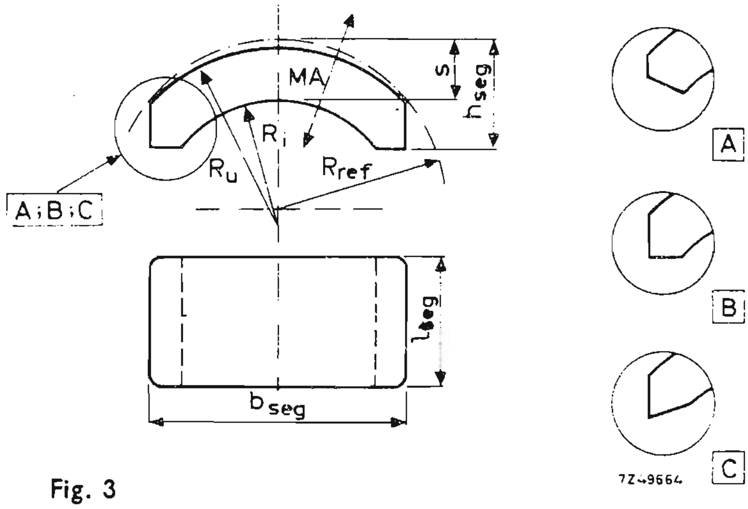
Segments for d.c. motors



Material: Fxd 330 K
Direction of magnetisation: diametrical
Version: not magnetised

Fig. 2

R_i	R_u	s	h_{seg}		b_{seg}		l_{seg}		catalog number	Fig.
mm	tol.	mm	mm	tol.	mm	tol.	mm	tol.		
⩾ 8.315	⩾ 12.025	⩽ 3.66	8	±0.6	18	±0.5	15	+1	4322 020 61561	2
⩾ 20.3	⩾ 29	⩽ 8.7	16	±0.6	42	±1	19.8	±0.5	4311 021 30471	2
⩾ 20.3	⩾ 29	⩽ 8.7	16	±0.6	42	±1	41	+1	4311 021 30362	2



Material: Fxd 330 Rad.
Direction of magnetisation: radial
Version: not magnetised

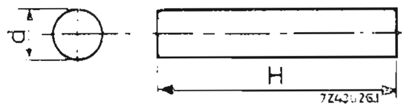
Fig. 3

R_i	R_u	s	h_{seg}		b_{seg}		l_{seg}		catalog number	Fig.
mm	mm	mm	mm	tol.	mm	tol.	mm	tol.		
⩾ 27.94	⩾ 35.41	⩽ 7.39	24.99	−0.93	60.71	+2.5	25.4	+1.27	4322 020 61601	3B
⩾ 28.58	⩾ 35.13	⩽ 6.55	25.5	±0.6	62.4	+0.4	26.7	±0.75	4322 020 61512	3A
⩾ 28.41	⩾ 35.55	⩽ 7.15	21.4	−1.2	60.3	+3.0	39.4	+1	4322 020 61581	3C
⩾ 29.03	⩾ 36.02	⩽ 7.49	21.79	±0.38	62.7	+3.0	27.88	±1.25	4322 020 61591	3B
⩾ 26.85	⩾ 35.09	⩽ 8.18	24	±0.7	60	±1.5	40	±1	4322 020 61621	3B

ISOTROPIC FERROXDURE

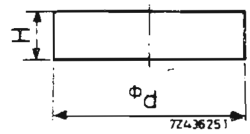
Discs and bars

Material: Fxd 100



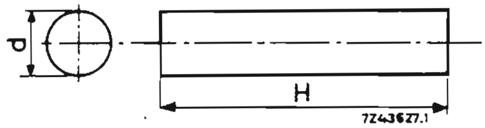
a) axially magnetised

diam. d mm	diam. d tolerance	H mm	H tolerance	type number	catalog number
3	±0.2	7.5	±0.25	VK.300.23	4312 020 60131
5	±0.3	10	±0.5	VK.300.03	60021
5	±0.2	20	±0.5	VK.300.00	60001
5	±0.3	30	±0.8	VK.300.02	60011
5	±0.2	39	−1	VK.300.25	60101
5	±0.3	50	±1.0	VK.300.22	60151
6	±0.3	33	±0.6	VK.300.17	60071



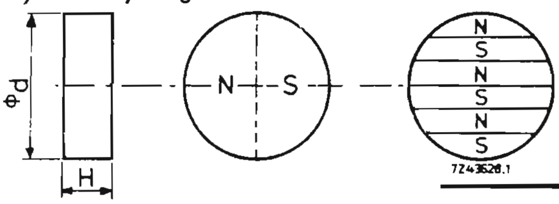
diam. d mm	diam. d tolerance	H mm	H tolerance	type number	catalog number
4	±0.2	3.5	±0.2	VK.310.07	4312 020 65951
5.5	±0.3	5	±0.3	VK.310.09	65931
8	±0.3	3	±0.3	VK 310 11	65911
8	±0.5	5	±0.5	VK 310 06	65961
10	±0.3	2.5	±0.3	VK 310 05	65971
10	±0.5	5	±0.5	VK 310 08	65941
14	±0.5	4	±0.5	VK 310 12	65901
14	±0.5	5	±0.3	VK 310 13	65891
14	±0.3	10	±0.5	VK 310 17	65831
20	±0.35	5	±0.3	VK 310 27	65881
25	±0.5	5	±0.4	VK 310 18	65871
32	−1	8.7	±0.3	VK 310 34	65811

b) diametrically magnetised



dimensions				type number	catalog number
diam. d		H			
mm	tolerance	mm	tolerance		
4	±0.1	5	±0.2	VK 300 18	4312 020 60081
4	±0.1	10	±0.2	VK 300 13	60041
4	±0.1	20	±0.2	VK 300 14	60051
4	±0.1	30	±0.2	VK 300 15	60061
5	±0.5	15	±0.5	VK 300 26	60111

c) laterally magnetized

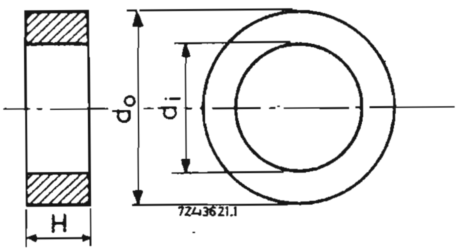


dimensions				type number	catalog number
d		H			
mm	tol.	mm	tol.		
14	±0.5	5	±0.3	VK 310 21[1]	4312 020 65861
20	±0.4	3	±0.3	VK 310 36[2]	65791
25	±0.5	5	±0.4	VK 310 23[2]	65851

[1] 2 poles on 1 face. [2] 6 poles on 1 face.

Rings

Material: Fxd 100



a) diametrically magnetised

dimensions						type number	catalog number
outer diam.		square hole		H			
mm	tolerance	mm	tolerance	mm	tolerance		
12.25	±0.25	3.2	±0.5	10	±0.5	VK 320 06	4312 020 62111
12	+0.5	3.2	±0.5	12	±0.5	VK 320 07	62121

Rings

Material: Fxd 100

b) axially magnetised

dimensions						type number	catalog number
outer diam.		inner diam.		H			
mm	tolerance	mm	tolerance	mm	tolerance		
11.9	±0.4	5.75	±0.25	6.5	±.05	VK 320 19	4312 020 62211
14	±0.5	1.5	±0.5	5	±0.5	VK 320 16	62181
14	±0.5	4	±0.25	4	±0.25	VK 320 18	62201
15.6	±0.3	6.25	±0.2	3	−0.1	VK 320 03	62101
18	±0.45	5	±0.2	5	±0.2	VK 320 12	62141
29.9	−0.05	10	±0.3	5	−0.1	VK 321 10	62271[1]
36	−0.1	10	±0.2	5	−0.1	VK 321 18	62731[1]
37	±0.8	25	±0.5	3.5	±0.5	VK 321 06	62261

[1] 4p axially magnetised.

c) radially magnetised

dimensions						magnetisation	type number	catalog number
outer diam.		inner diam.		H				
mm	tol.	mm	tol.	mm	tol.			
13	±0.3	5.3	±0.2	8	±0.3	N pole on o.d.	VK 320 13	4312 020 62151
13	±0.3	5.3	±0.2	8	±0.3	S pole on o.d.	VK 320 14	62161
18	±0.5	12	±0.5	3	±0.5	S pole on o.d.	VK 320 47	62251
27	±0.7	20	±0.6	3.5	±0.5	S pole on o.d.	VK 321 28	62341

d) laterally magnetised

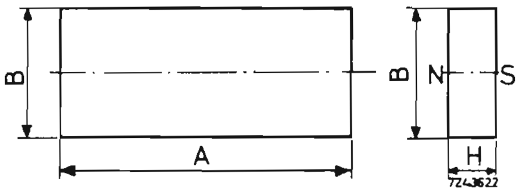
dimensions						magnetisation	type number	catalog number
outer diam.		inner diam.		H				
mm	tol.	mm	tol.	mm	tol.			
24	−0.05	10	±0.5	21.25	±0.45	8 poles on outer ø	VK 375 14	4312 020 62471
24	−0.04	12	±0.3	12	±0.4	16 poles on outer ø	VK 321 30	62351
29.9	−0.05	10	±0.5	18.2	±0.4	4 poles on outer ø	VK 375 23	62481
37	±0.8	25	±0.5	3.5	−0.5	4 poles on one surface	VK 321 42	62401

e) rings for couplings (laterally magnetised)

dimensions						*magnetisation*	*type number*	*catalog number*
outer diam.		*inner diam.*		*H*				
mm	*tol.*	*mm*	*tol.*	*mm*	*tol.*			
48	±0.05	30	±0.05	12	±0.1	14 poles on outer ø	VK 321 24	4312 020 62751
55	±0.05	15	±0.5	13	±0.1	12 poles on outer ø	VK 322 09	62431
72	±0.05	52	±0.05	12	±0.1	14 poles on inner ø	VK 322 07	62791
78	±1.5	58	±0.05	13	±0.1	12 poles on inner ø	VK 322 08	62421
86	+0.2	32	±0.5	23	±0.1	8 poles on outer ø	VK 322 10	62441
120	±0.5	96	−0.2	23	±0.1	8 poles on inner ø	VK 323 00	62451

Blocks

Material: Fxd 100

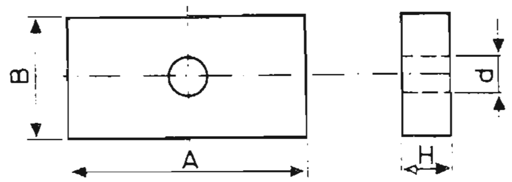


magnetised ⊥ *A* × *B*

dimensions						*type number*	*catalog number*
A		*B*		*H*			
mm	*tolerance*	*mm*	*tolerance*	*mm*	*tolerance*		
50	±1.25	22	±0.55	5	±0.1	VK 312 02	4312 020 66981
40	±1	25	±0.75	10	±0.1	VK 312 10	66931
40	±1	17	±0.4	4	±0.1	VK 312 04	66971
28	−0.5	13	−0.5	3.5	+0.5	VK 312 13	66751
15	±0.5	15	±0.5	5	±0.3	VK 312 08	66951
8	±0.5	8	±0.5	5	±0.5	VK 312 11	66771
10	±0.5	5	±0.5	3	±0.5	VK 312 12	66761

Blocks with holes

Material: Fxd 100

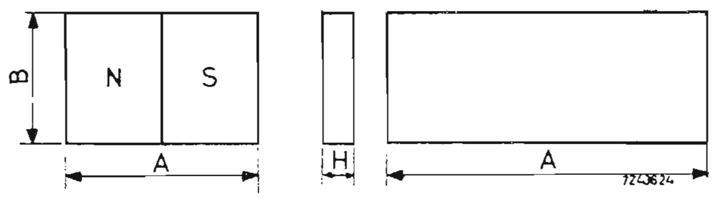


magnetised ⊥ *A* × *B*

dimensions								*type number*	*catalog number*
A		*B*		*H*		*D*			
mm	*tolerance*	*mm*	*tolerance*	*mm*	*tolerance*	*mm*	*tolerance*		
25	±0.4	15	±0.3	5.5	±0.3	4.6	±0.25	VK 312 20	4312 020 66711
25	±0.4	12	±0.3	5	±0.3	4.6	±0.25	VK 312 21	66901

Blocks

Material: Fxd 100

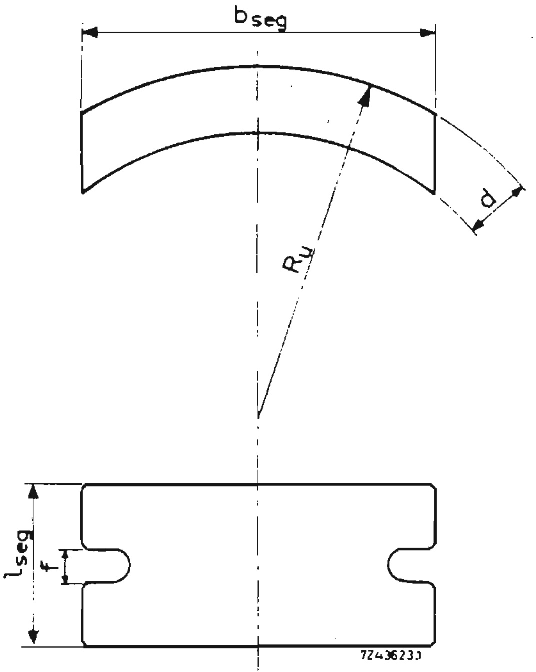


laterally magnetised

dimensions						*magnetisation*	*type number*	*catalog number*
A		*B*		*H*				
mm	*tolerance*	*mm*	*tolerance*	*mm*	*tolerance*			
18	±1	7	±1	6	±1	2 poles on 18 × 6	VK 303 01	4312 020 66801
20	±0.35	10	±0.25	4	±0.25	2 poles on 20 × 10	VK 312 14	66741
75	±2	15	±0.4	4	±0.05	8 poles on 75 × 15	VK 303 02	66861

Segments

Material: Fxd 100



not magnetised

type number		**VK 360 04**	
catalog no.		**4312 020 61501**	
		mm	*tolerance*
dimensions	R_u	54.55	+2.5
	b_{seg}	54	±0.5
	l_{seg}	27	±0.3
	f	5.2	+0.5
	d	7.4	±0.2

ISOTROPIC PLASTIC-BONDED FERROXDURE

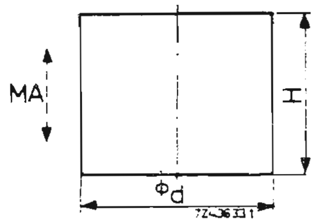
Material: see below
Direction of magnetisation: see below
Version: magnetised

article	*dimensions*	*material*	*direction of magnetisation*	*catalog number*
Strip	(9±0.3)×(3±0.1)	P40	2 poles lateral	4312 020 70021
Ring	Ø(21.5+0.3)×(16—0.25)×(12+0.4)	D55	2 poles radial	4312 020 72011
Block	(10.6—0.6)×(10.6—0.6)×(3±0.15)	P30	diametrical	3122 104 93541
Bar	Ø(5±0.2)×(40—1)	P30	axial	3122 104 90361

ANISOTROPIC "TICONAL"

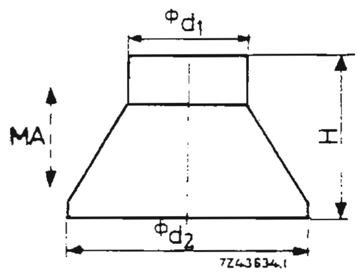
Slugs (I)

Material: see below
Direction of magnetisation: axial
Version: unmagnetised



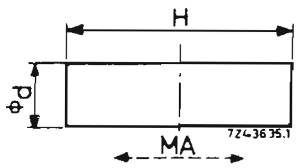
dimensions				material	type number	catalog number
d		H				
mm	tolerance	mm	tolerance			
9.1	+0.2	5	−0.05	"Ticonal" 750	—	4322 059 75001
9.1	−0.1	10	−0.05	,, 750	—	75011
12.9	−0.3	10	−0.05	,, 750	—	75061
15.1	−0.03	11.5	±0.05	,, 750	—	75041
15.8	−0.1	13.4	±0.1	,, 750	—	75031
16.4	±0.3	13.4	−0.1	,, 650	3C 010 33	65021
18	−0.4	12	−0.1	,, 600	3C 010 18	60001
19.4	±0.3	9.4	±0.1	,, 750	—	75081
19.4	±0.3	15.4	−0.1	,, 650	3C 010 32	65031
19.4	±0.3	15.4	±0.1	,, 750	—	75071
21	±0.5	16	±0.05	,, 600	3C 007 45	60011
21	±0.5	22.5	±0.05	,, 600	3C 010 30	60041
24.2	−0.4	16	±0.05	,, 600	3C 009 96	60021
27.5	±0.5	18.5	±0.05	,, 600	3C 007 46	60031

Slugs (II)



dimensions						material	type number	catalog number
d1		d2		H				
mm	tolerance	mm	tolerance	mm	tolerance			
13.2	−0.5	18	−0.5	13	±0.05	"Ticonal" 600	3C 007 44	4322 059 60051
18	−0.3	26	±0.5	17.5	±0.05	600	3C 010 35	60061

Rods

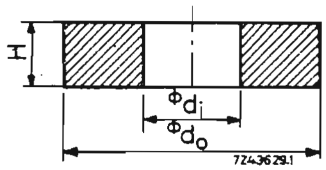


Material: Ticonal 500
Direction of magnetization: axial
Version: see below

dimensions				*version*	*type number*	*catalog number*
d		*H*				
mm	*tolerance*	*mm*	*tolerance*			
4	±0.2	6	±0.2	unmagnetised	3C 009 80	4322 059 50071[1])
5	±0.3	13	±0.1	unmagnetised	3C 010 16	50081
5	±0.3	19.5	±1	magnetised	3C 009 82	50091
5.5	−1	25	±0.5	magnetised	3C 001 24	50101[1])
8.1	−1	65	±0.5	magnetised	3C 002 36	50111[1])

[1]) Bars in these diameters can be supplied in any length between 8 and 100 mm.

Rings



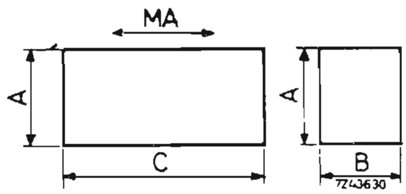
Material: see below
Direction of magnetisation: see below
Version: see below

dimensions						*material*	*d/m*	*version*	*type number*	*catalog number*
outer diam.		*inner diam.*		*H*						
mm	*tol.*	*mm*	*tol.*	*mm*	*tol.*					
18.1	+0.1 −0.2	5	+1	10	−0.05	"Ticonal"600	a	unmagnetised	3C 010 36	4322 059 60071
30	±0.5	7	±0.5	25	±0.2	400	a	magnetised	3C 000 60	40001
56	±0.5	48	±0.5	10	±0.5	400	d	unmagnetised	3H 717 83	40011

d/m = direction of magnetisation
d = diametrical
a = axial

Blocks

Material: see below
Direction of magnetization: ⊥ face A × B
Version: see below

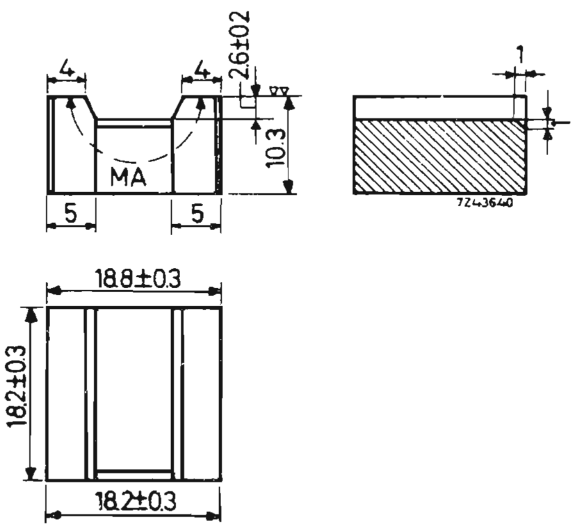


dimensions						material	version	type number	catalog number
A		B		C					
mm	tol.	mm	tol.	mm	tol.				
2	±0.05	2.6	±0.05	2.25	−0.03	"Ticonal" 900	unmagnetised	—	4322 059 90002
4	±0.05	4	±0.05	5	±0.02	,, 900	unmagnetised	—	90011
8	−1	5	−0.4	14	−1	,, 400	magnetised	3H 717 36	40021
27	−1	20	±0.5	17	±0.05	,, 450	unmagnetised	3C 009 94	45031
21.5	±0.5	14.5	±0.5	22	+0.2	,, 500	magnetised	3C 000 59	50121
100	±1	12	±0.1	29.1	±0.05	,, 500	unmagnetised	3C 000 09	50131[1]
22	±0.3	9.1	−0.4	40	±0.1	,, 500	magnetised	3C 008 40	50141
32	±0.5	20.8	±0.5	40	±0.05	,, 500	unmagnetised	3C 005 06	50151[2]
10	±0.5	5	±0.5	50	±1	,, 500	magnetised	3C 002 02	50161
10.5	±0.2	17	±0.3	40	±0.05	,, 500	unmagnetised	3C 010 46	50171

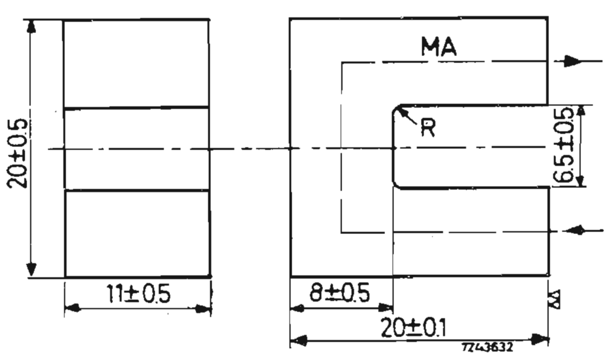
[1] with two mounting holes. [2] with one mounting hole.

Special types

Type number: 3C010.25 (unmagnetised)
Catalog number: 4322 059 10001
Material: "Reco I"
Version: unmagnetised



Type number: 3C009 72.1 (unmagnetised)
Catalog number: 4322 059 400 31
Material: "Ticonal" 400
Version: unmagnetised



DESIGN ADVISORY SERVICE

Our Application engineers offer technical assistance on the use and design of permanent magnets and complete permanent-magnet systems. Guidance is also offered on ancillary problems such as installation, handling and magnetisation. If you require more specific information than is provided here please send your enquiry to us.

When ordering new types of magnet, the following information should be given:

(1) The purpose for which the magnet is to be used should be stated.

(2) A sketch or drawing of the magnet should be provided showing the shape and the dimensions, with tolerances.

(3) The pole faces that have to be ground must be clearly indicated.

(4) The direction of the magnetic axis should be clearly shown.

(5) It should be stated whether the magnet is to be supplied magnetised or unmagnetised. (It is usual to supply magnets unmagnetised as the most efficient use of magnetic materials necessitates magnetisation in position after assembly.)

(6) The quantity required and the desired rate of delivery should be stated.

THEORY OF PERMANENT MAGNETS

The magnetic quantities are expressed in the MKSA system of units (V, A, s, m) or in the cgs system of units (Gs, Oe).

When a magnetic material is subjected to a magnetising field, the extent of the resulting magnetisation of the material will depend on the nature and immediate history of the material, and on the direction and magnitude of the magnetising field.
This dependence will be explained by describing the magnetic changes in a permanent magnet material accompanying a complete cycle of magnetisation and demagnetisation (hysteresis loop), and also the changes accompanying smaller variations in field strength (recoil line).

HYSTERESIS LOOP

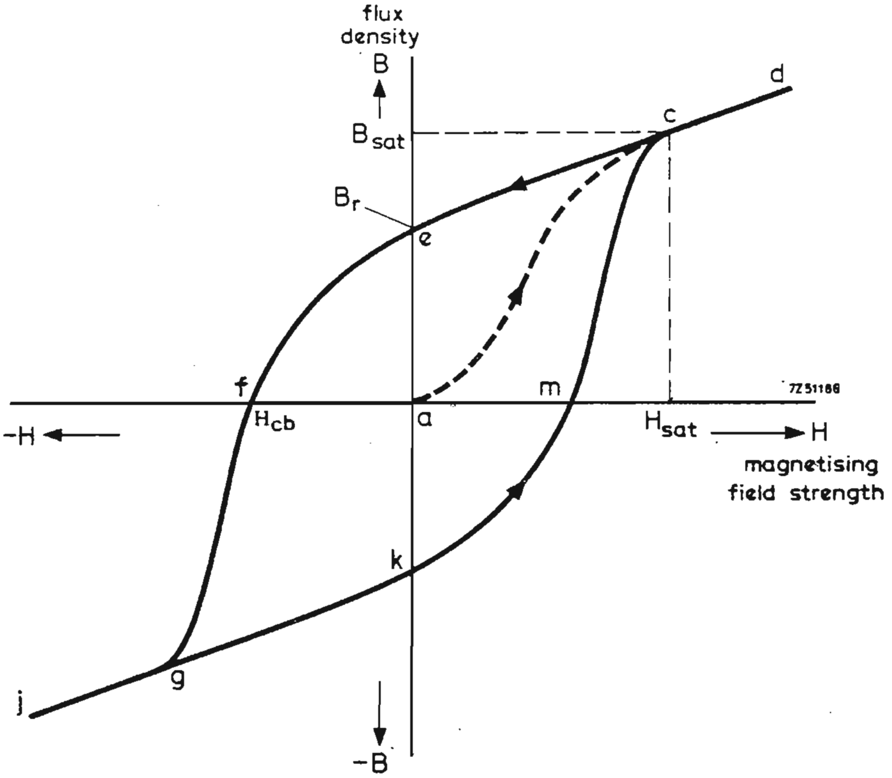


Fig.1. Hysteresis loop, variation of flux density with applied magnetising field strength.

If the material is assumed to be completely unmagnetised before the magnetising field is applied, then the state of the material can be represented by the point a on the graph of Fig.1, which shows the variation of flux density B in the material with magnetising field strength H applied to the material. If H is increased steadily from zero, the corresponding values of B will increase in accordance with the "virgin magnetising curve" ac. If H is increased further, B will increase linearly, the slope of the straight line being constant. Point c corresponds to the magnetic saturation of the material. The material no longer contributes to the increase in flux density, the further increase in B being attributable entirely to the relationship between the magnetising field strength and the flux density of the free space coincident with the magnetic material ($\frac{dB}{dH} = \mu_0$). The point c is defined as the point of magnetic saturation.

Saturation field strength H_{sat}

This is the minimum field strength that has to be expended to reach the region of magnetic saturation. Here we have

$\frac{dB}{dH} = \mu_0$, provided $H \geqq H_{sat}$.

μ_0 = 1 gauss/oersted or $4\pi.10^{-7}$ Vs/Am.

Saturation induction B_{sat}

This is the value of the induction corresponding to H_{sat}.

If after saturation has been reached, H is steadily reduced, the value of B corresponds to the curve ce. When H is zero, flux density corresponding to ae resides in the material. This residual flux density is termed the remanence B_r of the material.

Remanence B_r

This is the induction of a magnet remaining in a closed magnetic circuit if after attaining of the saturation state the field strength returns to zero (point of intersection of the hysteresis loop with the B-axis).
The units for the induction are Vs/cm^2 or gauss.
1 gauss = 10^{-8} Vs/cm^2
= 10^{-4} Vs/m^2

When the magnetising field is reversed and is increased steadily in the opposite direction, the flux density decreases along the "demagnetisation curve" ef. At f, the flux density is zero, and the corresponding field strength is defined as the coercive force H_{cb} of the material.

Demagnetisation curve

The operating range of permanent magnets lies in the second quadrant of the hysteresis loop. This part is the demagnetisation curve.

Coercive force (coercivity) H_{cb}

This is the magnetic field strength at which the induction of a magnet previously magnetised up to saturation becomes zero (point of intersection of the demagnetisation curve with the H-axis).
The units for the field strength are A/m, A/cm or oersted.

1 oersted = 0.796 A/cm = 79.6 A/m
1 A/cm = 1.26 oersted

Permanent magnets have a high coercive force, i.e. broad hysteresis loops, while magnetically soft materials have a small coercive force. The difference may be greater than three powers of ten.

As the magnetising field strength is increased beyond H_{cb}, the flux density increases in the opposite direction along the curve fg. The point g is reached which corresponds to magnetic saturation in the opposite sense to that occurring at c.

Any further increase in the magnetising field gives rise to increases in B corresponding to the straight line gj. This again represents the linear relationship between the flux density in the free space coincident with the material and the magnetising field strength.

If after saturation in the negative direction is reached, the magnetising field is reduced to zero, the flux density follows the curve gk. If the magnetising force is again reversed, the flux density follows the curve kmc, so that the loop cefgkmc is completed.

The area of the hysteresis loop indicates the energy expended in completing the magnetisation cycle. The slope of the hysteresis loop at any point is defined as the differential permeability of the material at that point.

The initial slope of the virgin magnetisation curve gives the initial permeability of the material. The slope of curve when saturation is reached is the permeability of the vacuum in the magnetic material.

Differential permeability

(Absolute) differential permeability	μ'_d	$= \frac{dB}{dH}$ at points lying on the hysteresis loop (in Vs/Am or Gs/Oe)
(Relative) differential permeability	μ_d	$= \frac{1}{\mu_0} \frac{dB}{dH}$ at points lying on the hysteresis loop (dimensionless)
Initial permeability	$\mu_{d\,o}$	$= \mu_d$ at origin of virgin magnetisation curve
(Absolute) permeability of vacuum, magnetic constant	μ_0	$= 4\pi \cdot 10^{-7}$ Vs/Am $= 1$ Gs/Oe

INTRINSIC HYSTERESIS LOOP

The flux density plotted in Fig.1 is the algebraic sum of the intrinsic flux density B_i of the material and the flux density B_0 of the space that the material occupies.

$$B = B_i + B_0 = B_i + \mu_0 H$$

B_i is also called magnetic polarisation.
If B_i is plotted against H, the effect of B_0 is excluded, and the resultant loop is shown in Fig.2 together with the B-H loop.

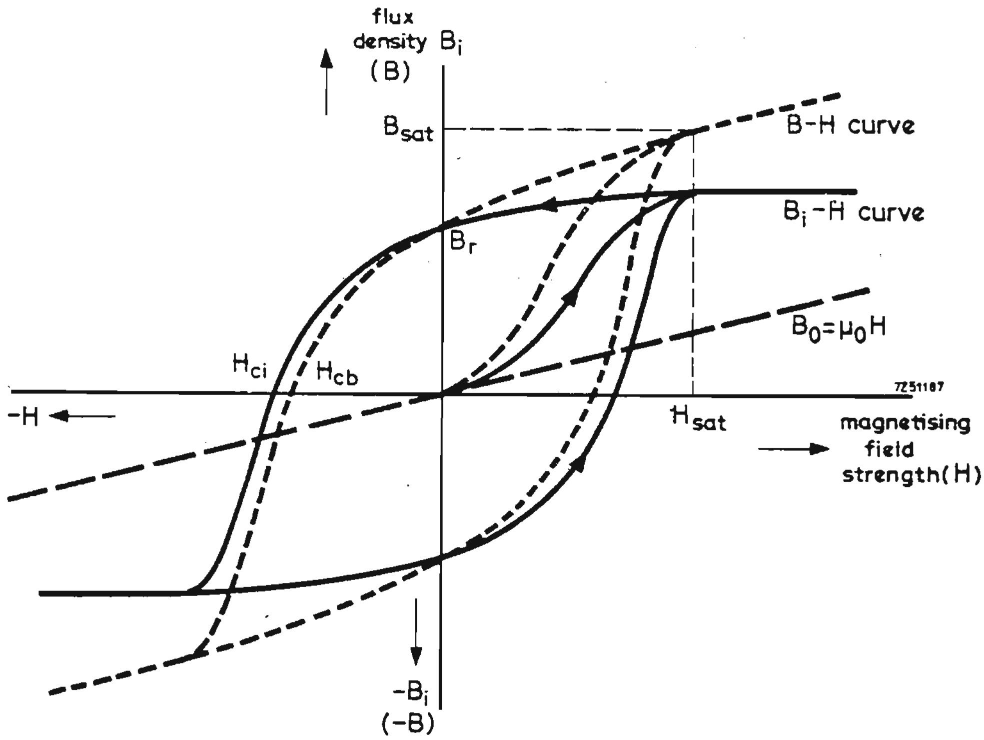


Fig.2. Comparison of variations of flux density and intrinsic flux density with applied magnetising field strength.

At saturation, the intrinsic hysteresis curve is horizontal. For zero applied field, the intrinsic flux density equals the flux density, and equals the remanence of the material. The magnetising field required to remove the intrinsic flux density is shown by the intersection of the curve and the horizontal axis. This field strength - the intrinsic coercive force H_{ci} - is greater than the coercive force H_{cb}. The difference between H_{cb} and H_{ci}, however, depends on the shape of loop: if the loop cuts the horizontal axis at a small angle, the difference will be significant; if the loop cuts at an angle approaching 90^o, it will be negligible.

Intrinsic coercive force H_{ci}

This is the magnetic field strength at which the intrinsic flux density (magnetic polarisation) of a magnet previously magnetised up to saturation becomes zero (point of intersection of the intrinsic demagnetisation curve with the H-axis).

DEMAGNETISATION CURVE

Complete hysteresis loops are important when considering soft magnetic materials, but with hard or permanent magnetic materials, it is the second (or fourth) quadrant that is of importance to the designer. The second quadrant shows the response of the magnetised material to demagnetising forces, and is therefore called the demagnetisation curve.

A typical normal demagnetisation curve for permanent magnetic materials is shown in Fig.3. Also shown in Fig.3 is a curve indicating the variation of the product BH with B. The product BH indicates the energy available in the material for a given value of B. It can be seen that a maximum value of BH-product exists, and this is designated $(BH)_{max}$. This maximum corresponds to a flux density of B_d and demagnetising field strength H_d and these, in general, represent the ideal operating point for the most efficient use of the material under static conditions.

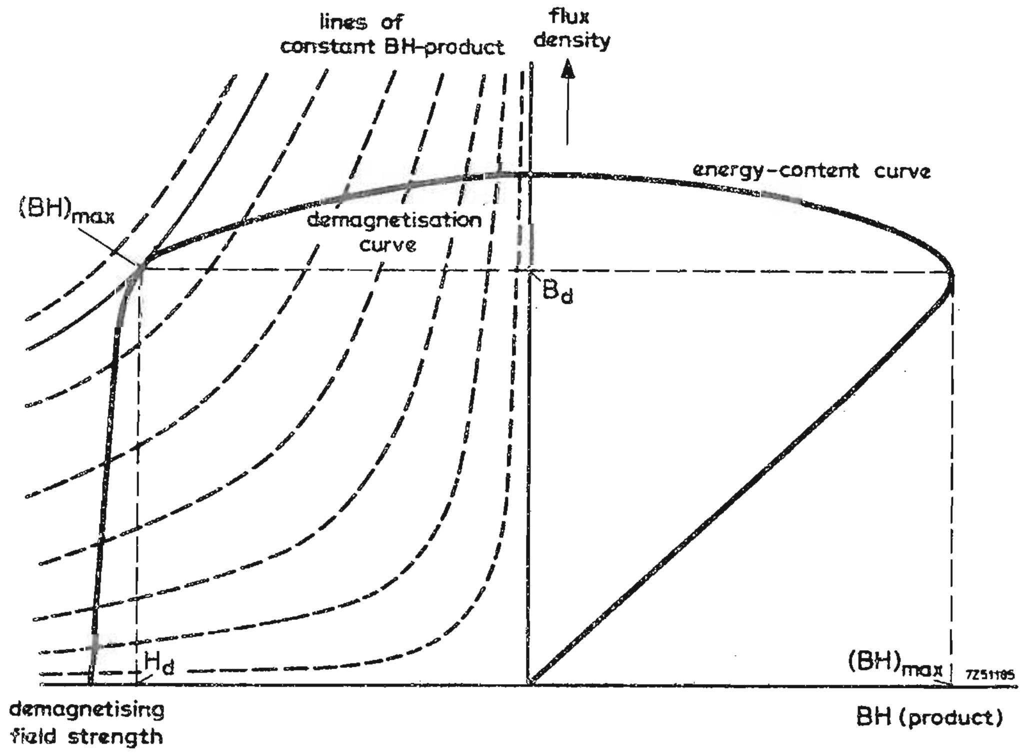


Fig.3. Demagnetisation curve with contours of constant BH-product, and energy-product curve.

Maximum energy product $(BH)_{max}$.

This is the maximum product of the flux density and field strength of a permanent magnet attained on the demagnetisation curve. The maximum energy in the field external to the magnetic material, per unit volume of the permanent magnet, is:

$$\frac{(BH)_{max}}{2}$$

The units of $(BH)_{max}$ are mWs/cm^3 or gauss-oersted

$1\ mWs/cm^3 = 1.26 \times 10^5$ gauss-oersted

1 gauss-oersted $= 8 \times 10^{-6}\ mWs/cm^3$

The values of B and H at $(BH)_{max}$ are designated B_d and H_d.

Energy content can also be represented by contour lines of constant BH-product superimposed on the demagnetisation curves. The maximum energy product of a material occurs at the point on the demagnetisation curve where a contour line would just touch it.

RECOIL LINE

The demagnetisation curve of a permanent magnetic material is a smooth curve indicating the decrease in flux density with a steadily increasing demagnetising field. If a constant demagnetising field is applied to the magnetic material, the corresponding value of flux density can be obtained from the curve. However, under practical conditions, the demagnetising field will probably not be constant. Small variations can be caused by small local magnetic fields, and large variations can occur in motors and generators (which are subject to varying armature reaction and can even have their armatures removed completely). It is therefore necessary to study the effects of such variations in the demagnetising field.

If a demagnetising field of strength H_1 is applied to magnetic material which has been saturated, the flux density will fall from its remanence value B_r to some value B_1 which corresponds to the point A_1 on the demagnetisation curve of Fig.4.

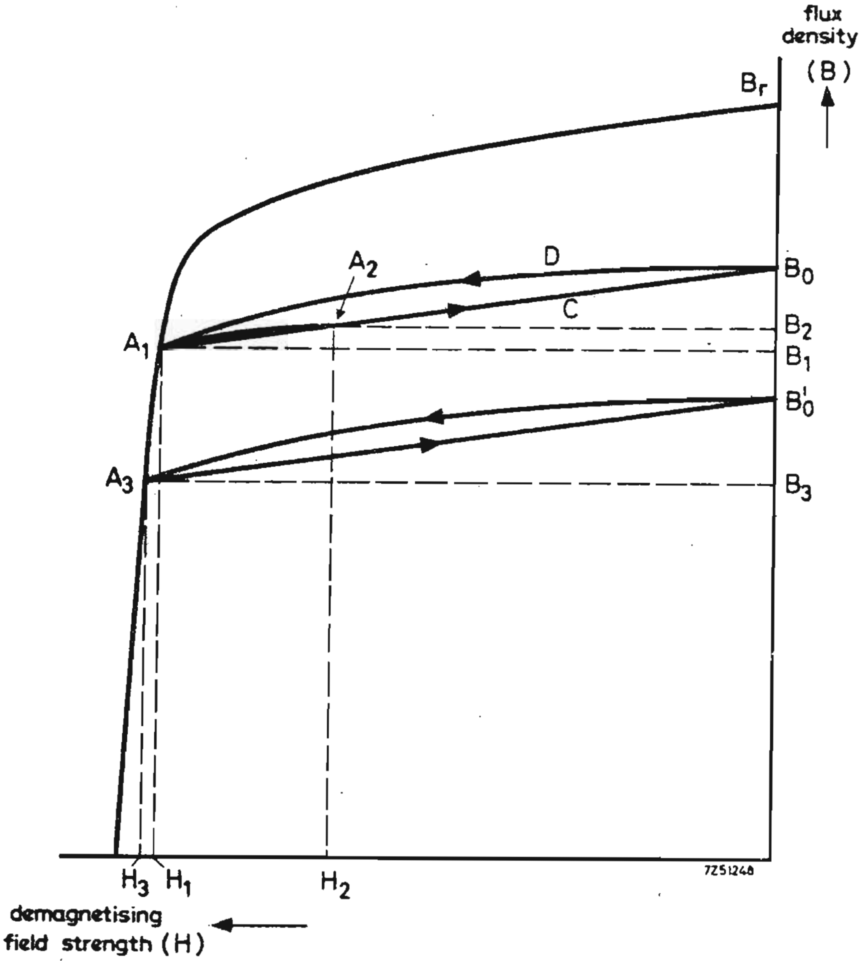


Fig.4. Recoil lines.

If H is reduced to zero, the flux density does not follow the demagnetisation curve back to the starting point, but follows a path A_1CB_0 which leaves the demagnetisation curve abruptly. If H_1 is now restored, the flux density follows the path B_0DA_1 which ends in A_1, but which deviates from the path A_1CB_0.

The loop $A_1CB_0DA_1$ so formed constitutes a minor hysteresis loop of the material. If the demagnetising field strength H_1 is only reduced to some value H_2 instead of being removed completely, and is then restored, another minor hysteresis loop is formed ($A_1A_2A_1$). For permanent magnetic materials, these minor hysteresis loops are very slender, and can be considered to form the straight line joining A_1 and B_0. This line is called a recoil line. The slope of the recoil line is the recoil permeability. It can be shown that the slope of a recoil line is approximately equal to the slope of the demagnetisation curve at its intersection with the vertical axis.

Recoil line

Actually a very narrow hysteresis loop which touches the demagnetisation curve, if at all; it is traversed during a limited variation of the demagnetising field strength in a permanent magnet.

Recoil permeability or reversible permeability μ_{rec} or μ_{rev}

The relative permeability corresponding to the slope of the recoil line.

$$\mu_{rec} = \frac{1}{\mu_0} \frac{\Delta B}{\Delta H_{rec}}$$

If the demagnetising field strength H_1 is increased to some value H_3, the operating point will move along the demagnetisation curve to the point A_3 corresponding to a flux density of B_3. Reduction of the demagnetising field strength to H_1 does not restore the working point to A_1, but moves it along another recoil line $A_3B'_0$, parallel to A_1B_0. Any reduction in H_3 will only cause the working point to move along the recoil line: the point A_1 can only be regained by resaturating the material and then applying the demagnetising field strength H_1.

The effects of increases in the demagnetising field when the operating conditions of the material correspond to a point on the demagnetisation curve are thus irreversible (except by the expedient of resaturation), so in designs where a high degree of magnetic stability is required it is usual to operate on a recoil line. A demagnetising field greater than that likely to be encountered in normal use is applied, and this is then reduced to the normal working value (stabilisation). Fluctuations in the demagnetising field will then only cause fluctuations of the working point along a recoil line.

TEMPERATURE COEFFICIENT

To characterise the behaviour of the material of a permanent magnet with changes in temperature the temperature coefficient of the remanence or of the coercive force is indicated in percent per degree

$$TC\ B_r = \frac{1}{B_r} \frac{dB_r}{dT} \times 100\ \%/\text{deg C}$$

$$TC\ H_{cb} = \frac{1}{H_{cb}} \frac{dH_{cb}}{dT} \times 100\ \%/\text{deg C}$$

CURIE TEMPERATURE AND TRANSITION TEMPERATURE

At the Curie temperature the material becomes practically non-magnetic, and the magnetism can only be restored by renewed magnetisation below this temperature. At the transition temperature the crystal structure is changed (e.g. formation of mixed crystals); this also leads to irreversible changes of the magnetisation, but these cannot be nullified by renewed magnetisation. The limit for the practical application of permanent magnet materials is in specific cases set by whichever of these temperatures is the lower.

MAGNETIC CIRCUIT DESIGN

Dimensions of magnet

The principal object of magnet circuit design is to provide efficiently a specified magnetic field in a given load (or air gap). The design of the circuit is governed by the required field strength, the dimensions of the air gap, the flux leakage from the surfaces of the magnet and the reluctance of the assembly.

In the simple circuit of Fig.5, A_g and L_g are the area (assumed equal to that of the pole pieces) and length of the air gap respectively, and A_m and L_m are the area and length of the magnet necessary to produce the required gap field strength H_g.

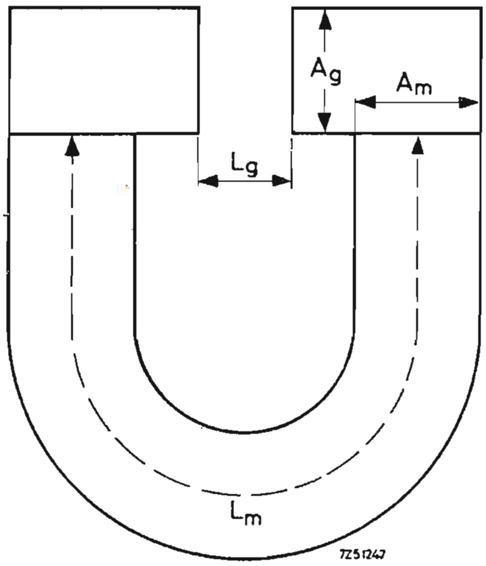


Fig.5. Simple magnetic circuit

If, initially, flux leakage is neglected, then all lines of flux in the magnet cross the air gap. Therefore the total flux in the gap equals the total flux in the magnet. By definition, total flux equals the product of flux density and area. Thus:

$$B_m A_m = B_g A_g,$$

where B_g and B_m are the flux densities in the gap and magnet respectively. Since for an air gap, $B_g = \mu_0 H_g$, this equation can be written:

$$B_m A_m = \mu_0 H_g A_g. \qquad (1)$$

NOTE: When B is expressed in gausses and H in oersteds, then $\mu_0 = 1$ gauss/oersted; when B is expressed in Vs/m^2 and H in A/m, the $\mu_0 = 4\pi.10^{-7}$ Vs/Am.

Magnetic flux is produced by magnetomotive force, and the ratio between m.m.f. and flux is termed the reluctance of the magnetic circuit. (This relationship is the magnetic analogy of Ohm's Law, flux, m.m.f., and reluctance corresponding to current, voltage, and resistance respectively.) In the cgs system the m.m.f.

between two points is the work done in moving unit magnetic pole between two points. It is thus the product of the force exerted on unit pole (that is, the field strength) and the distance through which the pole moves. In Fig.5 the m.m.f. across the air gap is thus the product of the field strength H_g in the gap and the length L_g of the gap. The m.m.f. across the magnet is similarly the product of the field strength H_m in the magnet and the length L_m of the magnet. If there is no leakage from the surfaces of the magnet these values of m.m.f. are equal. Therefore:

$$H_m L_m = H_g L_g. \qquad (2)$$

Equations (1) and (2) give the formulas for the design of magnetic circuits, assuming no flux losses. In practice, a loss or leakage factor must be introduced into each equation. The practical design equations thus become:

$$B_m A_m = p\mu_0 H_g A_g \qquad (3)$$

and

$$H_m L_m = q H_g L_g \qquad (4)$$

where p and q represent the loss or leakage factors.

Leakage factor

The total flux in a magnetic circuit is made up of the useful flux and the leakage flux. A certain amount of leakage can never be avoided completely, and it becomes appreciable particularly in a magnetic circuit with small magnetic conductance of the air gap. In the calculation of a magnet the leakage is taken into account by the leakage factor

$$p = \frac{\text{total flux required}}{\text{useful flux in air gap}}$$

The leakage factor p in the equation (3) varies widely from one application to another. It will be a minimum when the magnet is as close to the working gap as possible. The precise calculation of p is extremely difficult, and an acceptable estimate must be based on experience. As a guide, some typical leakage factors are given in the following table.

Application	approximate leakage factor
Loudspeaker with "Ticonal" centrepole magnet 19 mm (3/4 in) speech coil up to 6.5 kGs	2
Loudspeaker with "Ticonal" centrepole magnet 25 mm (1 in) speech coil up to 8 kGs	2
Loudspeaker with ferroxdure ring magnet 36 mm ($1\frac{1}{2}$ in) speech coil up to 15 kGs	2

Application	approximate leakage factor
Loudspeaker with ferroxdure ring magnet 61 mm ($2\frac{1}{2}$ in) speech coil up to 14.5 kGs	2
Loudspeaker with "Ticonal" ring magnet 25 mm (1 in) speech coil up to 12 kGs	3
Loudspeaker with "Ticonal" ring magnet 25 mm (1 in) speech coil up to 16 kGs	6
Loudspeaker with "Ticonal" ring magnet 36 mm ($1\frac{1}{2}$ in) speech coil up to 16 kGs	5
Moving coil meter using "Ticonal" rectangular magnets	3
Moving coil meter using "Ticonal" semicircular magnets	2
Moving coil meter using "Ticonal" internal core magnet	1.5
Motors using ferroxdure segments	1.1
Motors and generators, "Ticonal" two-pole type	2
Motors and generators, "Ticonal" four-pole type	4

The loss factor q in equation (4) is attributable to unwanted reluctances in series with the useful air gap. Compensation for these can generally be effected by assuming a value of q of about 1.1 (thus increasing the required length of magnet by 10 %).

Equations (3) and (4) can be rewritten as:

$$A_m = \frac{p\mu_0 H_g}{B_m} \cdot A_g, \qquad (5)$$

and

$$L_m = \frac{q H_g}{H_m} \cdot Lg. \qquad (6)$$

The product of equations (5) and (6) gives:

$$V_m = \frac{pq\mu_0 H_g^2 V_g}{B_m H_m}, \qquad (7)$$

where V_m and V_g are the volumes of the magnet and gap respectively.

For a given magnetic material, and therefore a given demagnetisation curve, an infinite number of combinations of length and area of magnet can be chosen for a given volume by varying the point B_mH_m on the demagnetisation curve. However, the minimum volume of material will be given when the product B_mH_m is a maximum. Thus the most efficient use of the material is obtained by operating at the design points B_d and H_d, corresponding to maximum BH-product, $(BH)_{max}$.

Thus for greatest efficiency, the design equations become;

$$A_m = \frac{p\mu_0 H_g}{B_d} \cdot A_g, \tag{8}$$

and

$$L_m = \frac{q H_g}{H_d} \cdot L_g, \tag{9}$$

Equations (3) and (4) can be combined to give:

$$B_m = \left\{ \frac{p}{q} \cdot \frac{A_g}{A_m} \cdot \frac{L_m}{L_g} \right\} \cdot \mu_0 H_m, \tag{10}$$

which can be represented as the straight line OP_1 (load line), superimposed on the demagnetisation curve in Fig.6, having a slope

$$\text{cotg}\ \alpha = \frac{B_m}{H_m} = pA_g L_m \mu_0 / q A_m L_g. \tag{11}$$

The intersection of the load line and the demagnetisation curve, P_1, is the working point which, if the design is for maximum efficiency, will be the point having the coordinates B_m, H_m = B_d, H_d.
However, operation on the demagnetisation curve does not give maximum stability: for highly stable operation the working point should lie on a recoil line.

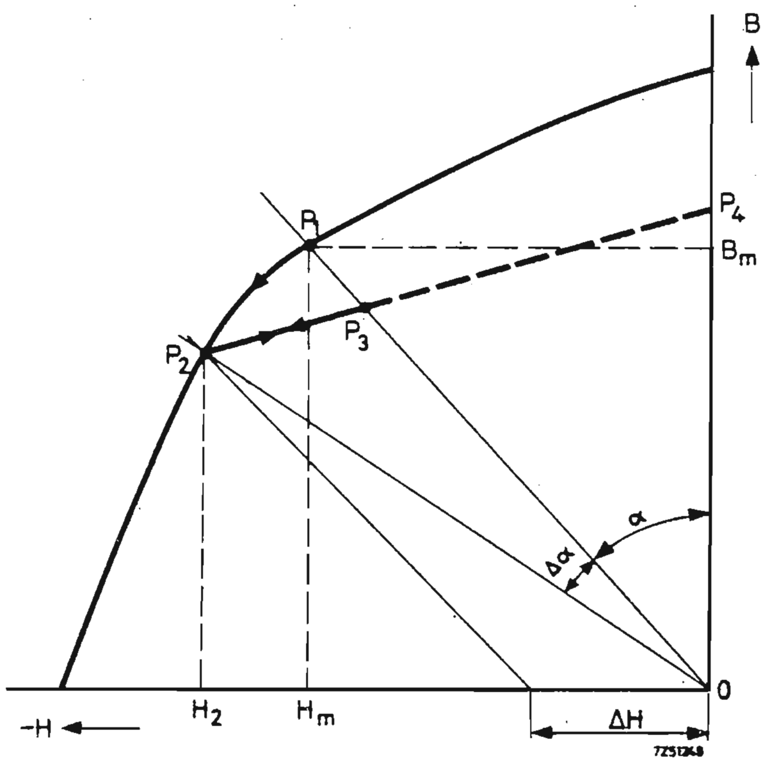


Fig.6. Demagnetisation curve with load line and recoil line.

VARIABLE WORKING POINT AND STABILISATION

If the dimensions of a magnet and its air gap are given, the working point on the demagnetisation curve is fixed. However changes in the dimensions of the air gap bring about changes in the slope of the load line (see equation 11), but the occurrence of an additional magnetic field (ΔH in Fig.6) causes the load line to be shifted to a parallel position, so that the working point moves, for example, to P_2 on the demagnetisation curve. If the change is reversed again, the working point returns along the recoil line; the new working point then lies at P_3, the point of intersection of this line with the old load line. (The slope of the recoil line equals $\mu_0 . \mu_{rec}$.)
For adequate stabilisation, a stabilising demagnetising force should be applied to the magnet greater than the maximum demagnetising influences likely to be encountered during normal operation.

Note: As long as the change from P_1 to P_2 takes place along the straight part of the demagnetisation curve, the working point P_3 will not differ appreciably from P_1.
It is therefore sometimes worth while to let the load line not pass through the point of $(BH)_{max}$ but to choose a smaller angle α, in order to remain always within the straight-line region of the curve. Especially with permanent magnets which will be magnetised outside their system or which may be taken out of their system it is then necessary to investigate whether, after assembly, the new working point will still lie on the straight part of the demagnetisation curve.

Changes in the induction will also take place on account of temperature changes below the Curie or transition temperatures, and are determined by the temperature coefficient. Such a change of the induction with temperature is only reversible within a certain temperature region. The irreversible changes may become particularly great if the working point on account of the temperature changes moves down beyond the knee of the demagnetisation curve. For this reason it is often advisable to arrange for the working point, by means of appropriate dimensioning of the system, to lie sufficiently far above the knee.

SYMBOLS

A_g = cross sectional area of the air gap perpendicular to the lines of flux

A_m = cross sectional area of permanent magnet perpendicular to direction of magnetisation

B = (magnetic) flux density/(magnetic) induction/normal induction

B_d = flux density at the point $(BH)_{max}$ on the demagnetisation curve

B_g = flux density (induction) in the air gap

$(BH)_{max}$ = maximum energy product/peak energy product

B_i = intrinsic flux density, intrinsic induction

B_m = flux density (induction) in the magnet

B_r = residual flux density, residual induction, remanence

B_{sat}, B_s = saturation flux density/saturation induction

F_m = magnetomotive force/magnetic potential difference

H = magnetising force/magnetising field strength/magnetic intensity

H_{cb} = coercive force/coercivity

H_{ci} = intrinsic coercive force/intrinsic coercivity

H_d = demagnetising force at $(BH)_{max}$ on the demagnetisation curve

H_g = magnetising force (field strength) in the air gap

H_m = demagnetising force (field strength) in the magnet

H_{sat}, H_s = magnetising force required for saturation/saturation field strength

L_g = length of the air gap parallel to the lines of flux

L_m = effective magnetic length of magnet

N = total number of turns

P = permeance

P_c = core loss

P_e = eddy current loss

P_h = hysteresis loss

R_m	=	reluctance
μ	=	permeability/normal permeability
μ_d	=	differential permeability
μ_{d_o}	=	initial permeability
μ_{rec}, μ_{rev}	=	recoil permeability/reversible permeability
μ_Δ	=	incremental permeability
ϕ	=	magnetic flux/total flux

APPLICATIONS OF PERMANENT MAGNETS

CLASSIFICATION ACCORDING TO MAGNETIC FUNCTION

As a rule, permanent magnets function as energy transducers which transfer energy from one kind into another, without permanently losing energy of their own. In keeping with this, permanent magnets may be classified as follows.

Magnets for the transfer of

- electrical energy into mechanical
  such as in motors, meters, loudspeakers, beam deflectors, mass spectrometers;
- mechanical energy into electrical
  such as in generators, alternators, cycle dynamos, microphones, phonographic pick-ups, electric stringed instruments, magnetic detectors;
- mechanical energy into other mechanical energy
  such as for attraction and repulsion, holding and lifting (e.g. in industrial and household appliances, separators, chucks, thermostats, toys, etc.);
- mechanical energy into heat
  such as in hysteresis-torque and eddy-current instruments, e.g. speedometers, brakes of watt-hour meters, balances, etc.
- A fifth group of magnets accomplish special effects such as the Hall effect, magnetic resistance and nuclear magnetic resonance.

EXAMPLES OF INDUSTRIAL USE

There is practically no industrial sector in which some means equipped with permanent magnets is not used. A few examples:

The ceramics industry	- separators.
Shipbuilding	- welding terminals.
Navigation	- attachment of rust-preventing anodes.
Typography	- magnetic cylinders for iron/rubber blocks.
Mining	- separators; non-skid cable wheels.
Rolling mills	- conveyors; plate lifters.
Office machines	- paper guides and holders.
Cattle raising	- garbage separation.
Foods and allied products	- separators.
Oil trade	- filling machines.
Machining	- chucks.
Miscellaneous	- clocks and watches.

ENUMERATION OF APPLICATIONS

Electrotechnical

Measurement and control

Galvanometers
Ammeters
Voltmeters
Fluxmeters
Photometers
Tachometers
Speedometers
Kilowatt-hour meters
Recording instruments
Vibrographs
Oscillographs
Cardiographs
Seismographs
Pressure gauges

Switchgear

Spark extinguishers

Motors and generators

Alternators
Magnets for IC engines
Cycle dynamos
Hand dynamos
Hysteresis motors
Synchronous motors
Clock motors
D.C. shunt motors
Screenwiper motors
Fan motors
Toy motors
Aeronautic motors and generators
Gyroscopes
Electrodynamic tachometers
Pulse generators

Electro-acoustics and communications

Tone generators
Telephones
Hearing aids
Cutting heads
Pick ups
Stringed instruments
Tape recorders
Dictaphones
Magnetrons
UHF directional isolators

Radio and TV

Loudspeakers
Transformers
Vibratory convertors
Picture tubes
Focusing units

Applied physics

Scientific

Magnetostrictive devices
Resonance measurements
Resistance modification

Industrial

Compass compensation
Material selection
Hardness testing
Film-thickness measurement
Crack detection
Polarity indicators
Water softening

General

Compasses
Coin check in vending machines
Replacement of springs
Magnetizing yokes

Mechanical

Measurement and control

Flow meters
Level indicators
Maximum thermometers
Thermocouples
Eddy-current brakes
Valves

Consumer goods

Visual demonstration
Calendars
Card-index systems
Guides of many kinds
Lamp holders
Inspection lamps

Switchgear and connectors

Switches
Microscopy
Buttons
Couplings
Pumps
Calorimeters
Mixers
Drives through a wall
Frictionless drives
Centrifugal couplings
Polarized contacts

Industrial

Holding devices
Plate lifters
Conveyors
Drain plugs
Filters
Separators
Floor cleaners
Indicating boards
Frictional brakes
Hammers
Screwdrivers
Refrigerators

Miscellaneous

Accessories

Cigarette holders
Name plates
Parking plates
Soap holders
Tin openers

Medical

Extraction of steel splinters
Blood testing
Prothesis

Toys

Toys of all kinds
Draughtsmen
Chessmen

Sundries

Magnetic drags
Veterinary uses (cow's stomach)