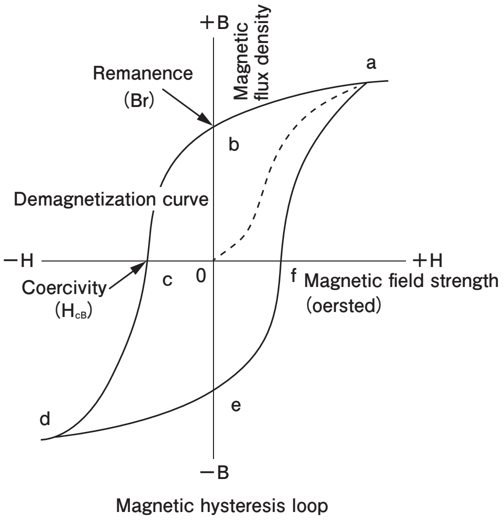
Basic Properties of Magnets

In order to achieve an optimal design according to the use, we will provide a guide on the basic properties of the magnets required and the fundamental equations for designing the magnetic circuit for your consideration. Please make use of them as reference material for a more efficient design.

1. Magnetic Hysteresis Loop (BH Curve)

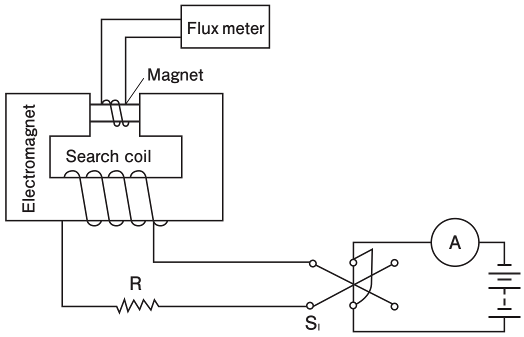
As shown in Figure 2, the magnetic flux density in the magnet increases as the current in the coil increases gradually to magnetize the magnet until it finally reaches saturation at a certain point. (Point a in the figure)



〈Figure 1〉

Subsequently, when the strength of the magnetic field is reduced by lowering the current from this saturated state, the magnetic flux density decreases from point a to point b without returning to 0. The magnetic flux density remains at point b even if the strength of the magnetic field becomes 0. This value is known as the remanence Br.Next, if the direction of the current is reversed and the magnetic field is increased in the opposite direction, the magnetic flux density decreases gradually from point b until it finally reaches 0 at point c. The strength of the magnetic field at this point is known as the coercivity or coercive force H_{cB}.

If this reverse magnetic field is increased further, the magnet will be magnetized in the opposite direction until it reaches saturation at point d. In this way, by gradually changing the magnetic field, the magnetic flux density of the magnet changes according to a fixed cycle from a to b to c to d to e to f. This cycle is known as the magnetic hysteresis loop or BH curve.

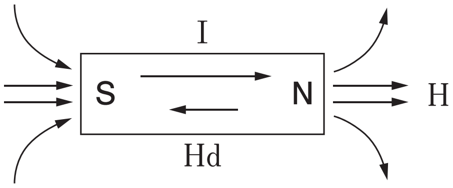


〈Figure 2〉

2. Impact of Demagnetization Field (Self-demagnetization Effect)

As shown in Figure 3, although the magnetic field generated on the surface of a magnetized magnet faces the S pole from the N pole, a magnetic field Hd acts in the opposite direction to the magnetization direction I inside the magnet. This internal magnetic field is known as a demagnetization field and since it acts in a direction to demagnetize the magnet, it is always represented in the second quadrant of the magnetic hysteresis loop in Figure 1 when a magnet is used. The curve in this section is known as the demagnetization curve.

This demagnetization field varies according to the proportions of the magnet, becoming smaller the longer and narrower the magnet is in the magnetization direction. In practice, the impact of this demagnetization field is often represented by the slope Bd/Hd, which is the ratio of the demagnetization field to the magnetic flux density. This ratio is known as the permeance coefficient P=Bd/Hd. The straight line traced by the permeance coefficient is known as the operating line and the intersection point of this line with the demagnetization curve is known as the operating point.

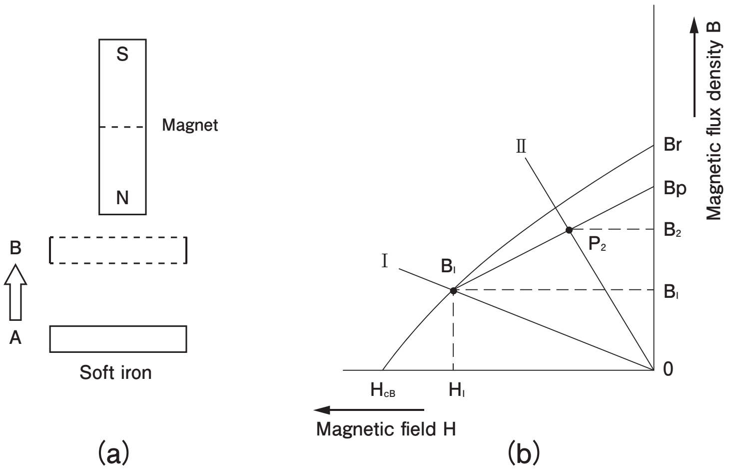


〈Figure 3〉

The product of Hd and Bd corresponding to the operating point is known as the magnetic energy and this value is the highest at a certain operating point. The value at this point is known as the maximum energy product BHmax and this BHmax serves as an important material property value of a magnet.

3. External Impact

The operating point of a magnet will move and the magnetic force will change when a magnetic field is applied from the outside or when a piece of soft iron is brought near the magnetized magnet.



(a) (b)

〈Figure 4〉

a.When a piece of soft iron is brought near a magnet

As shown in Figure 4 (a), the magnetic force of a rod magnet changes when a piece of soft iron is brought near the magnet. This is because the soft iron magnetized by the magnet creates a magnetic field on the outside which acts in a direction to strengthen the magnetic force of the magnet. When analyzing this action with the demagnetization curve, the permeance coefficient of the magnet changes depending on the position of the soft iron. Assuming that the permeance coefficient at Position A is I, the permeance coefficient at Position B will become larger and change to II due to a reduction in the length of the vacant space. At this point, the operating point will follow a separate path from the demagnetization curve starting from point P_1 to reach point P_2as shown in Figure 4 (b).This path P_1-Bp can be approximated by a straight line known as a recoil line. The gradient of this straight line $\mu r=(Bp-B_1)/H_1$ is known as the recoil magnetic permeability. μr is a material constant and this gradient is roughly the slope of the tangent to the demagnetization curve at the point Br. In a ferrite magnet, μr usually shows a value of between 1.05 and 1.2.

When the operating point moves from point P_1 to P_2 the magnetic flux density increases from B_1 to B_2. Care is required in measuring and evaluating magnetic forces as the magnetic force changes when a piece of soft iron is located near the magnet as shown here.

b.When a reverse magnetic field is applied on a magnet

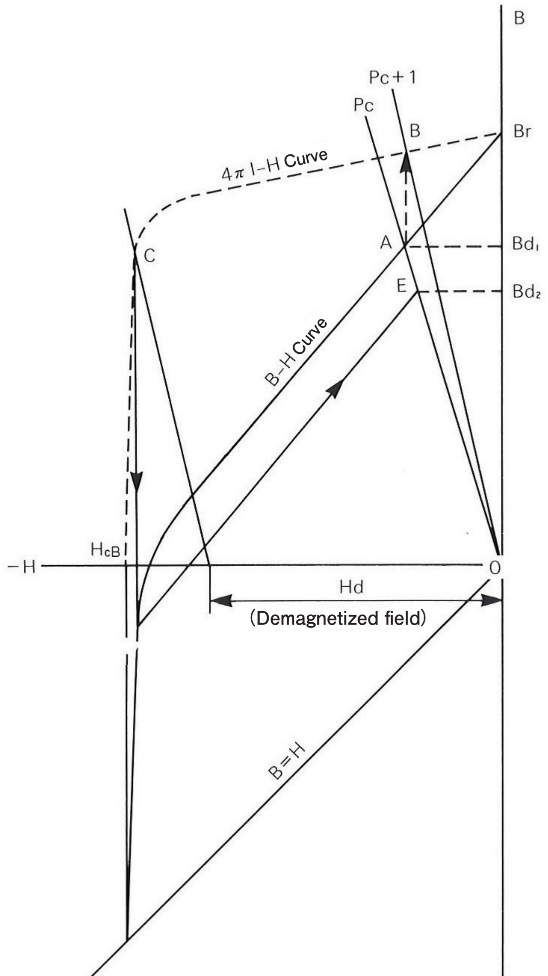
When an external magnetic field is applied in the opposite direction on a magnetized magnet, the magnetic flux density may change and the magnet may be demagnetized. This action can also be analyzed using the demagnetization curve. Although the BH curve expresses the change in the magnetic flux density when a magnetic field is applied on a magnet, the value of B at this point also includes the strength of the external magnetic field applied on the magnet in addition to the magnetic strength of the magnet itself.

$B=\mu 0H+I$ $\mu 0$:Magnetic permeability of a vacuum

In the Cgs unit system, the magnetic strength of a magnet is expressed as $4\pi I$ and $B=4\pi I+H$.

A curve that cancels out the impact of this external magnetic field in expressing the relationship between the magnetic strength of the magnet itself and the external magnetic field is known as the 4πI-H curve. Figure 5 shows the BH curve and 4πI-H curve. The coercive force H_{cB} on the BH curve is the strength of the magnetic field in which the magnetic flux density of the magnet apparently becomes 0, while the strength of the magnetic field in which the magnetization strength $4\pi I$ of the magnet itself becomes 0 is known as H_{cJ}. Therefore, after an external magnetic field with exactly the same magnitude as H_{cJ} is applied, upon removing the external magnetic field, the remanence of the magnet becomes zero completely. In this sense, H_{cJ} is said to be the true coercivity. When a demagnetization field acts on a magnet due to an external magnetization field, there is a need to analyze this with the 4πI-H curve rather than the BH curve depicted in the second quadrant.
In Figure 5, assuming the intersection point of the 4πI-H curve with the perpendicular that is raised from the operating point A with a permeance coefficient Pc is point B, then point B indicates the magnetization force when subjected to the impact of the self-demagnetization field alone without the influence of the external magnetic field. Considering the case of a demagnetization field Hd acting here, since the magnetization force when the demagnetizing field Hd is acting is expressed by the intersection point C between the 4πI-H curve and an operating line drawn parallel to the straight line OB, if you drop a perpendicular from this point C and take the intersection point of this line with the BH curve as point D, then point D represents the operating point when the demagnetization field Hd is acting on the magnet. If this demagnetization field Hd is removed, the operating point will move along the recoil line to the intersection point E with the permeance coefficient Pc. Therefore, ultimately the magnet is demagnetized irreversibly by the amount Bd_1-Bd_2 alone.

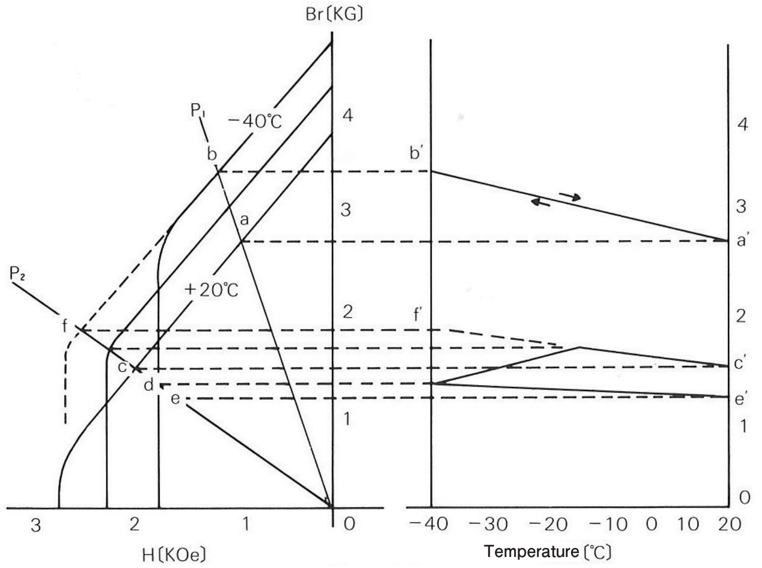
When using a magnet at a low temperature, this demagnetization ratio becomes even larger due to temperature changes of the BH curve. In this case, it is recommended that the magnet be designed with a permeance coefficient that is as high as possible while choosing a material with a high H_{cJ} at the same time.



〈Figure 5〉

4. Low Temperature Demagnetization of a Ferrite Magnet

If the permeance coefficient of an anisotropic ferrite magnet is not high, when it is cooled at a low temperature close to −40° C and then returned to normal temperature again, the magnet will exhibit a large demagnetization effect. Generally, the change in the magnetic force of a ferrite magnet due to a change in temperature is expressed by the respective temperature coefficients Br and Hc as shown in Table 2, with △Br/Br/° C≒−0.18 - −0.19%/° C and △H/H/° C≒+0.35 - 0.5%/° C. The operating point will move since the BH curve will fluctuate together with these rates of change. For a magnet with a permeance coefficient of P_1 as shown in Figure 6, the operating point at point a at a temperature of 20° C will move to point b at a temperature of −40° C. The gradient from point a' to point b' depends on the temperature coefficient of −0.18 - −0.19%/° C. The operating point returns to point a again if the temperature is returned to 20° C. However, for a magnet with a permeance coefficient of P_2, although the BR operating point at point c at a temperature of 20° C will move from point c to point f at a rate of −0.18 - −0.19%/° C as the temperature gets lower, Hc will be inverted midway and come to point d at a temperature of −40° C as it will decrease at a rate of +0.35 - +0.5%/° C. If the temperature is moved back to 20° C, this time Hc will come to point e from point d at the same rate again. Thereafter, at a temperature between −40° C and +20° C, it will move back and forth between points d and e.



〈Figure 6〉

Design of Magnetic Circuits

Fundamental Equations

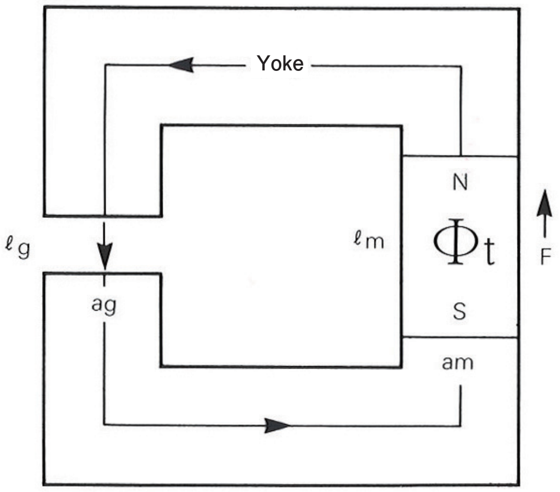
Circuit laws similar to those of electric circuits apply in magnetic circuits as well.
That is, a magnetic circuit can be replaced by an equivalent electric circuit for Ohm’ s Law to be applied. If the magnetomotive force of a magnet is F and the total magnetic flux is Φt, and assuming the magnetic resistance (reluctance) of the circuit is R, then the following equation is valid.

$$\Phi t=\frac{F}{R} \qquad (1)$$

Assuming the vacant length of the circuit as ℓg and the vacant cross-sectional area as ag, the magnetic resistance is then given by the following equation.

$$R=\frac{\ell g}{\mu ag} \qquad (2)$$

μ is the magnetic permeability of the magnetic path and is equivalent to the magnetic permeability μ0 of a vacuum in the case of air. (μ0=4π×10-7 [H/m])



〈Figure 7〉

Although the current in an electric circuit rarely leaks outside the circuit, as the difference in the magnetic permeability between the conductor yoke and insulated area in a magnetic circuit is not very large, leakage of the magnetic flux also becomes large in reality. The amount of the magnetic flux leakage is expressed by the leakage factor σ, which is the ratio of the total magnetic flux Φt generated in the magnetic circuit to the effective magnetic flux Φg of the vacant space.

$$\sigma=\frac{\Phi t}{\Phi g} \qquad (3)$$

In addition, the loss in the magnetic flux due to the joints in the magnetic circuit must also be taken into consideration. This is represented by the reluctance factor f. Since the leakage factor σ is equivalent to the increase in the vacant space area, and the reluctance factor f refers to the correction coefficient of the vacant space length, the corrected magnetic resistance becomes as follows.

$$Rc=\frac{\ell g}{\mu ag}\cdot\frac{f}{\sigma} \qquad (4)$$

The inverse of this magnetic resistance is known as permeance (P) and generally, this permeance is used in the calculations. Substituting this in Equation (1), P then becomes as follows.

$$\Phi t=PF \quad P=\frac{\mu ag}{\ell g}\cdot\frac{\sigma}{f} \qquad (5)$$

If you assume the cross-sectional area of the magnet as am, the length as ℓm, the demagnetized field in the magnet as Hd, the magnetic flux density as Bd, and the magnetic flux density in the magnet to be uniform, then F and Φt are expressed as follows.

$$F = \ell m \mathrm{Hd} \quad \Phi t = am \, \mathrm{Bd} \qquad (6)$$

Based on Equation (6), the permeance coefficient is determined by the following equation.

$$\mathrm{Pc} = \frac{\mathrm{Bd}}{\mathrm{Hd}} = \frac{\ell m}{am} \cdot \frac{\Phi t}{F} \qquad (7)$$

Substituting Equation (5) into this equation, the permeance coefficient becomes as follows.

$$\mathrm{Pc} = \mathrm{P} \frac{\ell m}{am} = \frac{\ell m}{am} \cdot \frac{\mu ag}{\ell g} \cdot \frac{\sigma}{f} \qquad (8)$$

Therefore, the external permeance as seen from the magnet can also be said to be the permeance coefficient of the magnet when converted to a per unit volume figure. The above equation shall serve as the basic equation for determining the permeance. Although the reluctance factor f is approximately 1.1 – 1.3 and no big error will result if a normal value of 1.2 is assumed, the leakage factor σ has to be determined based on calculation since it will fluctuate to a certain extent. Based on Equation (3), the leakage factor σ is determined as follows.

$$\sigma = \frac{\Phi t}{\Phi g} = \frac{\mathrm{Ft} \cdot \mathrm{Pt}}{\mathrm{Fg} \cdot \mathrm{Pg}} \qquad (9)$$

Since Ft/Fg is equivalent to the reluctance factor here, σ then becomes

$$\sigma = \mathrm{f} \frac{\mathrm{Pt}}{\mathrm{Pg}} \qquad (10)$$

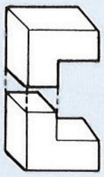
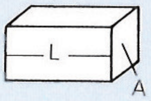
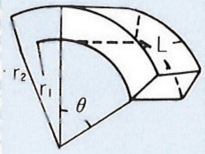
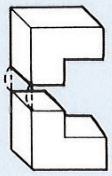
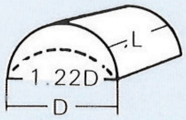
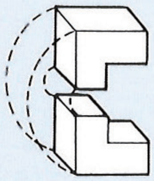
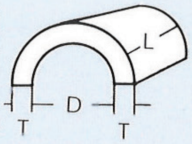
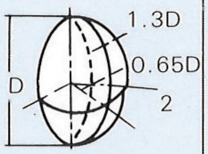
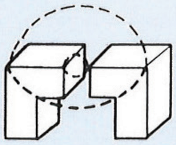
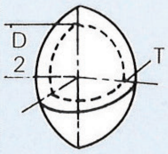
Since Pt is the sum of the vacant space permeance and the leakage permeance, it therefore becomes

$$\mathrm{Pt} = \mathrm{Pg} + \mathrm{P}_1 + \mathrm{P}_2 + \cdots\cdots + \mathrm{Pn} \qquad (11)$$

Although Pg can be computed easily as Pg=μag/ℓg, as the leakage permeance is quite complex, the respective terms are generally simplified and computed as shown in Figure 8. The respective permeance is determined in this manner to compute σ.

$$\sigma = \mathrm{f}\left(1 + \frac{\mathrm{P}_1 + \mathrm{P}_2 + \cdots + \mathrm{Pn}}{\mathrm{Pg}}\right) \quad (\mathrm{f} \fallingdotseq 1.2) \qquad (12)$$

Permeance of Various Types of Spaces

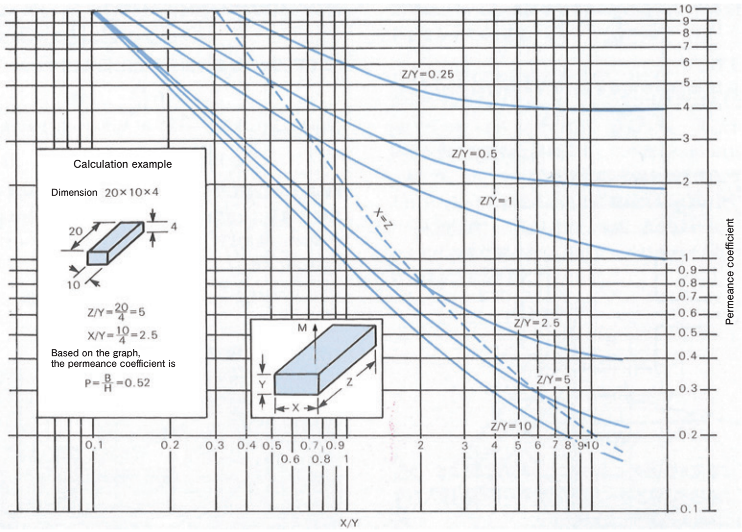
1	Permeance between two parallel and flat pole surfaces			$P=\mu\frac{A}{L}$
2	Permeance of a fan-shaped magnetic circuit			$P=\frac{\mu L}{\theta}\int_{r_1}^{r_2}\frac{dr}{r}$ $=\frac{2.3\mu L}{\theta}\log_{10}\frac{r_2}{r_1}$
3	Permeance between the two ends of the diameter of a semi-spherical tube			$P=0.264\mu L$
4	Permeance of a hollow, semi-spherical tube			$P=0.64\frac{\mu L}{(\frac{D}{T}+1)}$
5	Permeance between the two ends of the diameter of a quadrant sphere			$P=0.077\mu D$
6	Permeance of a quadrant spherical shell			$P=\frac{\mu T}{4}$

〈Figure 8〉

Permeance Coefficient in a Standalone Magnet

Generally, a magnet is used with an iron plate attached to the pole. It is also not rare for a magnet to be used on its own without a magnetic material attached. Refer to Figure 9 – Figure 11 when designing such a magnetic device.

Relationship between the proportion and the permeance coefficient of a square magnet



Calculation example

Dimension 20×10×4

$Z/Y=\frac{20}{4}=5$

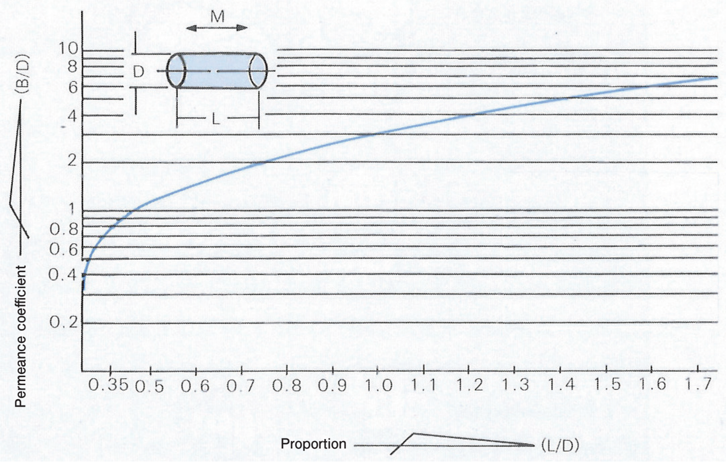
$X/Y=\frac{10}{4}=2.5$

Based on the graph, the permeance coefficient is

$P=\frac{B}{H}=0.52$

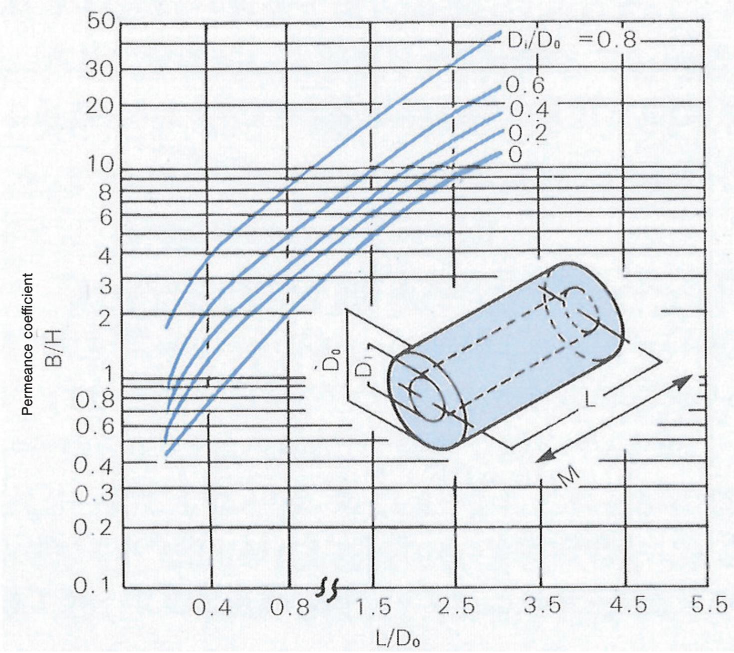
〈Figure 9〉

Relationship between the proportion (L/D) and the permeance coefficient of a cylindrical magnet



〈Figure 10〉

Permeance coefficient of a tubular magnet magnetized in the direction of the axis (B/H)



〈Figure 11〉

Precautions when Using Magnets

Safety Precautions

In using magnets, pay sufficient attention to the following precautions and use them safely. If the magnets are used incorrectly, the functions may be damaged, possibly leading to accidents. Before using these products, be sure to read the product catalog or technical materials such as the product manuals.

! Warning

1. Bringing magnets near a person fitted with an electronic medical device such as a pacemaker and other electronic medical devices is extremely dangerous. This may affect the normal operation of the medical device and put the life of the person at risk.
2. Make sure that magnets are not swallowed. Seek immediate medical attention if swallowed. Do not place magnets within the reach of children.

! Caution

●Adhere to the following precautions so that injuries and malfunctions do not occur.

1. Precautions Common to All Magnets

◎Precautions for Magnet Users

Design

⑴ Magnetic properties differ greatly depending on the magnetization direction in anisotropic magnets. Take note of the anisotropic direction in the design.

⑵ The magnetic property values in the catalog are not guaranteed. Depending on the dimensions, shapes, and environment when using the magnet, the magnetic property values in the catalog may not be attained. Check in advance using samples, etc.

⑶ Generally, the magnetization magnitude drops as a magnet is heated. If it drops, it will also vary greatly depending on the operating point. Refer to the temperature properties and make sure the temperature does not rise by too much during assembly or use. In addition, design the magnetic circuit so that demagnetization is minimized as much as possible.

⑷ If magnetization of the magnets is performed by the customer, apply a sufficient magnetic field according to the material and coercivity. If the strength of magnetic field is insufficient, the magnetic properties may not be derived as designed. Consult us regarding the magnitude of the magnetic field required for magnetization.

⑸ Depending on the type of magnets (material) and magnetic circuit, the magnets may be difficult to magnetize after insertion (assembly). Generally, the larger the coercivity, the harder it is for magnetization to be carried out after insertion.

⑹ Avoid using and storing magnets in the following environments. This may result in corrosion of the magnets and a deterioration in the strength and properties of the magnets.

1. Corrosive gas atmosphere（Cl, NH_3, SOx, NOx etc.）
2. Environment high in electrical conductivity (e.g. in water containing electrolytes)
3. Environment containing hydrogen
4. Acids, alkalis, organic solvents, etc.
5. In water or oil

⑺ When magnets are cut or divided by the customer, this may cause magnetization defects or deterioration in the magnetic properties. Consult us regarding your processing conditions. Breaking and chipping shall not be guaranteed during use and processing if processing is carried out by the customer.

⑻ The materials of most magnets are hard and brittle. When using magnets in applications subject to vibration such as in a vehicle, besides maintaining the strength by bonding the magnet to the yoke, pay attention to the design so that the magnet does not get detached even if it breaks.

⑼ When using adhesives between magnets and on joints with the yoke, pole piece, etc., study the type, quantity, conditions, strength of the adhesive carefully and check their reliability.

⑽ In high speed rotating bodies such as motors, the magnets may be damaged sometimes. During the design, adopt measures to prevent fragments from scattering even if the magnets are damaged.

⑾ When performing processes such as press fitting and shrink fitting, the properties of the magnet may deteriorate, or the magnet and the partner material may break. Be sure to check in advance using samples.

⑿ As leaking magnetic flux may exert an impact on other devices, design the magnetic circuit so that leakage is minimized as much as possible.

Assembly and Handling

⒀ A large magnetized magnet will generate an extremely strong attractive force (or repulsive force between magnets) with a magnetic body such as a piece of iron or another magnet. During the transport and assembly of magnets, your hands may get crushed, or unforeseen injuries may result when you lose your body balance as a result of the attractive and repulsive forces. Therefore pay sufficient attention when handling magnets by using an appropriate tool.

⒁ Injuries to the fingers and other parts of the body may be caused by sharp edges in the magnets. Pay adequate attention when handling magnets.

⒂ When magnetizing using a hollow core coil, the magnet may suddenly fly out of the coil and pose a danger. For safety reasons, place and secure the magnet in the center of the coil.

⒃ When laying magnetized magnets on top of one another, the magnets may chip or become difficult to separate. In this case, insert corrugated paper in between the magnets to act as a spacer.

⒄ When processing a magnet for cutting use, the machining dust may self-ignite. Take note of the following precautions regarding machining dust.

1. Never allow flames and flammable objects to get near magnets.
2. Do not use electric vacuum cleaners.
3. Ensure that powder extinguishers, sand, etc., are prepared in case of fire.

⒅ Some magnets may be surface treated (plating or painting) for rust prevention purposes. Rust will occur on magnets when the plating or painting peels off due to external impact such as attraction. Before use, check that the plating or painting is not peeled off when a magnet is knocked or dropped. Do not use magnets whose plating or painting is peeled off either.

⒆ Do not allow a magnetized magnet to be attracted to an iron plate and do not allow it to be attracted to or repulsed by another magnet as it may be demagnetized.

⒇ A magnetized magnet may be demagnetized when brought near a direct current or alternating current magnetic field.

(21) As magnetized magnets will attract dirt such as iron powder, take the magnets out of the packaging case in an environment free of dust.

(22) Be careful when handling magnets as fine magnetic bodies may be attached even if the magnets have not been magnetized. In addition, when using magnets in precision motors, clean the magnets first before use and after they have been assembled.

(23) Magnets have a specific Curie point for each respective material. If magnets are heated near the Curie point, they will lose their magnetism. Consult us if heating cannot be avoided during assembly.

(24) When bonding a magnet to the yoke, choose an adhesive and bonding method that will not leave behind mechanical distortions after bonding. If magnets are used with residual stress still acting on them, the magnets may break upon minor impact.

(25) Be careful when handling magnets as they are weak against impact and break or chip easily. If a magnet is broken or chipped during handling, it may result in a deterioration of the properties and strength.

Storage

(26) Care is required in handling magnets as there are many materials that chip easily in general. Store them in a location where they will not be subject to impact forces.

(27) Ensure that rainwater and other water does not splash onto the magnets in order to prevent rust.

(28) Besides clearly indicating that magnetized magnets are magnetized, cover the magnets with a non-magnetic material such as a wooden box.

Others

(29) Do not bring magnets near floppy disks, magnetic cards, magnetic tape, prepaid cards, tickets, cathode ray tubes, etc., as they may damage the data in the magnetic recording media.

(30) Do not bring magnets near electronic devices as they may affect the instrument and control panels, leading to accidents and malfunctions.

◎Precautions for General Consumers

(31) If a magnet is brought near a magnetic tape, floppy disk, prepaid card, ticket, or electronic clock, the magnetic recording may be damaged or magnetized, making the device unusable. In addition, do not place electronic keys, cards and tickets together in the pocket as an electronic key may cause them to become unusable.

(32) Make sure that magnets are not swallowed. Seek immediate medical attention if swallowed. Do not place magnets within the reach of children.

(33) For those with allergies who react sensitively to metals, the skin may become red and rough upon contact with a magnet. Stay away from magnets if such symptoms appear.

(34) In general, the components of a magnet may dissolve in water. Therefore, never drink water that has been in contact with a magnet.

(35) Bringing magnets near a person fitted with an electronic medical device such as a pacemaker is extremely dangerous. Be careful as this may affect the normal operation of the medical device.

(36) Magnets break easily in general. Be careful of broken fragments getting into your eyes or causing injuries.

(37) Since magnets exert a strong attractive force, be careful not to crush your hands.

2. Specific Precautions regarding Each Type of Magnet

Rare Earth Magnets

⑴ Depending on the operating environment, the surface of a magnet may oxidize and thus surface treatment such as plating is necessary to prevent oxidization. In particular, surface treatment is often required in neodymium magnets. Use magnets that have been surface treated to suit the operating conditions.

⑵ The alloy powders of rare earth magnets are designated as Category 2 (flammable solids) Type I dangerous goods under the Fire Services Act. The fine powder generated by friction during the use of the magnets may ignite or catch fire. Therefore, do not use magnets in situations where there is a risk of magnetic powder being generated.

⑶ The fine powder of a rare earth magnet may self-ignite. Therefore, if the magnet is processed by the customer, do not leave the machining dust and powder hanging in the air and be sure to store them in a vessel containing water. Ensure that sand is prepared in case of fire. Cover the fire with sand immediately if a fire breaks out and keep flammable objects away.

⑷ Among rare earth magnets, the rate of decline of the magnetic properties versus a rise in the temperature may be large in some neodymium magnets so sufficient care needs to be exercised during the design.

⑸ As the magnetic properties of neodymium magnets drop near the temperature of liquid nitrogen, exercise sufficient care during the design.

⑹ Avoid storing magnets in hot and humid places.

Ferrite Magnets

⑴ Take note of materials that may demagnetize at low temperatures such as anisotropic ferrite magnets. Be sure to check the operating temperature.

⑵ Although ferrite magnets are widely used in electrical components, they break very easily and thus adequate measures to withstand impact forces must be taken.

Bonded Magnets (Rubber Magnets and Plastic Magnets)

⑴ When a bonded magnet is heated above a certain temperature, it may be demagnetized, deteriorate in its properties, become soft or deformed and thus care is required. Consult us regarding the range of temperatures in which the magnet can be used.

⑵ Bonded magnets may drop in mechanical strength due to a reduction in brittleness not only at high temperatures but when the temperature is lowered as well. Take note of the operating temperature in the design.

⑶ Compared to general magnets, bonded magnets are weaker and care is required in handling and using them.

⑷ Corrosive gases may be generated due to the organic substances used in the binder, paint, etc. Consult us in advance to select the appropriate material.

⑸ As rare earth bonded magnets use metallic powders that rust easily, appropriate surface treatment (plating and painting, etc.) may be required. Consult us in advance before use.

⑹ Depending on the type of binder used, bonded magnets may undergo changes in dimension and a drop in mechanical strength due to swelling caused by water absorption or organic solvents. Consult us in advance.

⑺ When a bonded magnet is magnetized or demagnetized using a hollow core coil, the magnet may become hot depending on the magnetization conditions, resulting in burns upon contact. Be careful when handling the magnets.

⑻ The magnetic powder of a bonded magnet may get detached depending on the manufacturing conditions and result in severe damage when used in HDD and other devices. Use magnets that are surface treated even if there is no need for rust prevention.

⑼ When bonding a bonded magnet to a yoke, the desired bonding strength may not be obtained depending on the condition of the bonding surface and type of resin. Be sure to check with the adhesive to be used.