Industrial Furnaces for Magnets for Vehicle Motors

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Magnets are produced by means of many processes, such as the alloy production process, hydrogen embrittlement process, sintering process, and grain boundary diffusion process. To produce the high-performance magnets required for use in vehicle motors, ULVAC provides an appropriate furnace for each process. The "Magcaster-600" is a melting furnace for the alloy production process for producing magnets with good grinding characteristics. The "FHH series" includes hydrogen furnaces for the hydrogen embrittlement process without exposure to the air. The "FSC series" provides inline-type heat treatment furnaces for the sintering and aging processes. The "Magrise series" features heat treatment furnaces for the grain boundary diffusion process used to defuse heavy rare metals into neodymium. This article introduces the features of the line of furnaces manufactured by ULVAC for the production of magnets for installation in vehicle motors.

1. Introduction

Since people first began using automobiles, a wide variety of technologies have been developed. As these technologies advanced, motors began to be used in various parts of automobiles.

Motors are especially important in hybrid vehicles and all-electric vehicles, which use motors to provide motive power.

One of the parts essential to motors is the permanent magnet. Because an alloy consisting of neodymium (Nd), iron (Fe), and boron (B) is its main component, this magnet is generally called a neodymium magnet and is considered the most powerful among permanent magnets.

Because neodymium magnets are powerful, they are extremely useful when it is necessary to reduce the size, thickness, and weight of devices that require permanent magnets, and therefore are widely used. However, a weak point of neodymium magnets is the fact that their magnetic force weakens at high temperatures. This phenomenon in which a neodymium magnet loses its magnetic force (magnetic characteristics) at high temperatures is called heat-induced demagnetization. This phenomenon typically occurs in neodymium magnets when their temperature rises to several hundred degrees.

When a neodymium magnet is incorporated into a motor used in an automobile, it is being used in a high-temperature environment. Consequently, the magnet cannot be used as is because of the heat-induced demagnetization phenomenon mentioned above. To solve this problem, many innovative steps have been taken in developing industrial furnaces to be used for manufacturing on-board motors.

This paper introduces the characteristics of industrial furnaces to be used for manufacturing magnets, which ULVAC has already delivered to neodymium magnet manufacturers.

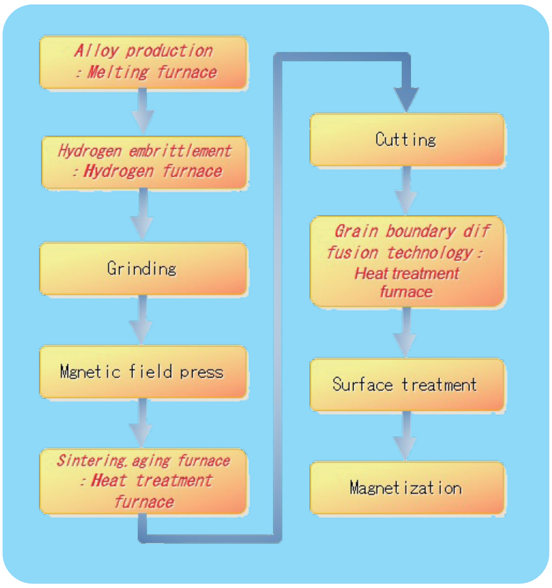

Fig. 1 Manufacturing processes for neodymium magnets

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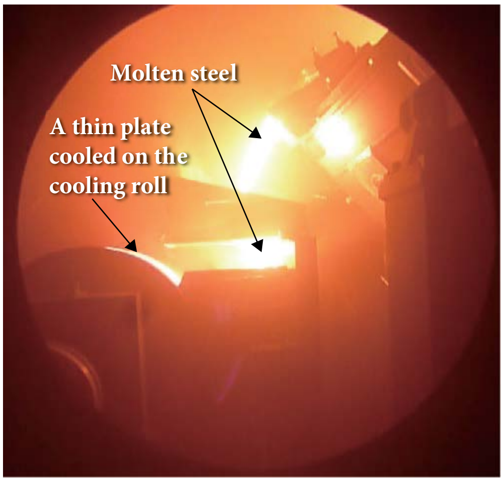

Fig. 2 Molten steel and cooling roll in a melting furnace

2. Neodymium Magnet Manufacturing Process

Figure 1 shows some of the representative steps constituting an ordinary neodymium magnet manufacturing process.

The processes handled by furnaces being manufactured and sold by ULVAC include the alloy manufacturing process, hydrogen embrittlement process, sintering/aging process, and grain boundary diffusion process, which are shown in red letters in the figure. First, an overview of each process will be provided.

2.1 Alloy manufacturing process

The various materials necessary for making neodymium magnets are first adjusted to their desired weights, and then they are fed into the crucible of the melting furnace. Once it is confirmed that all the materials have melted and reached the specified temperature, the molten metal is poured onto a copper rotating body whose interior is cooled with water, referred to as a water-cooled copper roll. Molten metal that comes into contact with the water-cooled copper roll cools instantly, forming a layer of around 300 µm in thickness (hereafter referred to as a "ribbon"). An attachment inside the melting furnace then breaks the ribbon into flakes.

2.2 Hydrogen embrittlement process

A hydro treating furnace is used to store hydrogen in the flakes manufactured in the aforementioned alloy manufacturing process. Afterwards, the flakes that have stored hydrogen are heated to release the hydrogen, and then they are coarsely milled. This process is carried out in order to improve their millability for subsequent fine-milling.

2.3 Milling process

Powders manufactured in the hydrogen embrittlement process that possess poor granularity distribution are further milled in a machine such as a jet mill, producing fine powders with a uniform granularity distribution and an average grain diameter of several microns. Because there is an increase in the surface area of the material during this process, nitriding and oxidizing tend to increase as milling time lengthens, adversely affecting the final characteristics of the product. Therefore, it is extremely important to optimize the conditions for the hydrogen embrittlement process and for milling.

2.4 Magnetic field pressing process

Fine powders manufactured in the milling process are placed in a mold and press-molded in a magnetic field. This process aligns the crystal orientation of powders with an average grain diameter of several microns, resulting in anisotropic orientation and improving the characteristics of the magnets following magnetization.

2.5 Sintering and aging processes

Heating and sintering the powders formed in a magnetic field pressing process changes them into a single solid, typically shaped magnet. An aging process is then applied to adjust the composition of the metal.

2.6 Machining process

A solid formed from the powders in the sintering and aging processes is machined into the shape of the final product.

2.7 Grain boundary diffusion process

Using heavy rare-earth elements such as dysprosium (Dy) and terbium (Tb), a grain boundary diffusion process is applied to magnets that have been shaped into the product's shape in the machining process. By diffusing rare-earth elements into the grain boundary layer of the magnets, this process improves the heat resistance (≒ coercivity) of the neodymium magnets.

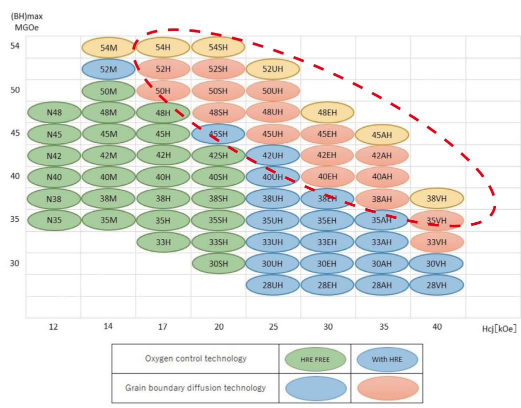

Fig. 3 Table of standards for neodymium magnets

2.8 Surface treatment

Because neodymium magnets react easily, they tend to rust if their surface has not been treated. Therefore, a process such as plating is usually applied.

2.9 Magnetization process

Before a neodymium magnet undergoes the magnetization process, it possesses hardly any magnetic force. After undergoing the processing called “magnetization,” in which the neodymium magnet material is placed inside a strong magnetic field and processed, the material gains magnetic force, becoming a neodymium magnet.

Figure 3 shows a table of specifications for neodymium magnets. The range of specifications of the magnets that are being manufactured using ULVAC’s furnace is indicated by the red broken-line circle. Magnets with specifications providing both a high magnetic flux density and coercivity are being manufactured.

3. ULVAC Furnaces Used for Manufacturing Neodymium Magnets and Their Features

3.1 Magcaster-600 (alloy manufacturing process)

3.1.1 Characteristics of the Magcaster-600

ULVAC developed the Magcaster-600 in FY2013 as a melting furnace for manufacturing neodymium magnet alloys. In manufacturing alloys for neodymium magnets, a water-cooled roll is usually used. However, the surface of the water-cooled roll must be polished for each batch, and a part called a “tundish” for pouring molten metal onto the water-cooled roll must also be cleaned. With the FMI-II-500R, a predecessor to the Magcaster-600 melting furnace, after each batch of metals had been melted, the interior of the furnace had to be cooled and the melting chamber had to be opened to the atmosphere. Then, maintenance had to be performed on the water-cooled roll and the tundish had to be installed in the melting chamber before the next batch could be melted, making production inefficient. To solve this problem, the Magcaster-600 is equipped with a load lock chamber, and the water-cooled roll and tundish have been designed to be movable into the load lock chamber. As a result, maintenance of the water-cooled roll and the tundish can now be performed inside the load lock chamber in parallel with evacuation of the melting chamber in preparation for the next batch, without having to cool down the interior of the furnace or open it to the atmosphere. This improvement increased the volume of alloy manufactured per year from approximately 1,300 tons to approximately 2,000 tons.

After mixing and melting several types of metals, which are then formed into ribbons after being cooled by the water-cooled roll, the Magcaster-600 performs several more processes. One of these processes involves standardization of the thermal history of the individual ribbons. When ribbons are formed and collected into a collection vessel, their temperature is approximately 700 degrees, but parts of the composition within the ribbons may not have solidified completely at this point. It is known that controlling the amount of time during which this unsolidified state lasts changes the composition within the ribbon, which is one of the factors that determines the magnetic performance and the yield.

For this reason, a water-cooled drum mechanism has been added to the Magcaster-600. This mechanism has an internal structure similar to that of a concrete mixer truck. When ribbons that have been cooled down to approximately 700 degrees are fed into the water-cooled drum mechanism, the ribbons are mixed and cooled by the rotation of the water-cooled drum. In a conventional cooling method, the ribbons are collected into a water-cooled collection vessel to be cooled. However, this method results in uneven cooling because the ribbons contacting the cooling surface cool more quickly while others cool more slowly.

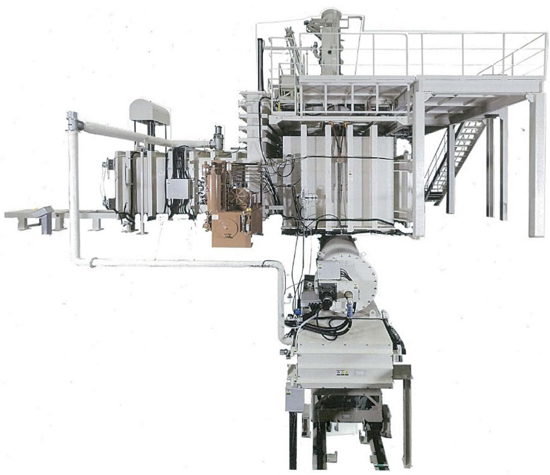

Fig. 4 ULVAC’s “Magcaster-600” melting furnace

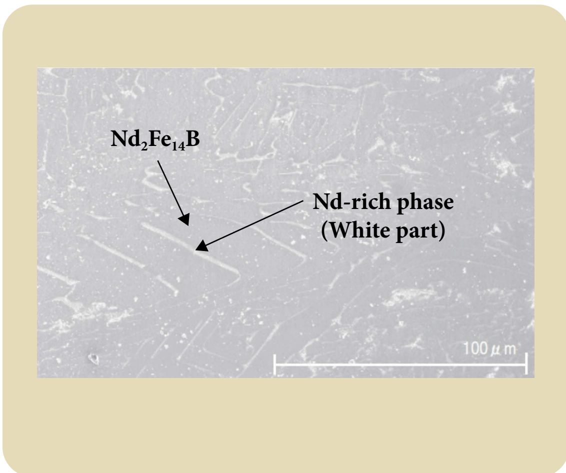

Fig. 5 SEM image of slowly cooled ribbons

Introduction of a water-cooled drum mechanism tends to cool the ribbons more evenly, reducing the variability in the thermal history of the individual ribbons.

3.1.2 Differences in the ribbon structures resulting from different cooling methods

The composition of the ribbons for neodymium magnets includes two principal phases. One consists primarily of iron, called the primary phase ($Nd_2Fe_{14}B$), and the other consists primarily of neodymium, called the Nd-rich phase.

The composition arrangement of the primary and Nd-rich phases is determined to some extent by when the ribbons separate from the water-cooled roll. However, at the point of separation, the Nd-rich phase will not have solidified completely, and it is known that using a mechanism such as a water-cooled drum to standardize and control the time during which the Nd-rich phase has not become fully solidified creates the composition arrangement of the primary and Nd-rich phases according to that time.

Figures 5, 6, and 7 show scanning electron microscopy images of three types of ribbons, with differing cooling times following separation from the water-cooled roll.

Figure 5 shows the composition arrangement that can be observed when the ribbons are cooled gradually following separation from the water-cooled roll. The Nd-rich phases are rounded and cut into granular shapes.

Figure 6 shows the composition arrangement that can be observed when the ribbons are cooled rapidly following separation from the water-cooled roll. This composition arrangement is notable in that the individual Nd-rich phases are crisp and separated into branches.

Figure 7 shows the composition arrangement of the ribbons that can be observed when they are first maintained at around the temperature following separation from the water-cooled roll and then cooled rapidly. This composition arrangement is in the middle between the ribbon composition following rapid cooling and the ribbon composition following gradual cooling. This is because, when the ribbons separate from the water-cooled roll, the primary phase has solidified but the Nd-rich phase has not. Maintaining this state reduces the volume of the Nd-rich phase and increases its concentration.

Because the composition arrangement of these ribbons varies depending on the cooling process inside the melting furnace, the effects this variation will have on later processes will also vary. Currently, composition arrangement such as that shown in Figure 7 is required for manufacturing high-performance neodymium magnets. This is because when the Nd concentration in the Nd-rich phase increases, the amount of hydrogen that can be stored in the ribbons in the subsequent hydrogen embrittlement process also increases. An increase in the amount of hydrogen that can be stored promotes embrittlement of the ribbons, as a result improving the millability. When the millability improves, the grain diameters of the powders that have been milled down to several μm tend to become more uniform. Although densification occurs during the subsequent sintering process, reducing the volume of magnets, the variability in the reduction becomes smaller, thereby improving the yield in the machining process. Additionally, improvement in the millability shortens the time required for the milling process. Milling changes the ribbons, which are several hundred μm thick, into powders of several μm, increasing their surface areas by a large factor. If the powders react with the oxygen and nitrogen existing inside the jet mill during this milling process, the coercivity will be reduced. However, improving the millability reduces the time required for obtaining the desired grain diameter inside the jet mill, thus reducing the rate of reaction with oxygen and nitrogen and improving the coercivity of the neodymium magnets that constitute the final product.

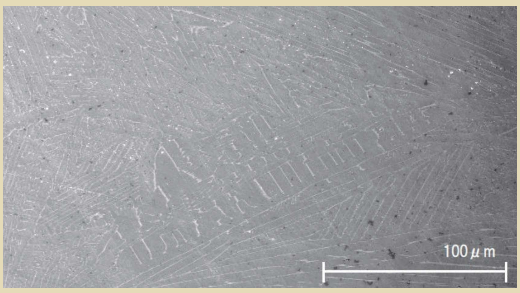

Fig. 6 SEM image of rapidly cooled ribbons

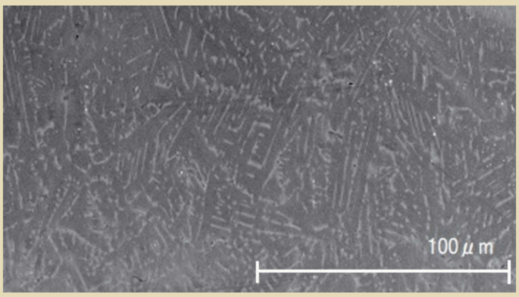

Fig. 7 SEM image of ideally cooled ribbons

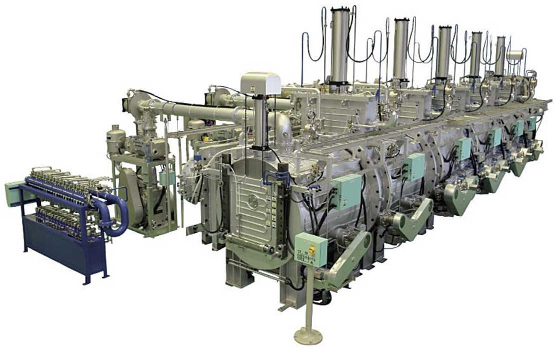

Fig. 8 ULVAC hydrogen furnace “FHH series”

3.2 FHH series for hydrogen processing (hydrogen embrittlement process)

3.2.1 Characteristics of the FHH series for hydrogen processing

ULVAC is manufacturing the FHH series for performing hydrogen embrittlement of ribbons for neodymium magnets. The purpose of this system is to use a hydrogen process to embrittle the flakes manufactured using the aforementioned Magcaster-600. This is an important process that determines the millability in a subsequent milling process.

One of the distinguishing characteristics of the FHH series is its structure, which can pressurize hydrogen up to 290 kPa·abs by pressurizing and sealing the space between the gasket of the loading door that isolates the hydrogen-processing chamber from the atmosphere outside the furnace and the gasket groove, during transport of the work material into the hydrogen-processing chamber. Processing the ribbons inside a space pressurized with hydrogen improves their hydrogen storage efficiency compared to processing inside a non-pressurized space, resulting in enhanced millability. As explained above, this leads to improvements in the efficiency of subsequent processes, the yield, and the coercivity of the neodymium magnets.

Furthermore, one of the characteristics of the FHH series for hydrogen processing that is important in terms of processing is the fact that it is capable of carrying out the entire process from hydrogen embrittlement to product collection without allowing the material to come into contact with the atmosphere.

This system consists of a furnace capable of carrying out a series of operations from hydrogen processing, thermal dehydration, and cooling to collection, without allowing the work material to be in contact with the atmosphere. In this way, the system is able to reduce the oxidation-caused reduction in coercivity.

Another distinguishing characteristic of the FHH series for hydrogen processing is safety. Systems for use in the hydrogen embrittlement process must always use hydrogen. Using hydrogen is always accompanied by the risk of explosion. For this reason, ULVAC’s FHH series for hydrogen processing is equipped with several safety functions.

One of the safety improvement functions is the automatic leak check function. After the work material is transported into the hydrogen-processing chamber and the loading door is closed, the chamber is pressurized with Ar gas and a leak check is performed. Afterwards, even after evacuation has occurred, a pressure rise check is performed on the reduced-pressure side to double-check for hydrogen leaks.

The next safety improvement function is the dual gaskets on the loading door. Ambient air is present on the outside of the loading door used for transporting the work material into the hydrogen-processing chamber. Consequently, any leak caused by deterioration of the gasket at the loading door or foreign matter trapped in the door, etc., could lead to the possibility of an explosion. Therefore, in addition to the typical door gasket, another gasket is installed on the outer side, creating a dual-gasket structure. Pressurizing the space between the two gaskets with Ar gas also reduces the risk of oxygen infiltration from the atmosphere side.

Furthermore, to handle the unlikely possibility of a hydrogen leak into the surrounding atmosphere, standard features include a hydrogen-capturing hood installed above the loading door, together with a control system that detects hydrogen to ensure safe operation.

3.3 FSC series (for the sintering process)

3.3.1 Characteristics of the FSC series for sintering

ULVAC is manufacturing the FSC series for sintering pressurized powders for neodymium magnets. One of the characteristics of this system is that, unlike a batch furnace, it does not result in system-caused individual differences. A single FSC series is a continuous furnace, equivalent to the multiple batch furnaces that would otherwise be required to achieve the same level of productivity. Furthermore, batch furnaces always have individual differences among them, even when manufactured to the same specifications. For this reason, an FSC series of continuous furnaces is far superior in its capability to manufacture magnets of uniform quality.

Additionally, because the FSC series heat treatment furnace for sintering is divided into chambers for debinding, degassing, sintering, and cooling, the probability that contamination by a binding material, etc., will reach another chamber is greatly reduced compared to that of a batch furnace, and the frequency at which consumables must be replaced is also low.

3.3.2 Future of the FSC series for sintering

Important considerations during the process of sintering neodymium magnets include the capability to keep the actual temperature of the material as close as possible to the target uniform temperature, and minimization of the differences in the thermal history of individual work materials during heating. To address these requirements, ULVAC has been developing a new sintering furnace in order to achieve heating uniformity and to reduce thermal history differences.

3.4 Magrise series for grain boundary diffusion

Normally, heat resistance is required of magnets that are to be installed in automobiles.

It is known that a magnet with low heat resistance loses some of its magnetic flux density, an index of the magnet's strength, when its temperature rises. One method developed to solve this problem is the use of dysprosium (Dy) and terbium (Tb) to improve coercivity. During the manufacture of an alloy, this method (called the single-alloy method) mixes heavy rare-earth elements such as dysprosium (Dy) and terbium (Tb) into the molten material to manufacture ribbons, and afterwards applies hydrogen embrittlement and milling processes to manufacture magnets. However, magnets manufactured with this method still have a problem of reduced magnetic flux density, even though their heat resistance improves. To solve this problem, a method called the "dual-alloy method" was invented, which efficiently positions heavy rare-earth elements along the crystal surfaces that need them. By now, a manufacturing method called "grain boundary diffusion" has become known, which positions heavy rare-earth elements on the crystal surface more efficiently than the dual-alloy method. This method heats a neodymium magnet together with heavy rare-earth elements to diffuse the latter into the grain boundary layers of the neodymium magnets. Magnets treated with the grain boundary diffusion method demonstrate the benefit of a reduction in the decline of their magnetic flux density, together with the improved coercivity possible with the aforementioned method.

ULVAC is manufacturing the Magrise series for performing grain boundary diffusion. This system heats a neodymium magnet and a heavy rare-earth element such as dysprosium together in a dedicated vessel. By heating and evaporating the heavy rare-earth element, the system diffuses the heavy rare-earth element into the grain boundary layers of the neodymium magnet.

4. Conclusion

This paper has introduced the characteristics of ULVAC's industrial furnaces for magnets to be used in automobiles. The market is demanding magnets of ever higher performance, as well as furnaces with new functions for manufacturing such magnets. We will continue contributing to magnet manufacturing by providing equipment that best suits the market needs.