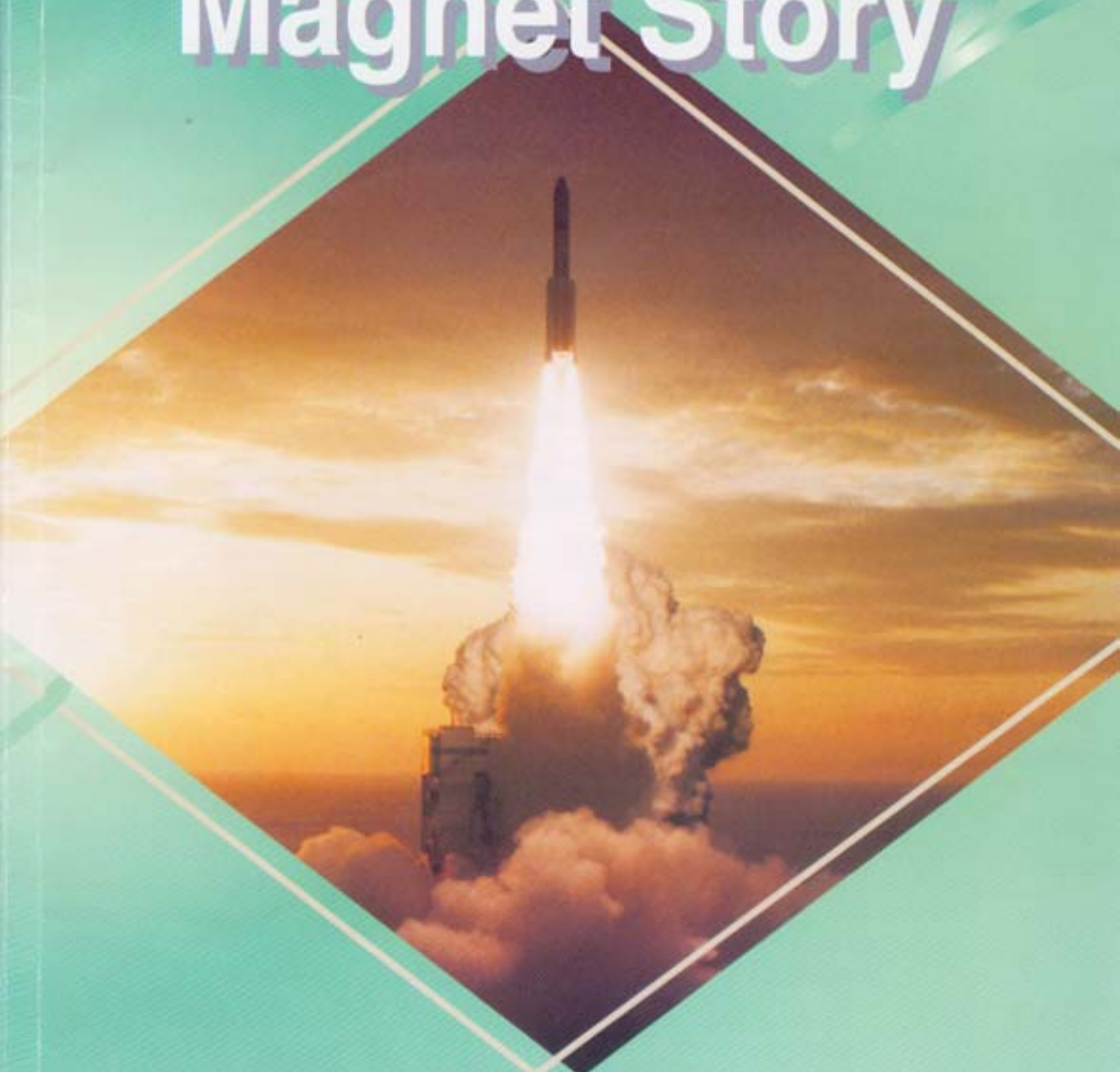


# Magnet Story



**EMAJ**

# CONTENTS

<b>Introduction</b> .....	1
<b>History of Magnets</b> .....	2
An Affectionate Mother and the Magnet .....	2
KS and MK Steel .....	2
Birth of Ferrite Magnets .....	3
Development of Rare Earth Magnets .....	3
From Ferrite Magnets To Rare Earth Magnets .....	5
<b>Categories and Properties of Magnets</b> .....	6
Requirements for a Good Magnet .....	6
<b>Cast Magnets</b> .....	8
Cast and Alnico Magnets.....	8
Manufacturing Process of Alnico Magnets.....	8
Important Points of Manufacturing Process .....	10
Merits of Alnico Magnets .....	11
Other Cast Magnets .....	11
<b>Ferrite Magnets</b> .....	13
Raw Materials of Ferrite Magnets.....	13
Manufacturing Process of Ferrite Magnets.....	13
Merits of Ferrite Magnets .....	15
<b>Rare Earth Magnets</b> .....	17
What are Rare Earth Magnets? .....	17
Samarium-Cobalt Magnets .....	17
Neodymium-Iron-Boron Magnets .....	17
Manufacturing Process of Rare Earth Magnets .....	17
Manufacturing Process Enhancing Magnetic Properties .....	20
Difference in Coercivity Mechanism.....	20
Merits and Demerits of Rare Earth Magnets.....	21
Problems of Rare Earth Magnets Awaiting Solution .....	22
<b>Bonded Magnets</b> .....	24
What are Bonded Magnets? .....	24
Raw Materials of Bonded Magnets .....	25
Manufacturing Process of Bonded Magnets .....	26
<b>Other Magnets</b> .....	28
Nd-Fe-B Ring Magnet by Hot Extrusion Molding.....	28
Manganese Aluminum Magnet .....	29
Praseodymium Magnet .....	30
(Pr-Fe-B-based Cast and Rolled Magnet)	
Platinum Magnet .....	31
<b>Applications of Magnets</b> .....	32
Applications in Many Fields .....	32
<b>Glossary of Terms Peculiar to Magnets</b> .....	35
Ferromagnetic Material.....	35
Magnetic Anisotropy .....	36
Spontaneous Magnetization .....	38
Magnetic Domains and Domain Walls .....	38
Magnetic Charge and Moment .....	41
Magnetic Field .....	41
Magnetization .....	41
Saturation Magnetization.....	41
Magnetizing .....	41
Magnetic Flux Density (Magnetic Induction) .....	41
Remanent Flux Density, Coercive Force and Hysteresis Loop.....	42
Demagnetizing Field .....	42
Demagnetization Curve .....	42
Operating Point .....	42
Maximum Energy Product .....	43
Minor Loop.....	43
Reversible Relative Permeability .....	44
(Recoil Relative Permeability)	
Irreversible Loss at High and Low Temperature .....	44
<b>Magnetizing Method</b> .....	46
<b>Measuring Method</b> .....	47
<b>Standards for Permanent Magnets</b> .....	48

## Introduction

The committee of Permanent Magnet made a booklet titled "Magnet Story" in Japanese on April 1994.

Magnetic products have expanded worldwide and a considerable number of people in overseas wish to learn more about magnets. We have translated from the Japanese booklet to English version to meet overseas requirement. We are happy to issue this English Version reprint.

Today, magnetic parts are used in various kinds of hardwares ranging from a personal computer to a car, in the field of which their roles essentially are increasing. Magnetic parts have been gaining an indispensable position in current electronics industries and their applications and demands are still expanding.

This booklet covers a wide range of knowledge on magnets, from just a beginner to the professional. We believe that this booklet will be of help for those who are already engaged in magnet-related business, in addition, to those who want to learn more about magnets.

We further wish that this English booklet will be useful not only Japanese transplant people but also for overseas native people, to understand magnets. In addition, it will lead to a successful business in magnet fields.

### An Affectionate Mother and the Magnet

Magnets have mysterious powers, like attracting iron and pointing in a north-south direction. People must have been amazed when they first found out these phenomena.

It was a long way back to around the 7th century B.C. in Europe, and around the 3rd century B.C. in China that the man found a magnet for the first time. The magnet was then only a natural dark iron ore having magnetic properties, unlike such powerful ones that are being manufactured today. At that time, the characters 慈石, Jishaku in Japanese (literally an affectionate stone), were used to mean "magnets" instead of 磁石, Jishaku in Japanese (used today).

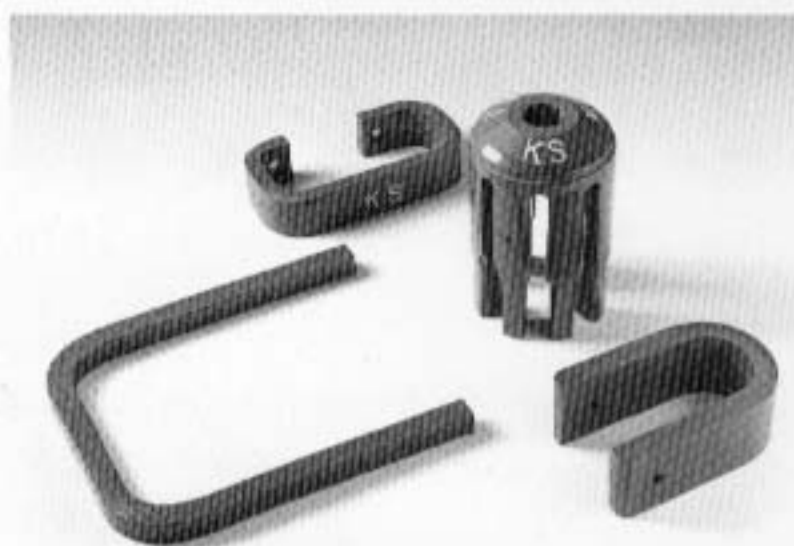
Like a child being attracted toward an affectionate mother, a piece of iron is pulled toward a magnet. Consequently, "magnet" was then written as 慈石 (affectionate stone) in China, and thus the region where magnets were mined was written as 慈州, Jisyuu. Confusingly, another 慈州, Jisyuu existed in China then, which necessitated different names being used for the two regions to avoid confusion. This situation led to the name 磁州, Jisyuu, being used for the region where magnets were mined (the region today is 河北省磁县 Hubei sheng Ci xian in China), by adding the left-hand side radical "stone", 石, of a Chinese character and taking away the bottom radical "heart", 心. Chinese character for the magnet also changed from 慈石 to 磁石 at the same time, both of which are pronounced Jishaku in Japanese.

In Europe, magnetic iron ores were mined in the Magnesia region of Greece, and were therefore called Magnesia stones, from which the word "magnet" originated.

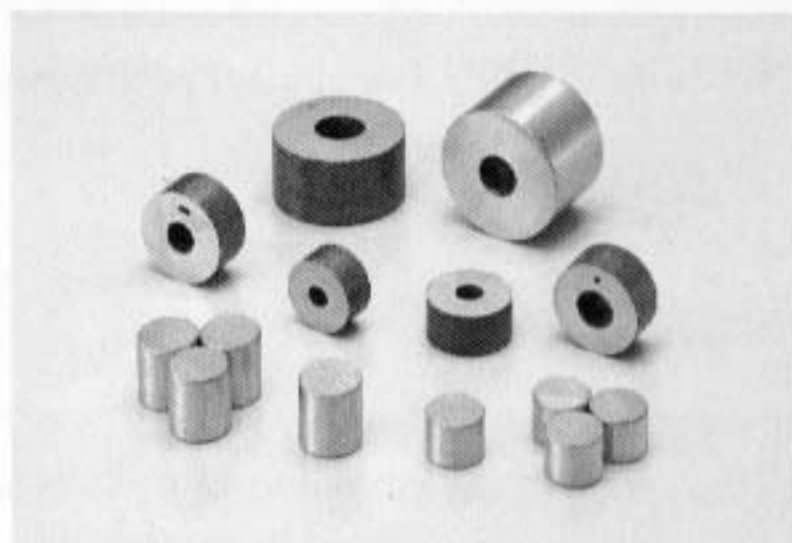
Magnets were developed by using mainly steel, which is called magnet steel.

### KS and MK Steel

Japan has achieved many successful results in research on magnets. For instance, in 1917, Dr. Kohtaro Honda in Tohoku University completed an iron alloy containing cobalt, tungsten, chromium and carbon. This was called KS steel and produced a surprisingly strong magnet at the time, which contributed to remarkably improving the



▲ KS steel was developed by Dr. Kohtaro Honda in 1917.



▲ MK steel has a stable microstructure because of precipitation hardening type steel.

accuracy of electrical measuring instruments.

Permanent magnet materials are required to have (1) a high magnetization and (2) a high coercive force, the resistance to the factors that weaken the magnetization. To increase the coercivity, the state of crystal structure having as many disorders and strains as possible is desirable, which is made by the methods such as cold working, and quenching or precipitation hardening during heat treatment. Many of the old magnet alloys have microstructures made by quenching (that is, martensitic structure), to which Dr. Honda's KS steel belongs.

From around 1930 on, progress was made in research on precipitation hardening structure alloys by heat treatment, and in 1932, Dr. Tokushichi Mishima completed a magnet alloy without carbon called MK steel made from iron, nickel and aluminum. Its merits were a stable microstructure due to precipitation hardening, and a more than two-fold increase in coercive force, 24~48 kA/m (300~600 Oersted), as that of KS steel, the highest ever coercivity up until then. The unit of magnetic field strength to express coercive force is kA/m or Oersted (Oe).

To make this magnet, the raw materials are molten and

cast. The cast material is heated up to 900 °C to 1,200°C to make a single phase, then cooled at a suitable speed to decompose the precipitated nucleus, and further heated at about 600°C for a few hours to let the precipitated nucleus grow to a proper size.

This MK steel, with cobalt and titanium added, was developed into the New KS steel, which was further improved by adding copper. This magnet had, for a long time, been playing the leading role of permanent magnets under the popular name of Alnico. However, the leading role has today been taken over by ferrite and rare earth magnets that invented thereafter.

## Birth of Ferrite Magnets

At around the same period as the MK magnet was invented, a totally different type of magnet was also born in Japan, the OP magnet invented by Dr. Yogoro Kato and Dr. Takeshi Takei of the Tokyo Institute of Technology.

The ferrite, made of oxides just as ceramics and porcelains are, was invented by the both doctors in 1931. Ferrite is the name of a group of magnetic oxides mainly composed of ferric oxides. Therefore, a natural magnetite,  $\text{FeO} \cdot \text{Fe}_2\text{O}_3$ , by which ancient people came to know the existence of magnetism for the first time, is an iron ferrite that has long been familiar to us. They invented the OP magnet by discovering the phenomenon in the course of their research that cooling the solid solution of cobalt ferrite and iron ferrite (which corresponds to alloy in metals) in a magnetic field resulted in a remarkable improvement in magnetic properties.

The coercive force of this magnet was still higher than that of the MK magnet and reached even 48 ~ 72 kA/m (600 ~ 900 Oe). This remarkable magnet, though born in Japan, attracted attention abroad. However, since market demand for the OP magnet then was at the predawn stage, the magnetic separation of iron sand was the only major application that could be found.

Before World War II, major progress in permanent magnets had been made by Japanese scholars. Thereafter, Philips in the Netherlands mobilized many scholars to conduct thorough and extensive (including basic) research on ferrites. As a result, a much more excellent barium ferrite magnet ( $\text{BaO} \cdot 6 \text{Fe}_2\text{O}_3$ ) was developed in

1952, which did not require expensive and difficult-to-procure cobalt and possessed a high coercive force of more than 160 kA/m (2,000 Oe). This was quite an achievement.

Later research made clear that anisotropic pressing processes enabled further improvement in the magnetic properties, resulting in successful industrialization. In Japan, commercial production of barium ferrite started around 1955. The barium ferrite was modified and further developed into a strontium ferrite having still better performance that today occupies the top market share (by weight) of commercial magnet material, enjoying a wide range of applications.

Today, the term, "ferrite magnet" refers only to "barium ferrite" or "strontium ferrite," while the OP magnet has merely the honor of being a pioneer magnet.

Since the ferrite magnet consist mainly of iron oxides, it is therefore the material having the most excellent cost performance. Switching from Alnico magnets to ferrite magnets began mainly in the speaker market, the major market for magnets then. Thereafter, the ferrite magnet contributed to the expansion of magnet applications, such as micro motors, automotive motors, etc. that are quickly growing.

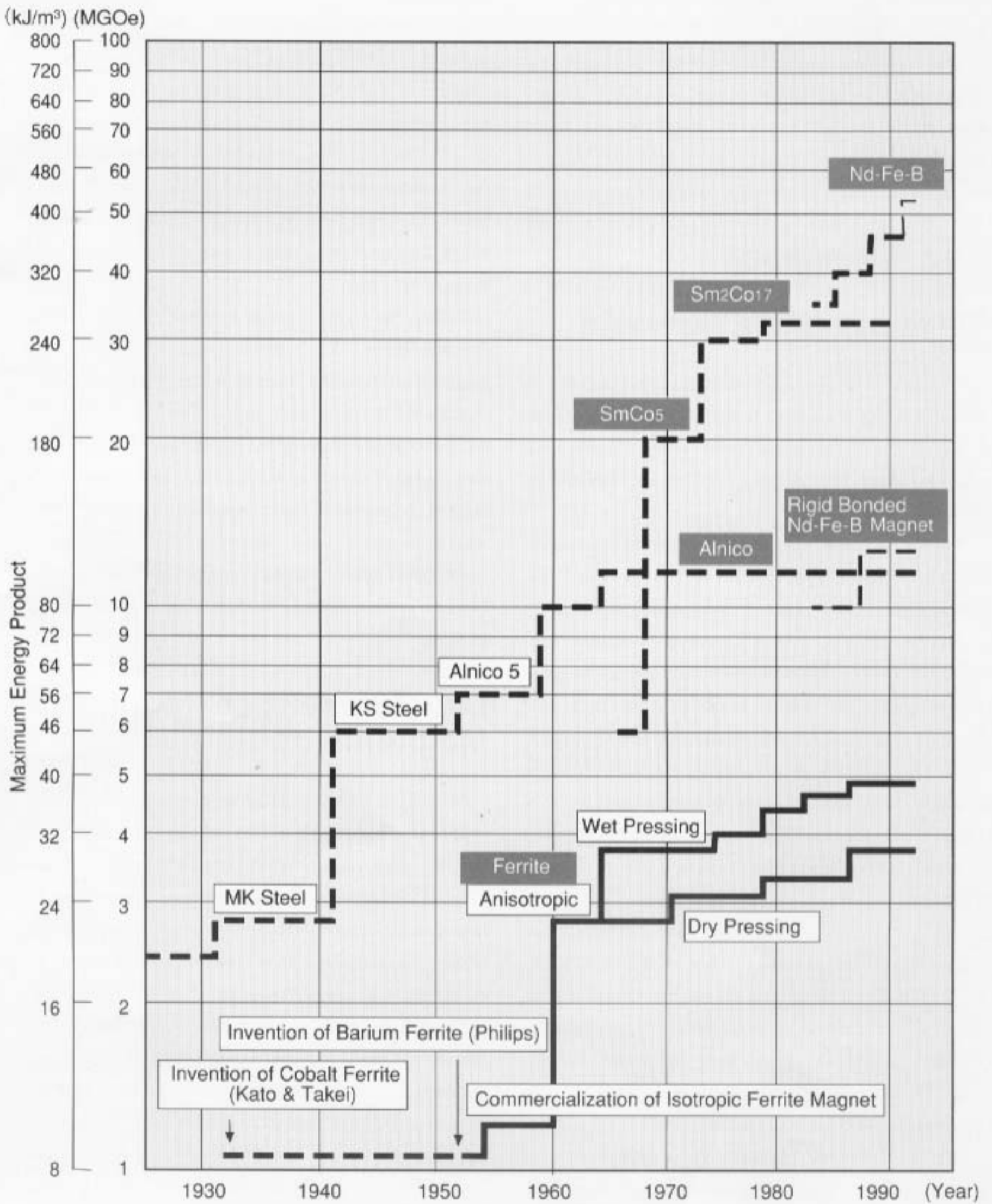
## Development of Rare Earth Magnets

After around 1960, research on magnetic properties of intermetallic compounds of rare earth elements and cobalt became more and more active. The U.S. Air Force Material Research Laboratory proved that  $\text{SmCo}_5$ , an intermetallic compound made from samarium (atomic number 62) and cobalt in the ratio of 1 : 5, produces an excellent magnet, samarium-cobalt magnet.

Through the efforts of researchers in many countries to develop and improve manufacturing methods, the magnet performance jumped, resulting in maximum energy product (a magnet performance indicator; expressed as  $(\text{BH})_{\text{max}}$ ) of 128 ~ 192 kJ/m<sup>3</sup> (16 ~ 24 MGOe) for  $\text{SmCo}_5$ , and 256 kJ/m<sup>3</sup> (32 MGOe) for  $\text{Sm}_2\text{Co}_{17}$ . The coercive force attained also was as high as 560 ~ 2,400 kA/m (7,000 ~ 30,000 Oe).

Meanwhile, research on the magnetic properties of intermetallic compounds of rare earth metals and iron

Development of Permanent Magnet



came to be presented at the same time. Generally, rare earth elements exhibit ferromagnetism (strong magnetism) at low temperatures, and lose it above room temperatures. The intermetallic compounds of rare earth elements and iron showed their strong magnetism in low temperature range, as well. To manufacture practical magnets, it was indispensable to extend this temperature range above room temperature.

In the 1980s, a ternary compound  $\text{Nd}_2\text{Fe}_{14}\text{B}$ , composed of neodymium (atomic number 60), iron and boron, broke through this problem and made its debut in Japan and in the US as a high performance magnet in 1983.

One developed by a company in Japan, and another in the US were of the same composition but made by different manufacturing processes. The magnet developed in Japan was made by a manufacturing process similar to that of Sm-Co based magnets; by first making the alloy powder, then pressing and sintering it.

On the other hand, the manufacturing process introduced in the US was a melt-spinning process, utilizing the manufacturing process of amorphous metals. The magnet powder made by the latter process is suitable for the manufacture of bonded magnets.

This neodymium-iron-boron magnet is the strongest with its maximum energy product exceeding  $400 \text{ kJ/m}^3$  (50 MGOe). As its raw materials are less expensive than those of samarium-cobalt magnet, its production scale has continued to expand year by year since its debut in the market, and the magnet has contributed to the miniaturization of electronic equipment and devices as well as to the expansion of applications.

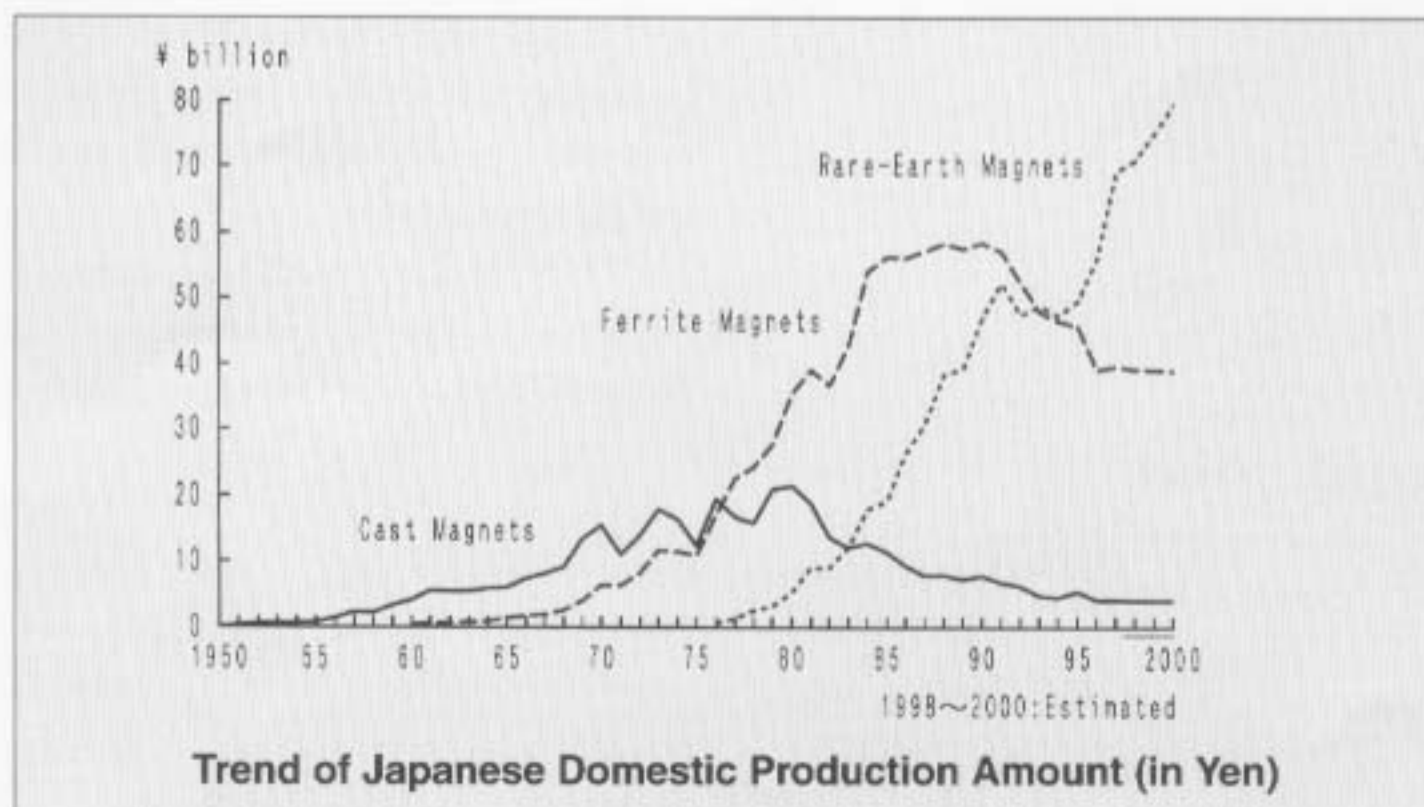
The progress made in magnet performance is shown chronologically in Fig. p-4.

The performance of permanent magnets has thus been improved year by year, sustaining the progress made in electronics technology in the form of materials and parts.

## From Ferrite Magnets To Rare Earth Magnets

Let's look at the permanent magnet history from a different angle. After 1950 when the first statistics on magnets appeared, the leading magnet gave way to other type of magnet as time went by. In 1977, the amount (in yen) of ferrite magnet production surpassed that of cast magnets, and in 1993, the ferrite magnet gave way to the rare earth magnets. The new leading magnet was the neodymium-iron-boron sintered magnet invented in Japan. Although ferrite magnet production is still active abroad, it is declining in Japan.

As the Japanese electronics industry grew, the major world magnet production shifted from the West to Japan, and then from Japan to NIES and ASEAN countries where production has increased supported by technology transfer from Japan. Recently, the trend has shifted toward in-market production in North America and Europe. As a result of this, the ratio of Japanese production of cast and ferrite magnets to total world demand is gradually decreasing and is now estimated at 30%. On the other hand, it is estimated that 70% of the world demand for rare earth magnets is supplied from Japan.



### Requirements for a Good Magnet

Requirements for a good magnet should meet the following three conditions:

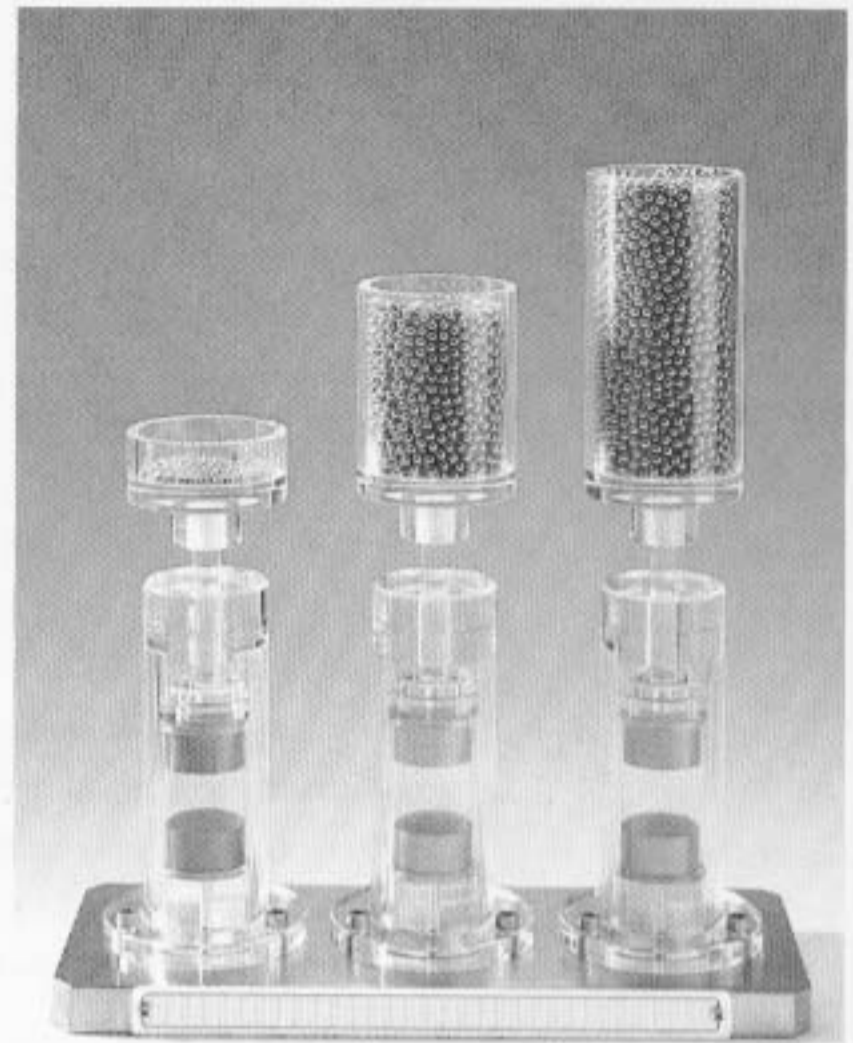
- (1) To have the ability to generate a strong magnetic field in an external space of the magnet which is small in size and volume.
- (2) To be stable against thermal and external demagnetization.
- (3) To have good cost performance, low cost per effective magnetic energy.

Condition (1) requires the magnet to have a high maximum energy product. In order to have a high  $(BH)_{max}$ , it is necessary to increase remanent flux density ( $B_r$ ) and coercive force ( $H_c$ ) as much as possible.

To reduce the temperature dependency of the magnetic properties [ in (2) above ], it is necessary to have as high a Curie temperature as possible, and for the magnet to have strong resistance to oxidation and rusting.

Condition (3) requires the cost of the magnet to be low and the effective magnetic energy high.

Although various magnet materials are available, none of them completely meets all of these requirements. A particular material is chosen for a particular application.



▲ From left to right, ferrite magnet, samarium-cobalt magnet and neodymium-iron-boron magnet holding up steel balls in cylinders by their repulsive force.

Let's talk about the much more detailed requirements needed to fulfill each condition mentioned above.

$B_r$  is proportional to spontaneous magnetization. In order to have a high  $B_r$ , it is necessary for the material to have a high density of atoms possessing a high magnetic moment in its crystal structure, the spins of which must be aligned in the same direction (called ferromagnetism). This is the general situation for metal magnet materials.

The ferrite magnet has an oxygen crystal lattice into which trivalent iron ions are incorporated, therefore, the spontaneous magnetization is diluted with the non-magnetic oxygen. In addition, some of the spins in the iron ions, which is the source of the magnetism, are aligned anti-parallel with others, partially cancelling each other. The difference in the cancellation produces spontaneous magnetization (called ferrimagnetism) in the magnet whose  $B_r$ , therefore, is lower than those of metal magnets.

$H_c$  is proportional to the difference between the magnetic energy of easy magnetization direction and that of hard one. In short, a high coercive force is resulted in a material having high magnetic anisotropy. In the case of practical magnet materials, those having a high "magneto-crystalline anisotropy" related to the crystal structure,





exhibit a higher  $H_c$ , rather than those having a high "shape magnetic anisotropy." In the case of Alnico magnet or iron-chromium-cobalt magnet, shape magnetic anisotropy is utilized to increase their  $H_c$ .

The larger the force\* that aligns the magnetic moments in the same direction, which are possessed by atoms in the crystal lattice, the more resistant the spontaneous magnetization is to thermal fluctuation, and therefore, the higher the Curie temperature (\* such a force is sometimes called a molecular field). The force aligning the moments varies, depending on the crystal structure, kind of ferromagnetic atoms incorporated in the lattice, the bonding system of moments (ferro- or ferri-magnetism), etc. Metal magnets containing cobalt have high Curie temperatures at around  $800^\circ\text{C}$ .

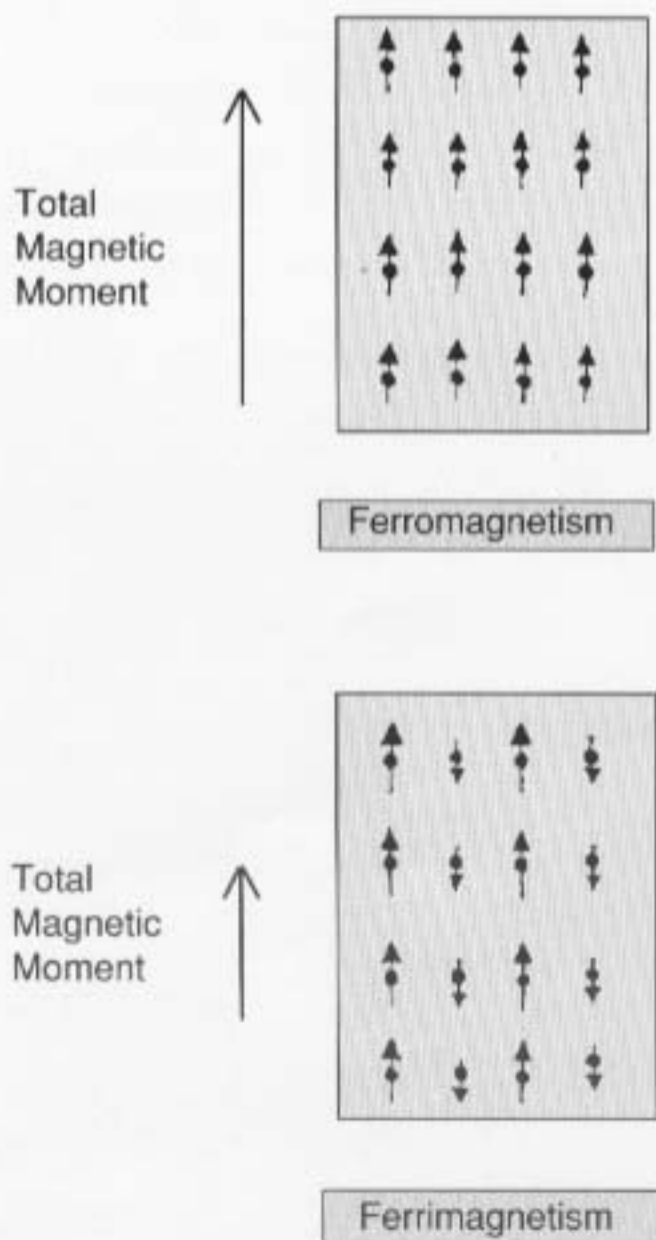
Alnico magnet, iron-chromium-cobalt magnet and samarium-cobalt magnet have a range of temperature coefficients of magnetic flux,  $-0.01 \sim -0.02 \text{ \%}/\text{K}$ , one order of magnitude smaller than that of ferrite

magnets,  $-0.18 \text{ \%}/\text{K}$ .

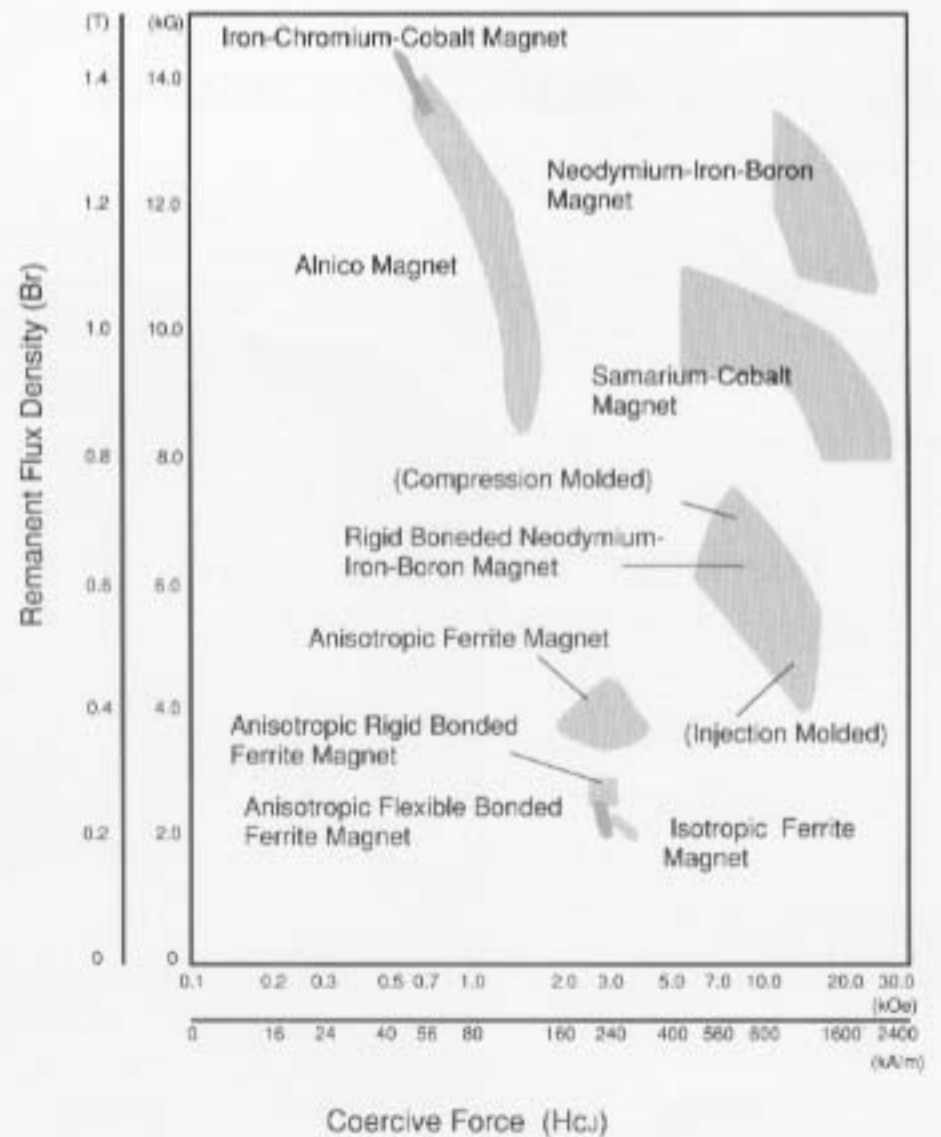
For magnets to be used in volume in practical applications, price and cost performance are important factors. Inexpensive but powerful magnets are what the market demands. Raw materials for ferrite magnets are iron oxide and barium or strontium carbonate. And the production method of ferrite magnet materials is relatively simple and easy, which accounts for the lower production cost than that of other magnet materials. Despite its low  $B_r$ , comparatively high  $H_c$  and low cost offer the best cost performance and the materials easy to use. Today, ferrite magnet material is No. 1 in production volume in the magnet industry worldwide.

Bonded magnets, consisting of ferrite or rare earth powder bonded with synthetic rubber or resin, are widely used. You are no doubt familiar with flexible rubber magnet sheets, which are used daily in homes and offices and easy to cut with a pair of scissors.

**Configuration of Magnetic Moments and Magnetism**



**Distribution of Permanent Magnet Properties**



### Cast and Alnico Magnets

As described in the chapter, "History of Magnets" of this booklet, the MK magnet invented by Dr. Tokushichi Mishima and the KS magnet invented by Dr. Kohtaro Honda are the roots of cast magnets.

Today's Alnico magnets were developed by improving the compositions and production processes of MK and KS magnets. As Alnico magnets are brittle and lacking in ductility, they are commonly manufactured by melting the raw materials at high temperatures and casting them in a mold called "a shell mold." For this reason, "cast magnets" are virtually the same as Alnico magnets, which represent almost all cast magnets.

The name Alnico was originally the brand name of an American product, which was derived from the atomic symbols, Al (aluminum) + Ni (nickel) + Co (cobalt), meaning an alloy based on Fe (iron) combined with Al, Ni and Co.

The term Alnico is also a general term for a group of such alloys additionally containing copper, titanium and niobium, which greatly differ in their magnetic properties, depending on their composition and method of manufacturing.

### Manufacturing Process of Alnico Magnets

The raw materials are precisely weighed according to predetermined ratios, put into a furnace to be completely melted at a high temperature about 1,600°C, and then cast into a mold to solidify. The melting furnace to be used here, is a vessel lined with a refractory material, outside of which is an induction coil wound to heat up and melt the raw materials in the vessel by its induced high frequency current.

This induction melting method is usually applied.

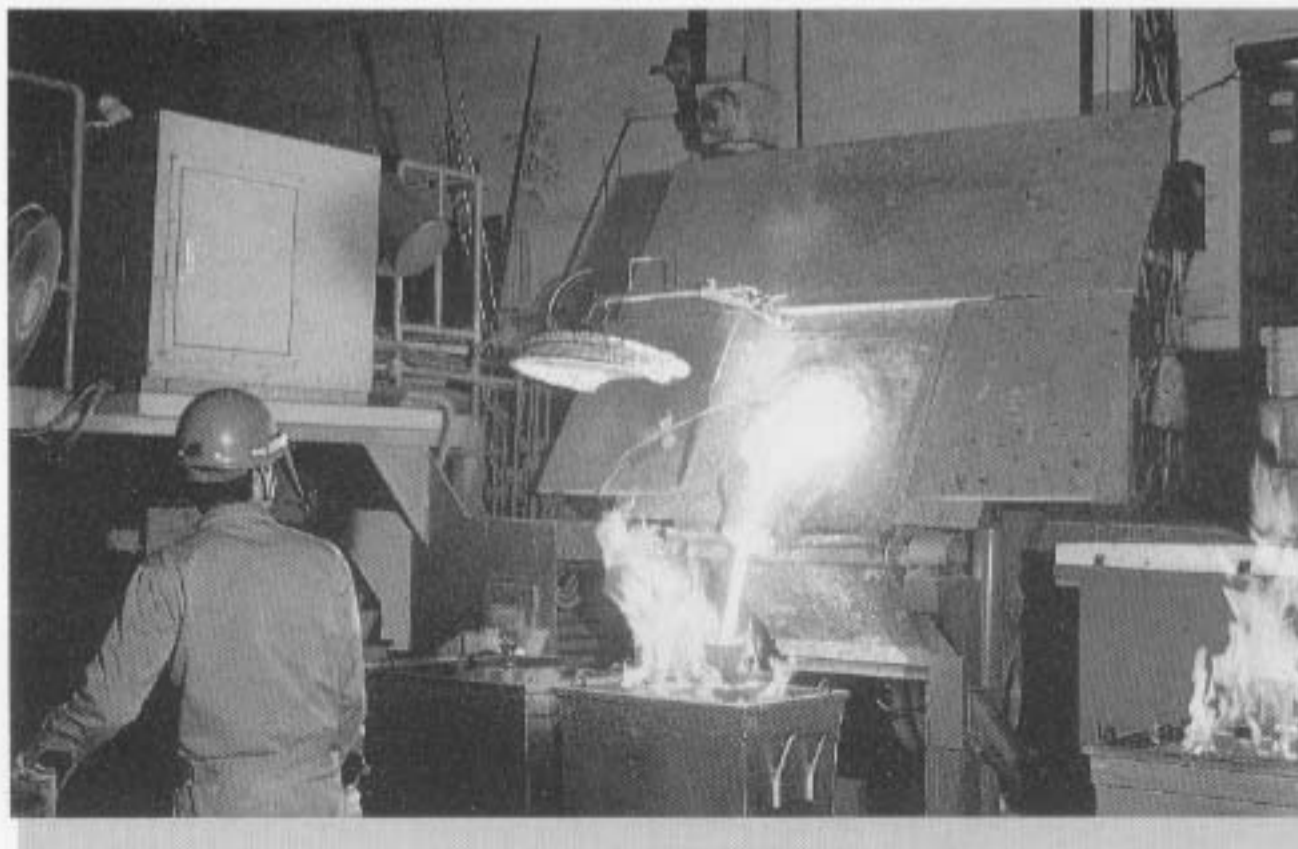
The part of shell mold to be used here is made by "baking" a plate of fine silica sand, each grain of which is precoated with a thin layer of phenol resin, on the surface of a heated metal mold. This process melts the resin to bind the sand, forming the part of the shell mold. Then, piling them horizontally, the complete shell mold is constructed.

Usually thousands of cast magnets can be obtained from one shell mold, which is then "shaked-out" and separate each cast magnet. These magnets are then roughly ground to shape.

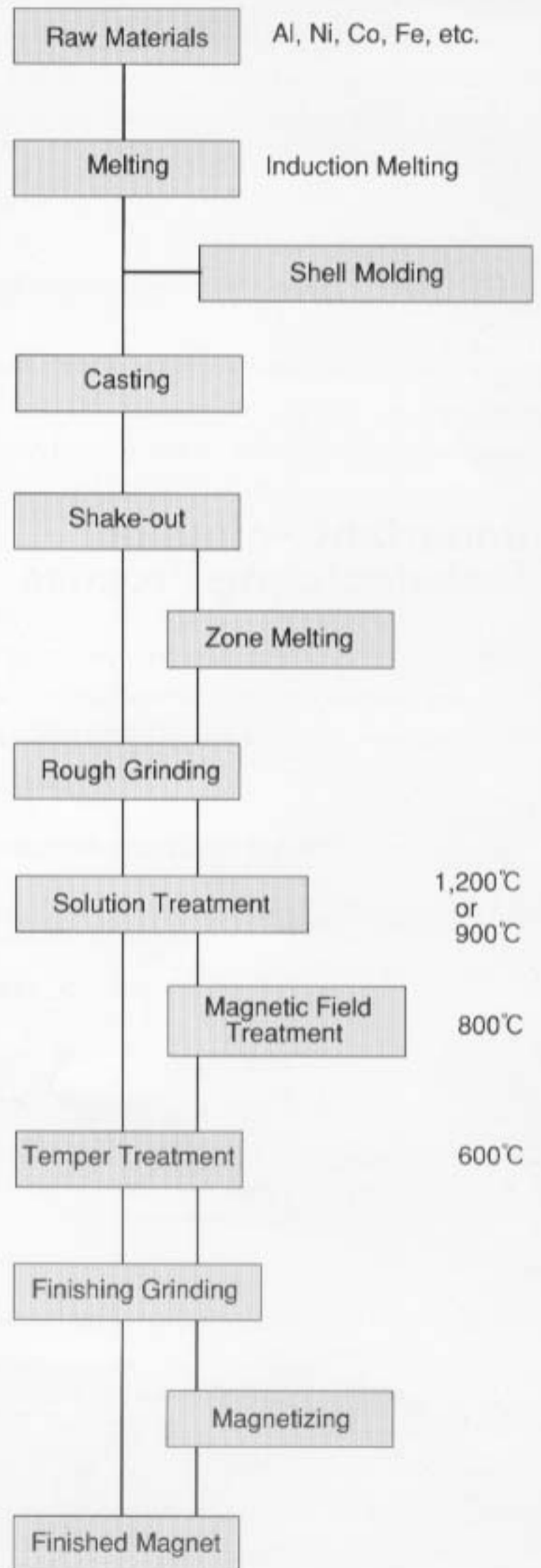
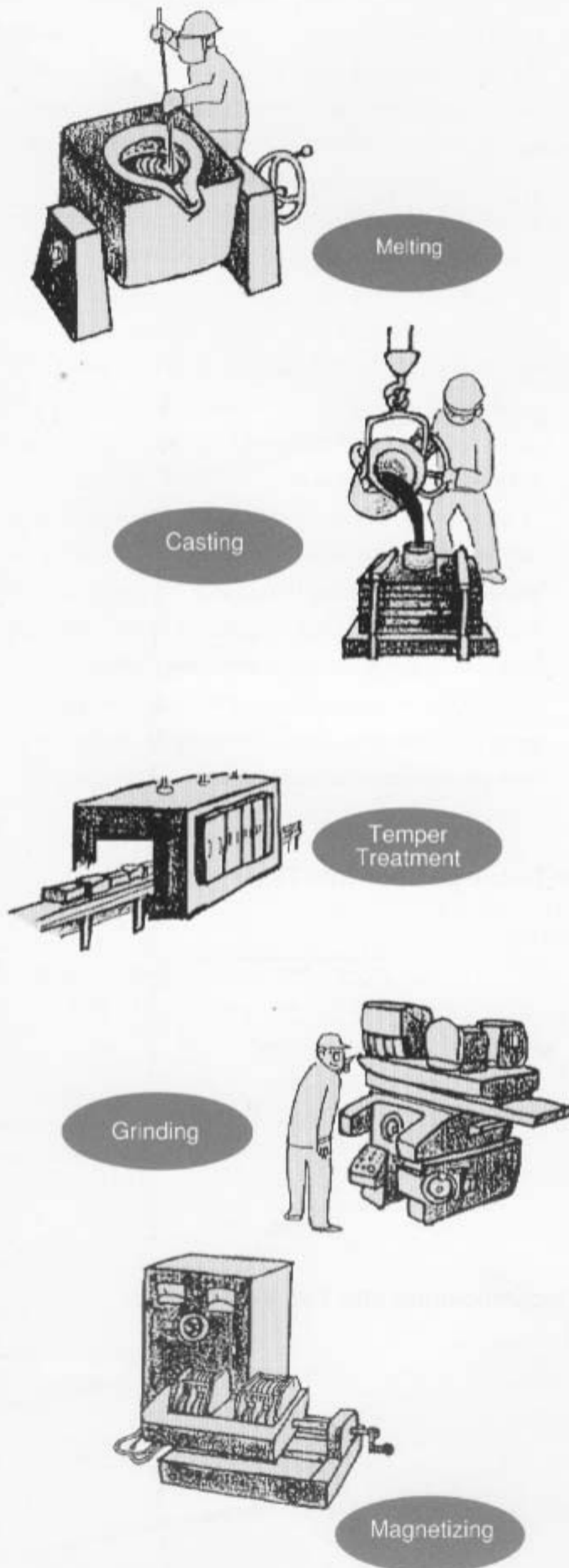
As these cast magnets are brittle, they are ground with a grindstone made of hard mineral grains bound together (grinding). Later finishing is accomplished in the same manner.

Heat treatment is required to give the magnet material the necessary magnetic properties. The treatment called "solution treatment" is applied, in which the material is kept at a high temperature around 1,200°C to get a homogeneous composition and structure all over the cast magnet by diffusing the atoms.

Around 900°C in the cooling process after the solution treatment, the phenomenon called "decomposition into two phases" occurs, when if an external magnetic field is applied to the magnet so that its magnetic properties can be improved in the magnetic field direction. This is called "magnetic field treatment," and is a particularly



▲Alnico magnet is manufactured by melting the raw materials and casting the molten alloy into a mold.



Manufacturing Process of Alnico Magnet

## Cast Magnets

important process for Alnico magnets.

It is necessary to keep the cooling speed within a certain range while the "magnetic field treatment" is being applied. If the magnet has a high cobalt content, it is necessary to keep it at around 800°C for tens of minutes. (If specially high magnetic performance is not required, a magnetic field is not applied but the cooling speed has also to be controlled.)

Finally, heat treatment called "temper treatment" is applied. In this treatment, the magnet is kept at around 600°C for more than 10 hours to improve its magnetic properties.

Thus the magnets that have acquired their magnetic properties are finally finish-ground with a finer grindstone to the required size and become finished products.

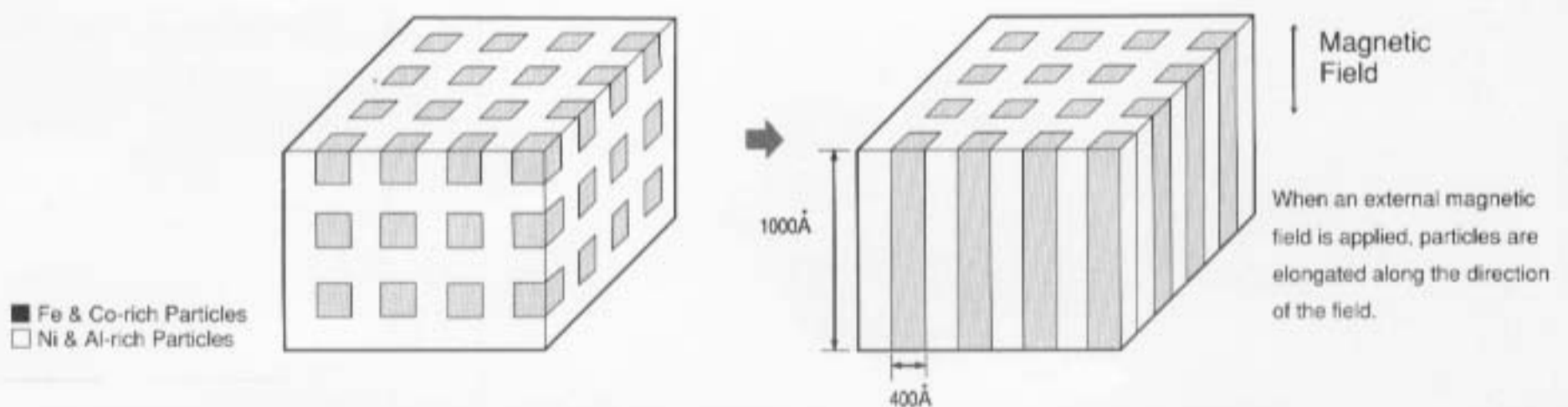
## Important Points of Manufacturing Process

Heat treatments are important processes in the manufacturing to obtain high performance Alnico magnets. Elongated single crystals of ferromagnetic phase are reg-

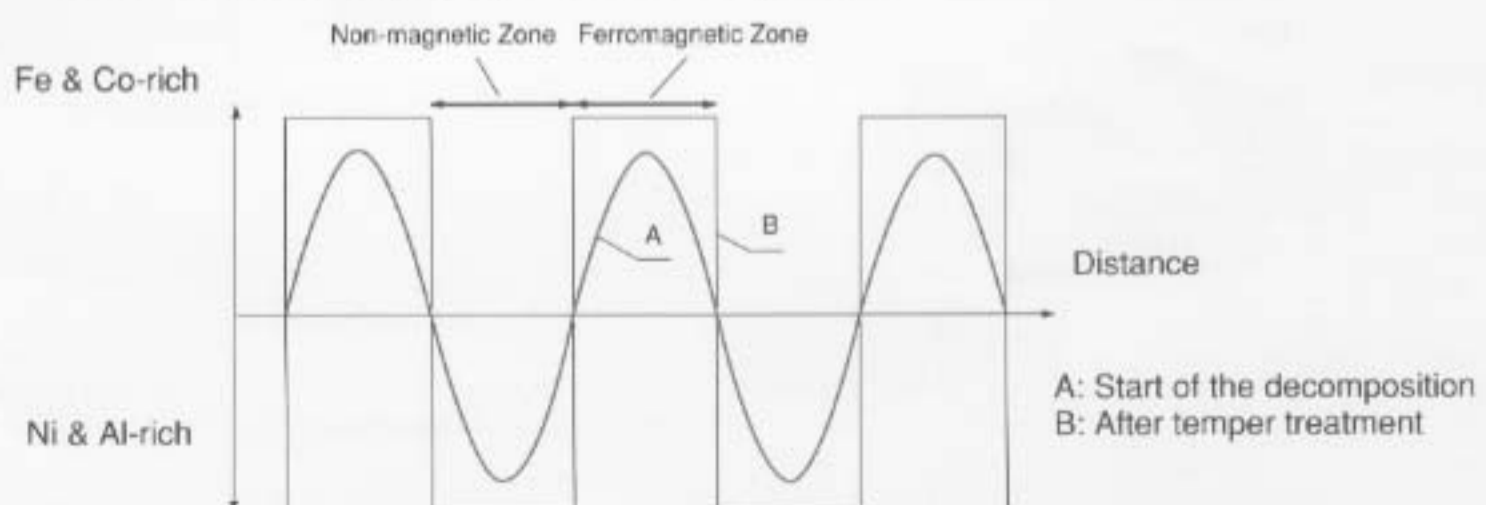
ularly aligned in the Alnico magnets. This phase consists mainly of iron and cobalt. The interstitial zones among the ferromagnetic phases are filled with non-magnetic phases consisting of nickel and aluminum. The ferromagnetic phase has a very small diameter of 40nm. This microstructure is generated by heat treatment. After the distribution of components in the magnet is homogenized, first of all, by the "solution treatment," decomposition into two phases starts in the magnet as it is cooled down below 900°C. This is the start of the phenomenon in which constituent elements of Alnico are divided into two groups, where one group of iron and cobalt gathers to some zones and another group of nickel and aluminum to other zones.

The zones where the iron (Fe) & cobalt (Co) and the nickel (Ni) & aluminum (Al) groups have gathered are respectively very small in size and very regularly and alternately aligned. And a long period of heat treatment later at around 600°C (temper treatment) further helps to separate the elements into two groups, increasing each group's own concentration and completing the ferromagnetic and non-magnetic characteristics in each particle.

### Internal Structure Resulting from Decomposition into Two Phases



### Concentration Fluctuation in Decomposition into Two Phases



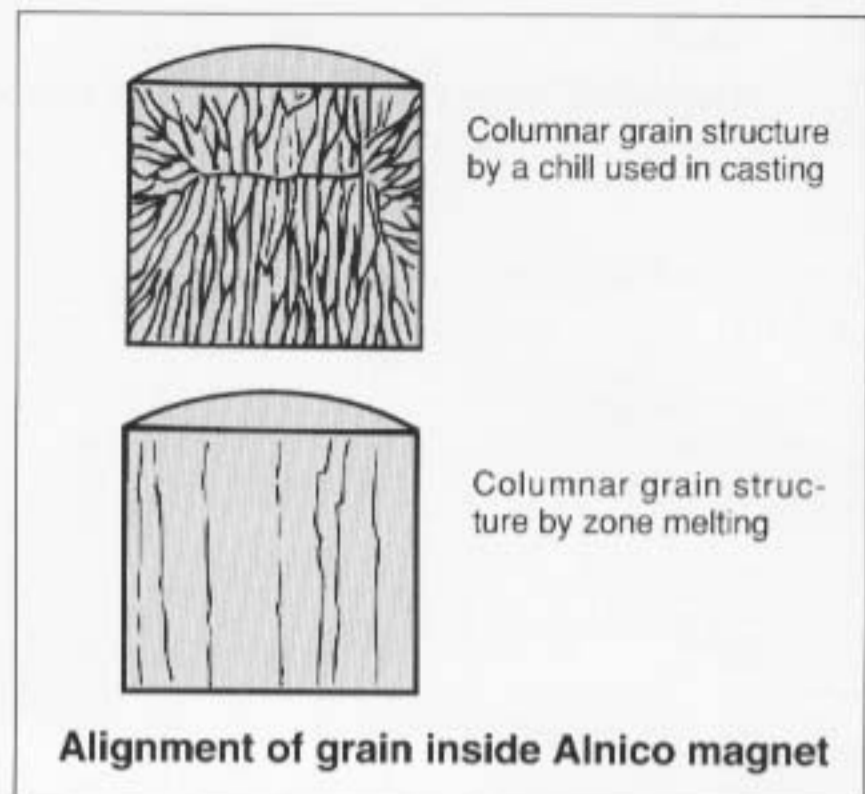
As a result of this, such a structure is obtained as the ferromagnetic particles rich in Fe and Co contents, which are important to magnets, are surrounded by non-magnetic particles with both ferromagnetic and non-magnetic particles being aligned regularly.

The crystal structure of this magnet is body centered cubic. Along the lattice edge of body centered cubic structure, the atom concentration occurs during the "decomposition into two phases" process. If this decomposition process is made to occur only in a single direction, the ferromagnetic particles will grow and be aligned only in that direction, and then the magnet will show excellent magnetic properties in that direction. One key technology for this is the aligning grain structure technology, and another is the magnetic field treatment.

One of the technologies for aligning the grain structure is to put a piece of metal called a "chiller" or a "cooling metal" in the mold when the molten alloy is cast. The alloy begins to solidify first from the side in contact with the chiller, and the solidified parts grows into the inner space in the mold. The direction of the crystal growth is advantageously the same as the direction of the crystal lattice edge of body centered cubic structure.

Another technology to have better alignment of the grain structure is a method called "zone melting." This method partially melts and re-solidifies the cast magnet material cylinder from one end to the other, shifting its melting zone, which very well aligns the crystal structure along the longitudinal axis of the cylinder. Owing to this, magnets manufactured by this method exhibit extremely high performance.

The "magnetic field treatment," as described earlier, is a method of applying an external magnetic field at a starting temperature of the decomposition into two phase. The field also acts to prevent this decomposition in the other directions. On account of this, the ferromagnetic particles grow themselves in the direction of the applied magnetic field, exhibiting excellent magnetic properties in this direction. While almost all other magnets introduced in this booklet are manufactured from powder materials, Alnico magnets are manufactured by casting the molten alloy, which has required development of these unique technologies to attain high magnet performance.



## Merits of Alnico Magnets

The merits of Alnico Magnets are high magnetic flux density, low temperature coefficient of magnetic properties, only few irreversible loss at low and high temperature, high mechanical strength and so on, and can be said, in short, to be extremely stable magnet materials.

Alnico magnets, having so many excellent magnetic properties, had long been the leading magnets in the market. However, the supply problem of their main raw materials, cobalt and nickel and their price instability allowed ferrite magnets to replace them. And today Alnico magnets have already yielded their leading role to other magnets. But they are still enjoying persistent demand owing to the low temperature coefficients of their magnetic properties mainly in the measuring instrument industry. Thus they remain an important type of magnet.

## Other Cast Magnets

"Fe-Cr-Co" magnets are cast magnets besides Alnico. Their main components are iron, chromium and cobalt, and their production process is almost the same as that of Alnico magnets.

The greatest merits are the remanent magnetic flux density still higher than those of Alnico magnets and the plastic workability, while retaining the advantages of Alnico. The cobalt content of Fe-Cr-Co magnets is less than that of Alnico magnets, and therefore, they are resource saving type magnets.

## Magnetic, Physical &amp; Mechanical Properties of Cast Magnets (Typical Examples)

Upper line: unit in SI Lower line: unit in C.G.S.

Item	Unit	AlNi	Alnico 5	Alnico 5-7	Alnico 8	Alnico 9	Fe-Cr-Co
Composition		12Al-26Ni-bal Fe	8Al-14Ni-24Co-3Cu-bal Fe	←	7Al-15Ni-34Co-4Cu-5Ti-bal Fe	7Al-15Ni-34Co-4Cu-8Ti-bal Fe	26Cr-11Co-bal Fe
Principal Factor in Magnetic Anisotropy		( Shape Isotropy )	Shape Anisotropy	Shape Anisotropy	Shape Anisotropy	Shape Anisotropy	Shape Anisotropy
Remanent Flux Density Br	mT	500-650	1,250-1,350	1,300-1,400	850-950	1,000-1,200	1,350-1,450
	kG	5.0-6.5	12.5-13.5	13.0-14.0	8.5-9.5	10.0-12.0	13.5-14.5
Coercive Force H <sub>cB</sub>	kA/m	39.8-49.3	46.2-52.5	51.7-59.7	107.5-119.4	111.5-135.4	43.8-55.7
	Oe	500-620	580-660	650-750	1,350-1,500	1,400-1,700	550-700
Maximum Energy Product (BH) <sub>max</sub>	kJ/m <sup>3</sup>	8.8-11.1	35.8-43.8	53.3-65.3	35.8-47.8	63.7-87.5	47.7-59.7
	MGOe	1.1-1.4	4.5-5.5	6.7-8.2	4.5-6.0	8.0-11.0	6.0-7.5
Temperature Coefficient of Br	%/K	-0.021	-0.021	-0.021	-0.020	-0.020	-0.03- -0.04
Permeance Coefficient at Optimum Operating Point P		10.5	20.0	20.5	6.5	5.6	22.0
Reversible Relative Permeability μ <sub>r</sub>		4.0-5.0	3.3-4.3	2.0-3.0	2.0-3.0	1.3-2.3	
Curie Temperature T <sub>c</sub>	K	1,123	1,123	1,123	1,118	1,118	943
	°C	850	850	850	845	845	670
Recoil Relative Permeability μ <sub>rec</sub>		4.8	3.6	2.5	2.4	1.3	2.6-3.6
Density	g/cm <sup>3</sup>	6.97	7.3	7.3	7.25-7.30	7.25	7.8
Flexure Strength	MPa	74.5	73.5	73.5	205.8	205.8	
	kgf/mm <sup>2</sup>	7.6	7.5	7.5	21.0	21.0	
Tensile Strength	MPa		37.2	37.2	274.4	274.4	441-490
	kgf/mm <sup>2</sup>		3.8	3.8	28.0	28.0	45-50
Thermal Expansion Coefficient (In direction of easy magnetization axis)	×10 <sup>-6</sup> /K	12.6	11.5-11.6	11.5	11.0	11.0	14.0
Hardness RC		45	50-54	50	58	58	(HV=450-500)
Required Field Strength for Saturation Magnetizing	kA/m	200	240	280	640	640	240
	Oe	2,500	3,000	3,500	8,000	8,000	3,000
Electrical Resistivity	nΩ·m	750	470	470	600-620	600	620

### Raw Materials of Ferrite Magnets

Let's review on the manufacturing processes of the main raw material, iron oxide and other auxiliary raw materials.

At the cold rolling plant in an iron works, the surface of the rolled steel sheet is washed and cleaned with hydrochloric acid to dissolve and remove the surface layer, the iron oxide. Ferrite magnet production begins with this green liquid of iron chloride.

In a chemical plant, this green liquid is roasted to be decomposed for the iron oxide powders to be collected, and such another decomposed product as chlorine gas is also collected in water to turn into hydrochloric acid for re-use in the acid cleaning process. The less impurities exist in the raw materials, the higher quality ferrite magnets can be manufactured. Therefore, to obtain a high purity iron oxide, the collected iron oxide powders are roasted at  $600 \sim 700^{\circ}\text{C}$  in a rotary kiln called a "roasting kiln" to further remove chlorine impurity, and after that, are washed with water to remove the chlorine and other

impurities.

In the manufacture of ferrite magnets, auxiliary raw materials such as strontium carbonate and barium carbonate are used besides iron oxide. These carbonates are produced by a highly productive process of direct carbonation of mined ores.

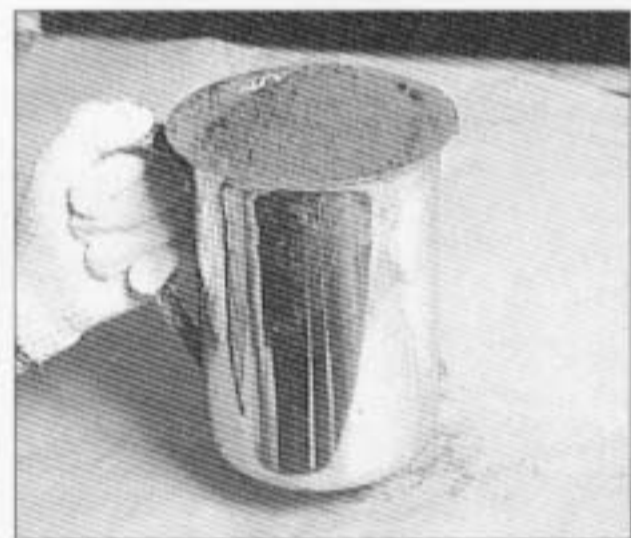
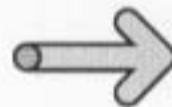
### Manufacturing Process of Ferrite Magnets

First, the raw materials are precisely weighed, followed by mixing. The mixing is an important process enabling the chemical reaction to proceed easily by bringing the different raw material particles in close contact, of which there are two processes, dry mixing and wet mixing. Generally, the products produced by wet mixing have a more homogeneous quality than the ones produced by dry mixing.

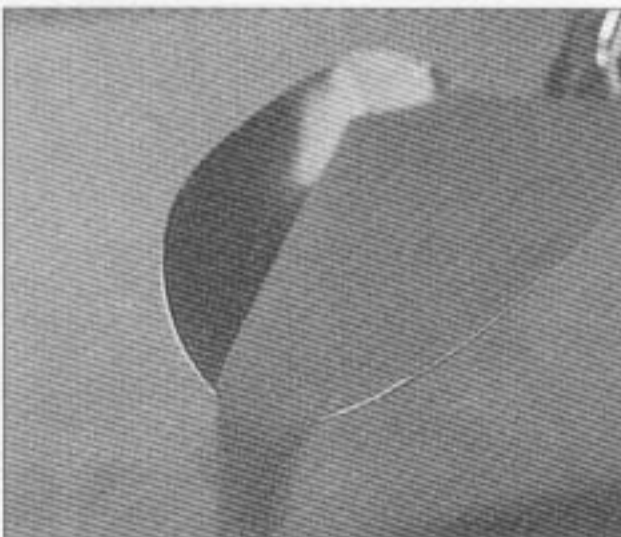
The mixed raw materials are then calcined. As mentioned later, there are two kinds of ferrite magnets, isotropic and anisotropic magnet. In case of isotropic magnet, the functions of calcination are to let the ferrite



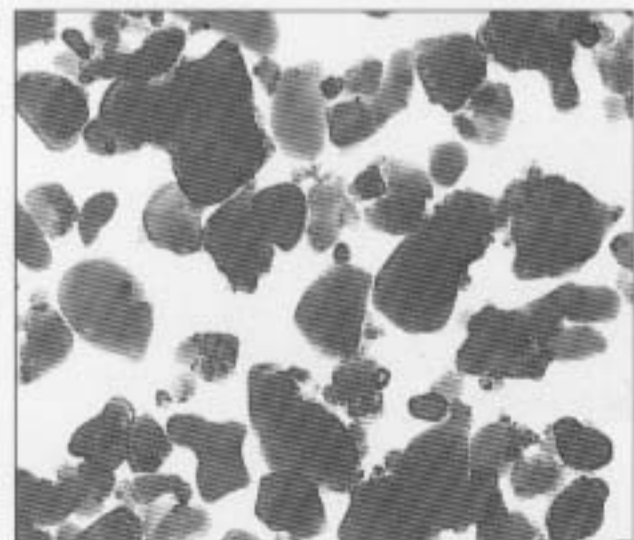
① Hydrochloric acid solution containing iron



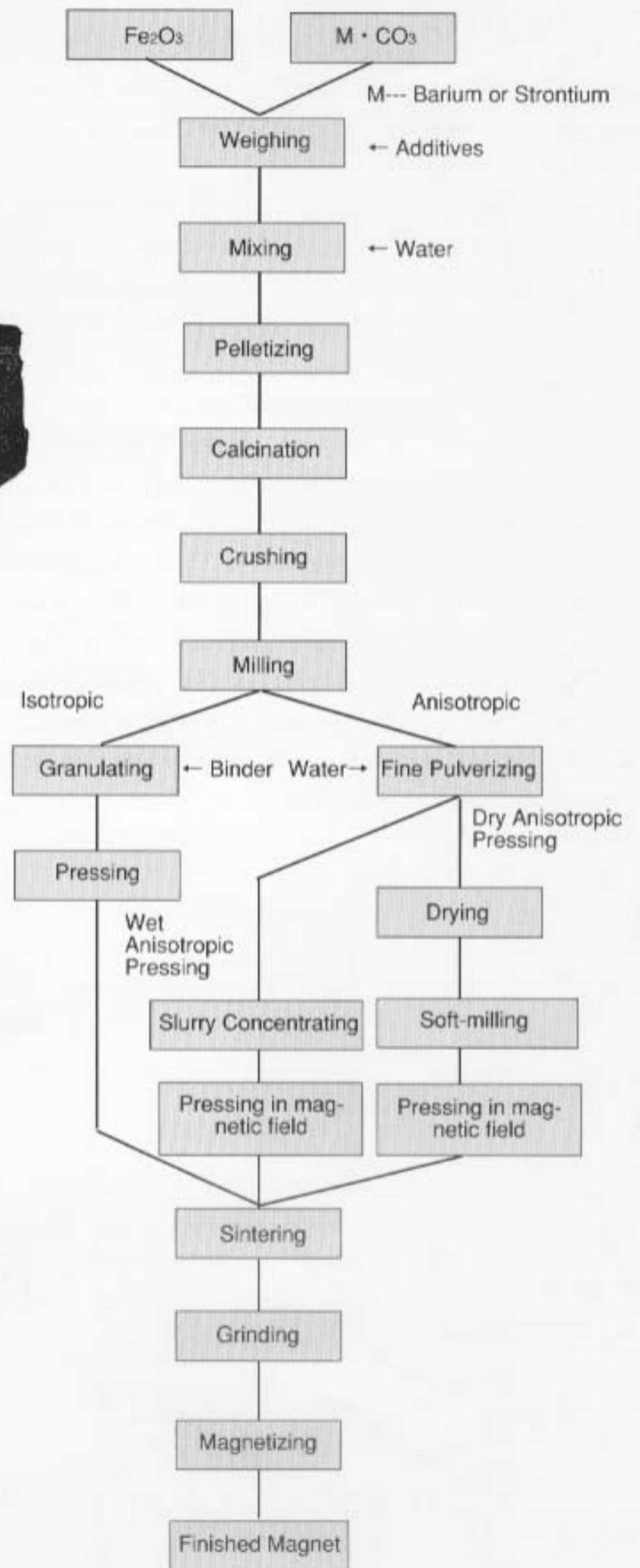
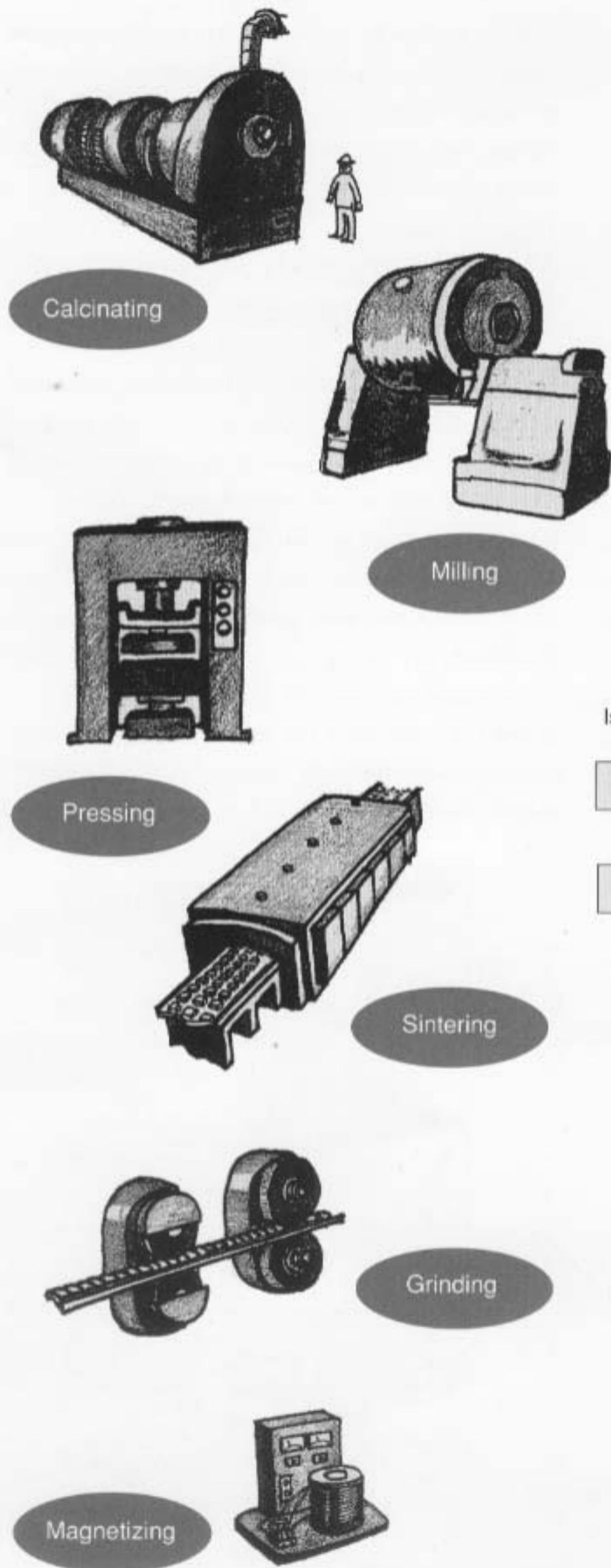
② Iron oxide collected after roasting



③ Granulated raw materials



④ Magnified picture of the granulated raw material



Manufacturing Process of Ferrite Magnets



formation reaction proceed to a certain extent, making it easy to control shrinkage in the later sintering process, and to decompose and degas the auxiliary raw materials that can generate gas during the sintering process. The mixed raw materials for isotropic magnet, therefore, are calcined at comparatively low temperature of  $1,000 \sim 1,100^{\circ}\text{C}$ . On the other hand, in case of anisotropic magnet, the function of calcination is to let the ferrite formation reaction proceed perfectly, making it easy to orient each pulverized particle to the same direction by external magnetic field in the later pressing process. The mixed raw materials for anisotropic magnet, therefore, are calcined at high temperature of  $1,250 \sim 1,300^{\circ}\text{C}$ .

The calcined products change into hard pellets, which are crushed and pulverized. For isotropic magnet, calcined powders are milled to around several micron by dry milling. The surface areas of the powder, enlarged due to having been milled into fine particles, improves the reactivity and sintering behaviors. For anisotropic magnet, calcined powders are pulverized to sub-micron order by wet pulverizing after dry milling to around several micron, until each particle becomes a single crystal.

Ferrite magnets are classified into two groups according to their manufacturing process. The first group is isotropic magnets. Since the milled powders are too fine to be fed into a die, they are formed into  $0.1 \sim 0.5$  mm sized granules with binder and lubricant added. This is called the granulation process. Thereafter, the granulated particles are fed into a die to be pressed under high pressure to become a green product having a desired shape, which is then sintered in a sintering furnace.

Ferrite magnet belongs to a hexagonal crystal system that has an easy magnetization axis along c-axis. When ferrite magnets are produced by above-mentioned process, the grains' axes of easy magnetization are spatially randomized in the product, which is called an isotropic magnet.

The second group is anisotropic magnets, which are stronger magnets utilizing magnetocrystalline anisotropy, enable ferrite permanent magnets several times stronger than isotropic magnets to be manufactured.

There are two methods for manufacturing anisotropic ferrite magnets, wet and dry processes. Compacting a slurry of fine-pulverized powders mixed with water in a magnetic field is the wet process, while compacting dry

powders in a magnetic field is the dry process. The industrial choice between the wet and dry processes is made according to the kind of product, its applications, cost and so on.

In the case of the wet process for anisotropic ferrite magnets, fine particles in the slurry state are poured into a die and the directions of easy magnetization of the particles become oriented in a magnetic field applied while being pressed.

Although the flotation of the particles in the water facilitates the rotation and orientation of them, dewatering takes longer time.

In the case of the dry process, the powder materials, after they have been pulverized in water and dried, are also pressed in an applied magnetic field. As the dried particles have a large frictional resistance, it is difficult to orient the particles to the same extent as in the wet process. However, the dry powder process increases pressing efficiency.

The green products thus pressed in a magnetic field are sintered in a sintering furnace to give them their excellent magnetic properties.

After finish grinding, it is permanently magnetized by applying a strong magnetic field, which is called the magnetization process.

## Merits of Ferrite Magnets

Ferrite magnets are the most excellent compared to all other type magnets in terms of cost performance.

Their chemically stable oxide composition assures their rust-free advantage. There is another merit that their main raw material, iron oxide, is a byproduct from iron-works.

These ferrite magnets have kept playing a leading role in the industry for forty years since their appearance in the market, in terms of both production volume and amount.

The leading role was taken over by rare earth magnets in 1993 in terms of production amount. However, ferrite magnets are the popular choice, serving all kinds of applications in all market sectors, are still No. 1 today in terms of production volume.

# Ferrite Magnets

## Magnetic, Physical & Mechanical Properties of Ferrite Magnets (Typical Examples)

Upper line: unit in SI Lower line: unit in C.G.S.

Item		Unit	Dry Isotropic	Dry Anisotropic	Wet Anisotropic
Composition			BaO · 6Fe <sub>2</sub> O <sub>3</sub>	SrO · 6Fe <sub>2</sub> O <sub>3</sub>	SrO · 6Fe <sub>2</sub> O <sub>3</sub>
Pressing Method			Dry Pressing	Dry Pressing in Magnetic Field	Wet Pressing in Magnetic Field
Remanent Flux Density Br		mT	200 ~ 235	360 ~ 390	410 ~ 430
		kG	2 ~ 2.35	3.6 ~ 3.9	4.1 ~ 4.3
Coercive Force H <sub>cb</sub>		kA/m	143 ~ 159	223 ~ 247	251 ~ 275
		Oe	1,800 ~ 2,000	2,800 ~ 3,100	3,150 ~ 3,450
Coercive Force H <sub>cj</sub>		kA/m	239 ~ 279	223 ~ 255	255 ~ 279
		Oe	3,000 ~ 3,500	2,800 ~ 3,200	3,200 ~ 3,500
Maximum Energy Product (BH) <sub>max</sub>		kJ/m <sup>3</sup>	7.2 ~ 9.6	23 ~ 27.8	32.6 ~ 35.8
		MGOe	0.9 ~ 1.2	2.9 ~ 3.5	4.1 ~ 4.5
Temperature Coefficient	Br	%/K	-0.18	-0.18	-0.18
	H <sub>cj</sub>	%/K	0.22	0.27 ~ 0.42	0.27 ~ 0.42
Curie Temperature T <sub>c</sub>		K	723	733	733
		°C	450	460	460
Recoil Relative Permeability μ <sub>rec</sub>			1.1 ~ 1.2	1.1 ~ 1.2	1.05 ~ 1.1
Density		g/cm <sup>3</sup>	4.6 ~ 4.9	4.8 ~ 4.9	4.9 ~ 5.0
Flexure Strength		MPa	29 ~ 68	49 ~ 88	49 ~ 88
		kgf/mm <sup>2</sup>	3 ~ 7	5 ~ 9	5 ~ 9
Compression Strength		MPa	> 686	> 686	> 686
		kgf/mm <sup>2</sup>	> 70	> 70	> 70
Tensile Strength		MPa	19 ~ 49	19 ~ 49	19 ~ 49
		kgf/mm <sup>2</sup>	2 ~ 5	2 ~ 5	2 ~ 5
Specific Heat		J/(kg · K)	0.84 × 10 <sup>3</sup>	0.84 × 10 <sup>3</sup>	0.84 × 10 <sup>3</sup>
		cal/g · °C	0.2	0.2	0.2
Thermal Expansion Coefficient	Parallel to easy magnetization axis	ppm/K	/	15	15
	Perpendicular to easy magnetization direction axis			9	10

### What are Rare Earth Magnets ?

Since rare earth magnets can store far higher energy per unit volume than other types of magnets, they have been able to ride the today's trend for lightweight, thin, small devices and equipment, and have found wide applications in the advanced technology markets. Today, rare earth magnets have become indispensable for high-tech products.

"Rare Earth" magnets are named after the group of rare earth elements including samarium and neodymium, and are represented by samarium-cobalt magnet and neodymium-iron-boron magnet, which are described below.

### Samarium-Cobalt Magnets

As described in the "History of Magnets," after around 1960 research on the magnetic properties of inter-metallic compounds of rare earth elements and cobalt became more and more active, and in 1967, the intermetallic compound of 1 samarium vs. 5 cobalt was found to be an excellent magnet material in the US. This was the historical start of SmCo<sub>5</sub> based magnets, from which the rare earth magnets can be said to have begun expanding in the permanent magnet market.

Through the improvements and developments that followed thereafter, a new magnet material, 2 samarium vs. 17 cobalt based magnets having magnetic properties superior to those of 1 Sm vs. 5 Co, was commercialized. The new Sm<sub>2</sub>Co<sub>17</sub> has today become the leading magnet material in the Sm-Co magnet market due to its high performance.

### Neodymium-Iron-Boron Magnets

The price of samarium and cobalt, the raw materials from which the magnets are made is high because of the low mining quantities and unstable supply due to disputes between the producing countries.

As a substitute for this magnet, the neodymium-iron-boron magnet was invented in 1982, which is said to be the strongest ever permanent magnet. While the Sm-Co

magnet is a binary alloy consisting of Sm and Co, the neodymium-iron-boron magnet uses a ternary alloy consisting of neodymium, iron and boron, which has the highest maximum energy product among the various magnets. Owing to its comparatively low price, application of this Nd-Fe-B magnet in various electronic equipment and devices is soaring and it accounts for almost the entire increase in rare earth magnet production.

### Manufacturing Process of Rare Earth Magnets

The manufacturing process of rare earth magnets is a powder metallurgical sintering process similar to that of ferrite magnet, excepting that anti-oxidation measures are required in all the stages of the manufacturing process as the Nd-Fe-B raw materials and magnets are very apt to oxidize.

#### (1) Manufacturing Process of Samarium-Cobalt Magnets

There are two different processes for the manufacture of SmCo<sub>5</sub> magnets, the "Reduction Diffusion Process" and the "Melting Process." As the latter process is common to both SmCo<sub>5</sub> and Sm<sub>2</sub>Co<sub>17</sub>, the melting process is described below.

The raw materials are precisely weighed in pre-determined composition, and melted in a high frequency induction furnace filled with argon gas. Then the molten material is cast into a mold cooled with water to obtain an ingot having the pre-determined composition. The ingot is then crushed and pulverized. The powder is then pressed in a magnetic field for orienting the c-axis of the particles to have anisotropy in the magnet.

Next the pressed material is put into the sintering furnace and sintered at 1,100 ~ 1,250°C, then solution treated at 1,100 ~ 1,200°C, and finally applied temper treatment at 700 ~ 900°C. After this series of heat treatments, a samarium-cobalt magnet is born. This sintered magnet is ground precisely to the predetermined size to become a final product.

#### (2) Manufacturing Process of Neodymium-Iron-Boron Magnets

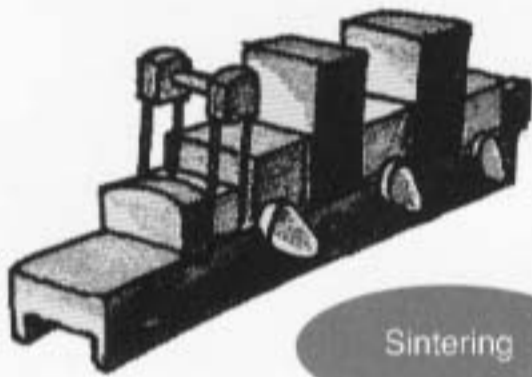
The manufacturing process of Nd-Fe-B magnets is



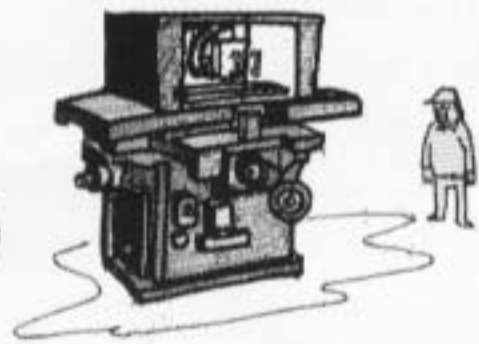
Crushing



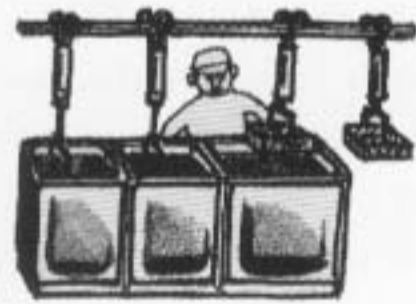
Pressing



Sintering



Grinding



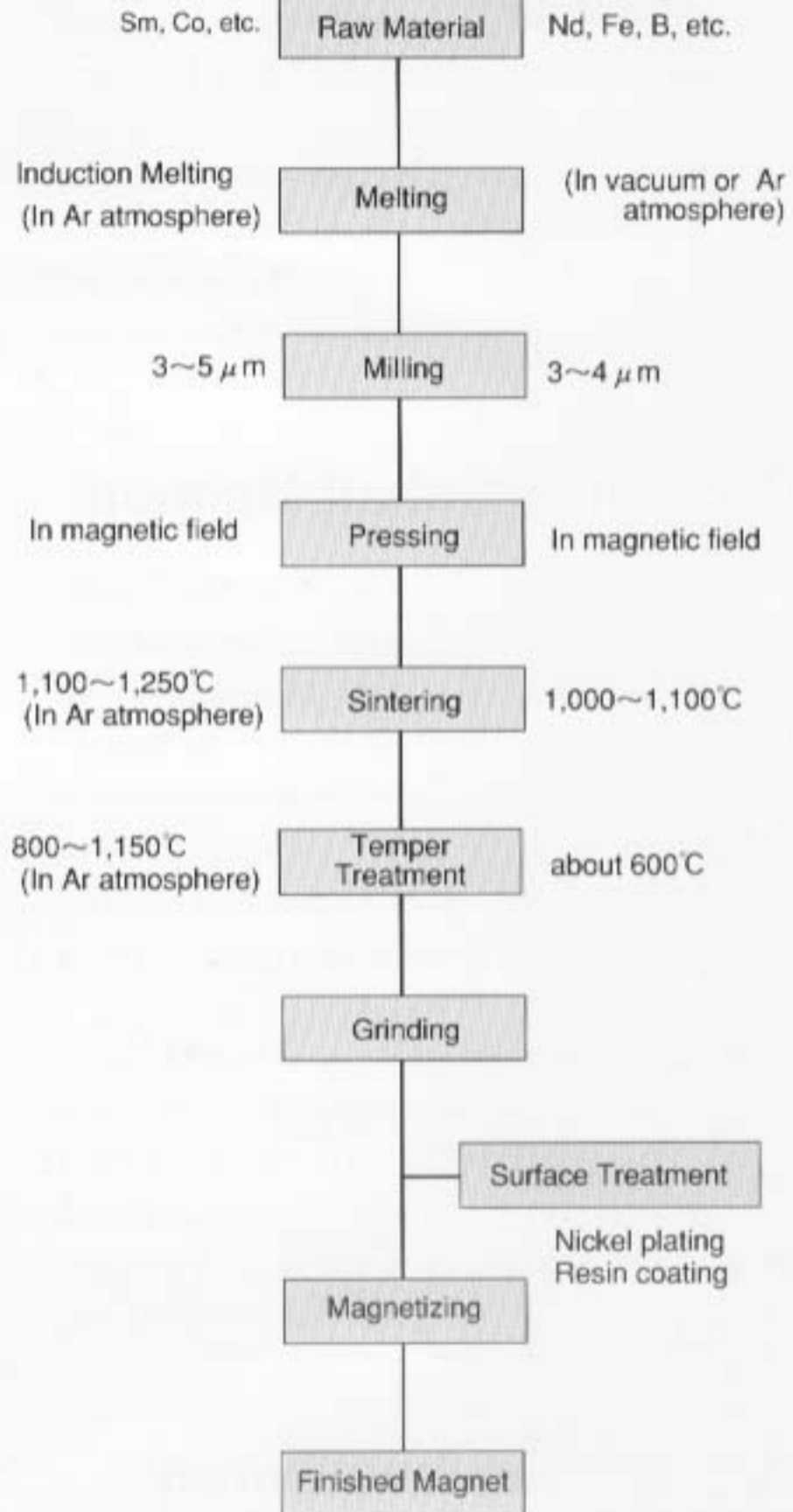
Surface Treatment



Magnetizing

Samarium-Cobalt Magnet

Neodymium-Iron-Boron Magnet



Manufacturing Process of Rare Earth Magnets