ACTA TECHNICA CORVINIENSIS – Bulletin of Engineering | e–ISSN: 2067 – 3809
Tome XVIII [2025] | Fascicule 1 [January – March]

[1.] Dragos–Dumitru CORNEA, [2.] Imre KISS

THE PRODUCTION OF PERMANENT MAGNETS: THE IMPORTANCE OF SMELTING (ALLOY PREPARATION) IN Nd–Fe–B MAGNET MANUFACTURING BY POWDER METALLURGY

[1.] University Politehnica Timisoara, Faculty of Engineering Hunedoara, Hunedoara, ROMANIA
[1.] University Politehnica Timisoara, Faculty of Engineering Hunedoara, Departmenent of Engineering & Management, Hunedoara, ROMANIA

Abstract: Electric vehicles have quickly gained in popularity due to their lower environmental impact and operating costs, and Neodymium magnets play an integral part in turning electrical energy into mechanical energy that powers these cars. Neodymium Magnets (or Neodymium–iron–boron alloy magnets) are one of the strongest types of permanent magnets. It is made up of an alloy made of Neodymium–iron and Boron elements. With the recent technological developments in metallurgy, powder metallurgy has become the essential process for the production of permanent magnets. Particularly, the manufacturing of Nd–Fe–B (neodymium–iron–boron) magnets by powder metallurgy involves several precise and controlled steps to produce high–performance permanent magnets widely used in electric vehicles and other advanced technologies. This powder metallurgy process enables the production of Nd–Fe–B magnets with high magnetic strength, thermal stability, and precise shapes, making them ideal for use in electric vehicle. The smelting stage of the process is indispensable in the manufacturing of sintered Nd–Fe–B permanent magnets by powder metallurgy. It is the very first step in the production process where the base elements—neodymium, iron, boron, and sometimes other additives—are melted in a smelting furnace.

Keywords: Neodymium–iron–boron alloy magnets, electric motor vehicles (EMVs), Nd–Fe–B magnets manufacturing, smelting steps

IMPORTANCE OF PERMANENT MAGNETS IN ELECTRIC VEHICLES

Electric motor vehicles (EMVs) have quickly gained in popularity as society moves toward sustainable transport solutions. Thanks to advanced technologies delivering impressive performance and efficiency. At the centre of this revolution is the permanent magnet technology, in general, and the neodymium magnet technology, in particular. Permanent magnets are critical components in the electric motors that power EVs. Their strong, stable magnetic fields enable:

- High Efficiency: Permanent magnet motors convert electrical energy to mechanical energy more efficiently than induction motors, improving vehicle range and performance.
- High Torque Density: These motors deliver more torque for a given size and weight, which is crucial for acceleration and hill–climbing.
- Compact Design: The strength of rare earth magnets allows for smaller, lighter motors, freeing up space and reducing vehicle weight.
- Reduced Heat Generation: Because they do not require external power to maintain their magnetic field, permanent magnets help motors run cooler and last longer.

Neodymium Magnets (or Neodymium–iron–boron alloy magnets) are among the strongest permanent magnets currently available and made up of an alloy composed of neodymium, iron and boron (Nd2Fe14B), making them suitable for applications including electric vehicle motors. It is used extensively across numerous applications such as electric motors, generators or wind turbines. Neodymium magnets are popularly utilized in electric motors for their ability to generate strong magnetic fields while remaining lightweight. Thus, making them suitable for electric vehicle usage that prioritizes fuel economy.

Neodymium Magnets are lightweight, which makes them suitable for electric vehicle batteries that weigh heavily, adding only minimal additional weight to their vehicles. This factor should also be taken into consideration as electric vehicle battery weight can add substantially. Also, Neodymium Magnets are corrosion resistant, meaning you don't have to replace them as frequently. This reduces maintenance costs while increasing electric motor reliability. And, finally but very important, electric motor vehicles rely on electric motors powered by magnets to generate rotational force. Neodymium magnets, among the strongest permanent magnets available today, are frequently employed in electric motors to power them. Therefore, Neodymium magnets' primary benefit lies in their exceptional power, which makes them indispensable in electric motors which must generate significant torque to power vehicles. Such strong magnetic forces also find uses in industrial settings like wind turbines. Overall, Neodymium magnets make for an outstanding selection for electric vehicle motors. Their strength, light weight, corrosion–resistance properties and efficiency makes them more efficient and reliable than other forms of magnets.

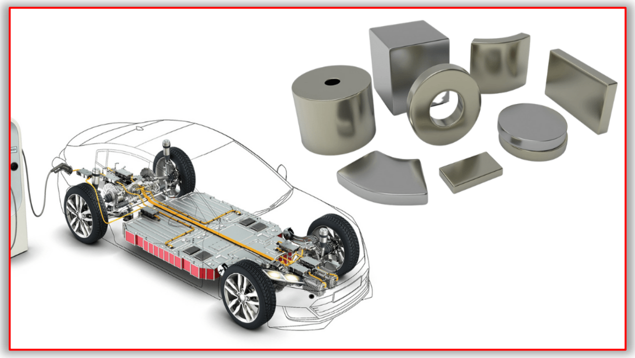

Figure 1. Nd–Fe–B (neodymium–iron–boron) magnets

Nd–Fe–B (neodymium–iron–boron) magnets are the preferred choice for electric vehicle motors due to their exceptional magnetic strength, efficiency, and compactness. They are integral to the design and performance of modern EV traction motors. Advantages driving their use

- High Magnetic Strength: Enables smaller, lighter, and more powerful motors and devices.
- Energy Efficiency: Permanent magnet motors using Nd–Fe–B magnets are more efficient than induction motors, contributing to energy savings.
- Thermal Stability: Certain grades withstand high operating temperatures, essential for automotive and industrial applications.
- Versatility: Available in various grades and shapes, suitable for a wide range of devices from tiny electronics to large industrial machinery.

The Nd–Fe–B magnets are preferred in EV motors, due to:

- High Magnetic Strength: Nd–Fe–B magnets generate a very strong magnetic field, enabling motors to produce high torque at low speeds, which translates to rapid acceleration and responsive driving performance.
- Energy Efficiency: The strong magnetic field reduces energy losses in the motor, improving overall efficiency and allowing EVs to travel longer distances on a single charge.
- Compact and Lightweight Motor Design: Their high power density allows for smaller, lighter motors, which contributes to reducing the vehicle's weight and improving space utilization.
- Low Noise and Vibration: Motors using Nd–Fe–B magnets operate smoothly with less vibration and noise, enhancing ride comfort and reducing noise pollution.
- Thermal Management: Although Nd–Fe–B magnets have a relatively lower Curie temperature compared to some other magnets, modern grades are engineered for improved thermal stability. Proper thermal management ensures sustained performance under the demanding conditions inside EV motors.

While Sm–Co magnets (Samarium Cobalt magnets) offer superior corrosion resistance and high–temperature stability (up to 350°C), they have lower magnetic strength and are more expensive than Nd–Fe–B magnets. Nd–Fe–B magnets remain the dominant choice for most EV motor applications due to their superior magnetic performance and cost–effectiveness.

PERMANENT MAGNETS PRODUCED BY POWDER METALLURGY

Powder metallurgy is one of the manufacturing techniques to produce precise and highly accurate parts. In powder metallurgy, the products are produced by pressing powdered metals and alloys into a rigid die under extreme pressure. With the recent technological developments in metallurgy, powder metallurgy has become the essential process for the production of permanent magnets.

Permanent magnets produced by powder metallurgy are fundamental to the efficiency, performance, and sustainability of electric vehicles. Their classification, properties, and manufacturing methods are central to advancing EV technology and meeting growing market demands.

Powder metallurgy is a key manufacturing technique for producing permanent magnets, especially for electric vehicle (EV) applications. This method involves compacting metal powders followed by sintering to create solid magnets with precise control over their microstructure and magnetic properties. Powder metallurgy is widely used for producing high–performance magnets such as neodymium iron boron (Nd–Fe–B) and samarium cobalt (Sm–Co), which are essential for EV motors.

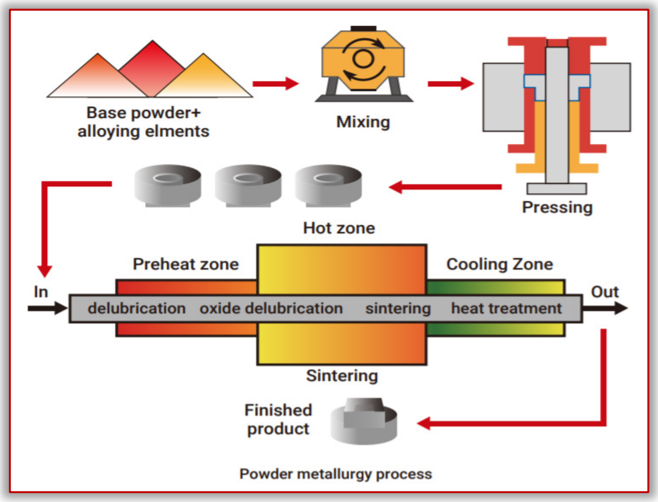

Figure 2. Powder metallurgy process

Neodymium magnet is still the most powerful and frequently used rare earth permanent magnetic material nowadays. Neodymium magnet can be classified to into:

- sintered Neodymium magnet,
- bonded Neodymium magnet, and
- hot pressed Neodymium magnet,

in accordance with the manufacturing process. Each form has their different magnetic properties, then their overlapped application scope is less and under a complementary relationship. Magnet users are wondering how Neodymium magnets are made.

Sintered Neodymium magnet is produced by conventional powder metallurgy process and occupies an absolute predominance in market share.

The importance of powder metallurgy for permanent magnets can be enounced as follow:

- Enables high magnetic performance by controlling particle alignment and microstructure.
- Allows production of complex shapes with minimal material waste.
- Produces magnets with high density and uniformity, critical for EV motor efficiency.
- Supports use of rare earth materials that provide superior magnetic properties.

In the powder metallurgy process (PM), fine powders of metals and alloys are compacted together by pressing the powder in a mould or die to control the shape of the finished product. The pressure used for compaction is high so that the metal or alloy particles get mechanically interlocked. The part also develops enough strength, so that it may be taken out of the die or mould cavity without damage or crumbling back to powder form. The product of this compaction process is known as "green compact". In Powder Metallurgy the accuracy and success of powder metallurgy is the sintering process that heats parts and places them under pressure to bond the powder particles. But, also, the smelting (alloy preparation) in Nd–Fe–B magnet manufacturing is very important.

OVERVIEW OF Nd–Fe–B MAGNET MANUFACTURING BY POWDER METALLURGY

Powder metallurgy is a widely used and essential process for manufacturing permanent magnets, especially high–performance types like Nd–Fe–B (neodymium–iron–boron) and Sm–Co (samarium–cobalt) magnets used in electric vehicles and other advanced applications. The process enables precise control over microstructure, magnetic alignment, and final properties.

Shortly, the key steps in powder metallurgy for permanent magnets are:

- POWDER PREPARATION: Rare earth and transition metal powders (e.g., neodymium, iron, boron) are prepared with controlled particle sizes.
- COMPACTION: The powders are pressed into a desired shape, often in the presence of a magnetic field to align the magnetic domains.
- SINTERING: The compacted powder is heated below its melting point to bond the particles together, creating a dense, solid magnet.
- FINISHING: Magnets may undergo machining, coating, and magnetization to meet specific application requirements.

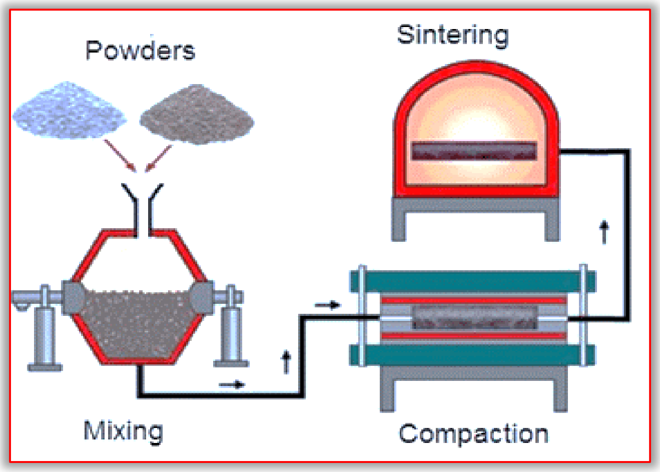

Figure 3. Manufacturing by powder metallurgy

But the process is more complex, the key steps in powder metallurgy for producing permanent magnets, particularly sintered rare earth magnets like Nd–Fe–B and Sm–Co, being:

- SMELTING AND ALLOY FORMATION: Raw materials (rare earth elements – including neodymium and minor additions such as dysprosium –, iron, cobalt, boron, etc.) are melted in vacuum or inert gas furnaces at high temperatures (~1300–1600°C) to form an alloy. The molten alloy is rapidly cooled, often by strip casting, to create thin metal strips or flakes with a uniform microstructure essential for magnetic properties.
- POWDER PRODUCTION (MILLING AND PULVERIZING): The alloy strips or ingots are crushed and milled into fine powders, typically with particle sizes around 3–5 microns. First, the alloy strips are crushed into coarse powder by hydrogen decrepitation (HD), where hydrogen gas is absorbed, causing the alloy to fracture along neodymium–rich phases. This produces powder particles typically less than 10 μm. The powder is then further refined by jet milling to achieve fine, spherical particles of about 3–4 μm in size with a narrow size distribution. This fine powder size is critical for good magnetic alignment and performance. This step ensures the powder particles are small, uniform, and often spherical or near–spherical, which is critical for good magnetic properties.
- MAGNETIC ALIGNMENT (ORIENTATION): The powder is placed in a mold and subjected to a strong external magnetic field to align the easy axes of the particles in a uniform direction. This alignment is essential for achieving high magnetic performance in the final magnet. Different pressing methods (axial, transverse, isostatic pressing) are used to compact the powder to form a "green compact", while maintaining this alignment.
- PRESSING/COMPACTION: The aligned powder is compacted into a "green" compact with about 60% theoretical density. Pressing can be done by die pressing or isostatic pressing, which affects the density and uniformity of the compact. Isostatic pressing often yields higher density and better magnetic properties.
- SINTERING: The pressed compact (green compact) is heated to a temperature below the melting point of the main phase (around 1050–1300°C for Nd–Fe–B) in a vacuum or inert atmosphere. Sintering densifies the compact by bonding particles into a solid magnet with 96–99% theoretical density, increasing strength, and developing the microstructure necessary for strong permanent magnetism, while maintaining particle alignment
- TEMPERING/HEAT TREATMENT: This involves controlled reheating and cooling to refine the microstructure and enhance magnetic properties. After sintering, the magnet is often quenched and then tempered (reheated to a lower temperature) to optimize the grain boundary phases and improve magnetic properties such as coercivity and stability. Post–sintering heat treatments optimize the microstructure, enhancing coercivity and thermal stability by modifying grain boundary phases.
- MACHINING AND FINISHING: The sintered magnet is machined to precise dimensions, sometimes coated (e.g., with nickel, epoxy) to prevent corrosion (especially for Nd–Fe–B magnets which are prone to oxidation) and prepared for magnetization.
- MAGNETIZATION: Finally, the finished magnet is magnetized by exposure to a strong magnetic field, aligning the magnetic domains permanently to achieve the desired magnetic strength and performance.

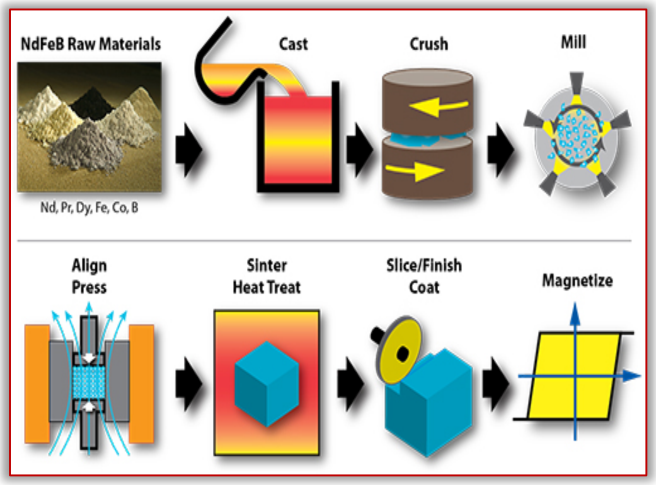

Figure 4. Key steps in powder metallurgy for producing permanent magnets

This powder metallurgy process allows precise control over magnet microstructure, shape, and magnetic properties, making it ideal for high–performance permanent magnets used in electric vehicles and other advanced applications.

This process (Table 1) is the foundation for manufacturing the powerful, compact permanent magnets essential for modern electric vehicles and many other technological applications.

Table 1. Summary table of key steps

STEP	DESCRIPTION	PURPOSE/OUTCOME
SMELTING	Melting raw materials to form alloy strips	Create uniform alloy with desired composition
POWDER MILLING	Crushing alloy into fine powders (~3–5 µm)	Prepare powder with controlled particle size
MAGNETIC ALIGNMENT	Aligning powder particles in magnetic field	Achieve anisotropic magnetic properties
PRESSING/COMPACTION	Compacting powder into green body	Form shape and increase density (~60%)
SINTERING	Heating compact below melting point	Densify and bond particles, develop microstructure
TEMPERING/HEAT TREATMENT	Reheating to optimize grain boundaries	Enhance magnetic performance and stability
MACHINING/FINISHING	Shaping and coating the magnet	Final dimensions and corrosion protection
MAGNETIZATION	Applying strong magnetic field	Permanently magnetize the finished product

Table 2. Summary table of Nd–Fe–B powder metallurgy process

STEP	DESCRIPTION	PURPOSE/OUTCOME
SMELTING	Melting raw materials and rapid strip casting at ~1300–1550°C	Uniform alloy strips with controlled microstructure
HYDROGEN DECREPITATION	Hydrogen gas breaks alloy into coarse powder (<10 µm)	Initial powder formation along Nd–rich phases
JET MILLING	Fine milling to 3–4 µm spherical powder particles	Fine, uniform powder for better alignment
MAGNETIC ALIGNMENT & PRESSING	Align powder particles in magnetic field and compact by pressing methods	Achieve anisotropic magnetic properties and desired shape
SINTERING	Heat compact below melting point (~1050–1300°C) in vacuum/inert atmosphere	Densify and bond particles, develop microstructure
HEAT TREATMENT (TEMPERING)	Reheat and cool to optimize grain boundaries and coercivity	Enhance magnetic stability and performance
MACHINING & COATING	Shape magnets and apply corrosion–resistant coatings	Final dimensions and durability
MAGNETIZATION	Apply strong magnetic field to permanently magnetize the magnet	Achieve maximum magnetic strength

Particularly, the manufacturing of Nd–Fe–B (neodymium–iron–boron) magnets by powder metallurgy involves several precise and controlled steps (Table 2) to produce high–performance permanent magnets widely used in electric vehicles and other advanced technologies.

This powder metallurgy process enables the production of Nd–Fe–B magnets with high magnetic strength, thermal stability, and precise shapes, making them ideal for use in electric vehicle motors, wind turbines, and various electronic devices.

IMPORTANCE OF SMELTING IN Nd–Fe–B MAGNET MANUFACTURING

SMELTING (ALLOY PREPARATION) is the first critical step in the production of sintered Nd–Fe–B permanent magnets by powder metallurgy. It involves melting the raw materials to form a homogeneous alloy with the desired composition and microstructure.

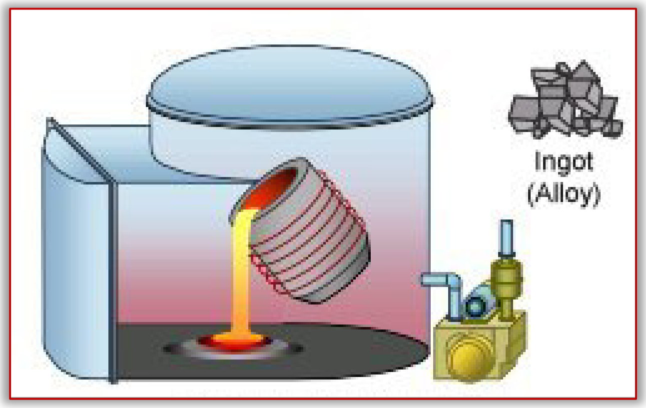

Figure 5. Vacuum induction furnace

The importance of smelting, can be summarized in the following ways:

- Establishes the chemical and microstructural foundation for the magnet.
- Influences magnetic properties such as coercivity and remanence.
- Affects subsequent powder milling and sintering quality.
- Improper smelting can cause defects that irreversibly degrade magnet performance

Smelting is the foundational and essential step in manufacturing sintered neodymium–iron–boron (Nd–Fe–B) permanent magnets through powder metallurgy. But, what happens during the smelting stage?

- The raw materials—High–purity neodymium (Nd), iron (Fe), boron (B), and sometimes additional elements like dysprosium (Dy) or cobalt (Co)—are selected and weighed according to the desired magnetic properties.

- The melting process: The raw materials are heated in a smelting furnace—typically a vacuum induction or inert gas furnace—to temperatures around 1300°C.
- The formation of alloy strips: During smelting, the elements are thoroughly melted, mixed, and then rapidly cooled (often by strip casting) to form thin alloy strips or ingots.

According to the general steps in the Nd–Fe–B magnet manufacturing, the key aspects of the smelting process are:

- Raw Materials: Neodymium, iron, boron, and minor alloying elements such as dysprosium, cobalt, copper, and others are precisely measured and mixed according to the target magnet grade.
- Melting Furnace: The mixture is melted in a vacuum induction furnace or under an inert atmosphere to prevent oxidation and contamination.
- Temperature: The furnace temperature is typically around 1300°C, maintained for about four hours to ensure complete melting and alloying.
- Rapid Solidification (Strip Casting): The molten alloy is rapidly cooled by pouring it onto a fast–spinning copper wheel (strip casting), producing thin alloy strips or flakes (0.2–0.45 mm thick). This rapid cooling creates a uniform crystalline microstructure essential for magnetic performance.
- Purity and Composition Control: Vacuum smelting removes impurities and gases, improving alloy purity. The composition often includes a slight excess of rare earth and boron to optimize magnetic phases. Control of raw material size and purity is crucial due to skin effect in induction melting, affecting heat penetration.
- Output: The smelting process yields alloy strips or ingots that are then processed further by hydrogen decrepitation and milling to produce fine magnetic powders.

Smelting is the foundation of Nd–Fe–B magnet production, ensuring the alloy's quality and uniformity essential for high–performance permanent magnets used in electric vehicles and other advanced technologies.

CONCLUSIONS

Nd–Fe–B magnets are fundamental to the performance and efficiency of electric vehicle motors. Their high magnetic strength, combined with advances in thermal stability and manufacturing, make them the magnet of choice for powering the growing EV market. They enable smaller, lighter, and more efficient motors that contribute to longer driving ranges, better acceleration, and overall improved vehicle performance.

Why is smelting critical? Due to:

- Homogeneous alloy formation: Smelting ensures all the alloying elements are uniformly distributed, preventing unwanted phases that degrade magnetic properties.
- Defines magnet quality: Variations or impurities introduced during smelting can irreversibly impact the performance of the final magnets.
- Prepares for pulverization: The resulting alloy strips from smelting are the precursor for the mill and powder formation steps, which follow immediately after.

Without successful smelting, the entire process of creating advanced sintered Nd–Fe–B permanent magnets would be compromised. Therefore:

- Smelting is indispensable: It is the first and most vital stage in the Nd–Fe–B magnet production chain.
- Precision criticality: Temperature, atmosphere, and timing control during smelting are crucial for producing high–performance magnets.
- Foundation for performance: Each subsequent step's success depends on the quality of the initial smelted alloy.

Smelting is indeed indispensable in the manufacturing of sintered Nd–Fe–B permanent magnets by powder metallurgy. It is the very first step in the production process where the base elements—neodymium, iron, boron, and sometimes other additives—are melted in a smelting furnace. This furnacing process, typically at around 1300°C for about four hours, produces alloy strips that serve as the essential starting material for all subsequent processing stages

Precision criticality in the production of sintered Nd–Fe–B magnets refers to how strictly process parameters—including temperature, time, and material purity—must be controlled at each production stage to ensure optimal magnetic properties and performance. Precision criticality means that any deviation in processing parameters across smelting, milling, alignment, sintering, and heat treatment stages can lead to significant deterioration of magnet quality, performance, or yield. Variations during smelting can cause unwanted phases and compositional inconsistencies, directly harming magnet quality.

The foundation for the performance of sintered Nd–Fe–B permanent magnets lies primarily in their precise microstructure and high–quality material phases, which are established early in the production process starting from smelting through sintering and heat treatments. In essence, the foundation for the high magnetic performance of sintered Nd–Fe–B magnets is the carefully engineered combination of elemental composition, microstructure, and phase purity achieved through each step—starting from smelting, continuing with powder processing, and finalized by sintering and heat treatment. This synergy enables the magnets to exhibit strong coercivity, high remanence, and good thermal stability crucial for advanced technological uses

Without this initial smelting step, a homogeneous and high–purity Nd–Fe–B alloy cannot be formed, which is crucial for achieving the desired magnetic properties in the end product. Smelting ensures the uniform distribution of elements and eliminates undesired phases or impurities that could degrade magnet performance. The success of later critical steps—such as powder milling, magnetic alignment, compaction, sintering, and tempering—relies entirely on the quality and consistency achieved during smelting.

Obviously, the subsequent steps rely on successful smelting. Once smelting is complete, the alloy strips undergo:

- Hydrogen decrepitation and jet milling: Breaking down the strips into fine particles (3–4 μm).
- Magnetic alignment and pressing: Orienting and compacting the powder in a magnetic field.
- Sintering, tempering, and machining: Achieving final density, microstructure, and shape

The smelting stage is non–substitutable and acts as the foundation for the entire powder metallurgy route of sintered Nd–Fe–B magnet production. Any compromise in this stage irreversibly impacts the material quality and the performance of the final magnets

References:

[1] Nakamura, H. (2018). The current and future status of rare earth permanent magnets. Scripta Materialia, 154, 273–276.
[2] Herbst, J. F. (1993). Permanent magnets. American Scientist, 81(3), 252–260.
[3] Sagawa, M., Fujimura, S., Togawa, N., Yamamoto, H., & Matsuura, Y. (1984). New material for permanent magnets on a base of Nd and Fe. Journal of applied physics, 55(6), 2083–2087.
[4] Campbell, P. (1994). Permanent magnet materials and their application, 1994
[5] Masato Sagawa, Satoshi Hirosawa, Hitoshi Yamamoto, Setsuo Fujimura and Yutaka Matsuura, Nd–Fe–B Permanent Magnet Materials, Japanese Journal of Applied Physics, 26 785, 1987, pp. 785–800
[6] Coey, J. M. D. (2020). Perspective and prospects for rare earth permanent magnets. Engineering, 6(2), 119–131.
[7] Coey, J. M. D. (2012). Permanent magnets: Plugging the gap. Scripta Materialia, 67(6), 524–529.
[8] Coey, J. M. D. (2014). New permanent magnets; manganese compounds. Journal of Physics: Condensed Matter, 26(6), 064211.
[9] Croat, J. J. (1997). Current status and future outlook for bonded neodymium permanent magnets. Journal of applied physics, 81(8), 4804–4809.
[10] Herbst, J. F. (1993). Permanent magnets. American Scientist, 81(3), 252–260.
[11] Brown, D., Ma, B. M., & Chen, Z. (2002). Developments in the processing and properties of NdFeb–type permanent magnets. Journal of magnetism and magnetic materials, 248(3), 432–440.
[12] Dobrzanski, L. A., & Drak, M. (2007). Permanent magnets Nd–Fe–B. International Journal of Microstructure and Materials Properties, 2(2), 133–149.
[13] Drak, M., & Dobrzański, L. A. (2007). Corrosion of Nd–Fe–B permanent magnets. Journal of Achievements in Materials and Manufacturing Engineering, 20(1–2), 239–242.
[14] Fidler, J., & Schrefl, T. (1996). Overview of Nd–Fe–B magnets and coercivity. Journal of Applied Physics, 79(8), 5029–5034.
[15] Hono, K., & Sepehri–Amin, H. (2012). Strategy for high–coercivity Nd–Fe–B magnets. Scripta Materialia, 67(6), 530–535.
[16] Herbst, J. F., & Croat, J. J. (1991). Neodymium–iron–boron permanent magnets. Journal of magnetism and magnetic materials, 100(1–3), 57–78.
[17] Croat, J. J., Herbst, J. F., Lee, R. W., & Pinkerton, F. E. (1984). Pr-Fe and Nd-Fe-based materials: A new class of high-performance permanent magnets. Journal of Applied Physics, 55(6), 2078–2082.
[18] Matsuura, Y. (2006). Recent development of Nd–Fe–B sintered magnets and their applications. Journal of magnetism and magnetic materials, 303(2), 344–347.
[19] Dobrzanski, L. A., Drak, M. (2007). Permanent magnets Nd–Fe–B. International Journal of Microstructure and Materials Properties, 2(2), 133–149.
[20] Kim, A. S., & Camp, F. E. (1996). High performance NdFeB magnets. Journal of applied physics, 79(8), 5035–5039.
[21] Sagawa, M., Hirosawa, S., Yamamoto, H., Fujimura, S., & Matsuura, Y. (1987). Nd–Fe–B permanent magnet materials. Japanese journal of applied physics, 26(6R), 785.
[22] Dent, P. C. (2012). Rare earth elements and permanent magnets. Journal of applied physics, 111(7).
[23] Ma, B. M., Herchenroeder, J. W., Smith, B., Suda, M., Brown, D. N., & Chen, Z. (2002). Recent development in bonded NdFeB magnets. Journal of magnetism and magnetic materials, 239(1–3), 418–423.
[24] Ahmed, F. M., Edgley, D. S., & Harris, I. R. (1994). Effect of niobium addition on the Nd–Fe–B alloy and magnet. Journal of alloys and compounds, 209(1–2), 363–368.
[25] McCallum, R. W., Lewis, L. H., Skomski, R., Kramer, M. J., & Anderson, I. E. (2014). Practical aspects of modern and future permanent magnets. Annual Review of Materials Research, 44(1), 451–477.
[26] Du, X., & Graedel, T. E. (2011). Global rare earth in-use stocks in NdFeB permanent magnets. Journal of Industrial Ecology, 15(6), 836–843.
[27] Coey, J. M. (2002). Permanent magnet applications. Journal of Magnetism and Magnetic Materials, 248(3), 441–456.

[28] Sagawa, M., Fujimura, S., Togawa, N., Yamamoto, H., & Matsuura, Y. (1984). New material for permanent magnets on a base of Nd and Fe. Journal of applied physics, 55(6), 2083–2087.
[29] Sugimoto, S. (2011). Current status and recent topics of rare–earth permanent magnets. Journal of Physics D: Applied Physics, 44(6), 064001.
[30] Brown, D., Ma, B. M., & Chen, Z. (2002). Developments in the processing and properties of NdFeb–type permanent magnets. Journal of magnetism and magnetic materials, 248(3), 432–440.
[31] Sugimoto, S. (2011). Current status and recent topics of rare–earth permanent magnets. Journal of Physics D: Applied Physics, 44(6), 064001.
[32] Sagawa, M., Fujimura, S., Togawa, N., Yamamoto, H., & Matsuura, Y. (1984). New material for permanent magnets on a base of Nd and Fe. Journal of applied physics, 55(6), 2083–2087.
[33] Ormerod, J., Constantinides, S. (1997). Bonded permanent magnets: current status and future opportunities. Journal of Applied Physics, 81(8), 4816–4820.
[34] Kramer, M. J., McCallum, R. W., Anderson, I. A., & Constantinides, S. (2012). Prospects for non–rare earth permanent magnets for traction motors and generators. Jom, 64(7), 752–763.
[35] Popov, V., Koptyug, A., Radulov, I., Maccari, F., & Muller, G. (2018). Prospects of additive manufacturing of rare–earth and non–rare–earth permanent magnets. Procedia Manufacturing, 21, 100–108.
[36] Strnat, K. J., & Strnat, R. M. (1991). Rare earth–cobalt permanent magnets. Journal of Magnetism and Magnetic Materials, 100(1–3), 38–56.
[37] Sagawa, M., Fujimura, S., Yamamoto, H., Matsuura, Y., Hirosawa, S. (1985). Magnetic properties of rare-earth-iron-boron permanent magnet materials. Journal of applied physics, 57(8), 4094–4096.
[38] Sagawa, M., Fujimura, S., Yamamoto, H., Matsuura, Y., & Hiraga, K. (2003). Permanent magnet materials based on the rare earth–iron–boron tetragonal compounds. IEEE transactions on Magnetics, 20(5), 1584–1589.
[39] Sagawa, Masato, et al. Permanent magnet materials based on the rare earth–iron–boron tetragonal compounds. IEEE transactions on Magnetics, 2003, 20.5: 1584–1589.
[40] Özdemir, M. S., Ocak, C., & Dalcalı, A. (2021, June). Permanent magnet wind generators: neodymium vs. ferrite magnets. In 2021 3rd International Congress on Human–Computer Interaction, Optimization and Robotic Applications (HORA) (pp. 1–6). IEEE.
[41] Boisson, J., Rouby, C., Lee, J., & Doaré, O. (2015). Dynamics of a chain of permanent magnets. Europhysics Letters, 109(3), 34002.
[42] Boisson, J., Rouby, C., Lee, J., & Doaré, O. (2015). Dynamics of a chain of permanent magnets. Europhysics Letters, 109(3), 34002.
[43] Shaw, S., & Constantinides, S. (2012, November). Permanent magnets: the demand for rare earths. In 8th International Rare Earths Conference (Vol. 33). Hong Kong: Arnold Magnetic Technologies.
[44] Constantinides, S., & De Leon, J. (2011). Permanent magnet materials and current challenges. In Adv. Powder Metall. Part. Mater.–2011, Proc. 2011 Int. Conf. Powder Metall. Part. Mater. PowderMet (pp. 858–875).
[45] Heim, J. W., & Vander Wal, R. L. (2023). NdFeB permanent magnet uses, projected growth rates and Nd plus Dy demands across end–use sectors through 2050: a review. Minerals, 13(10), 1274.
[46] Schultz, L., Schnitzke, K., Wecker, J., Katter, M., & Kuhrt, C. (1991). Permanent magnets by mechanical alloying. Journal of applied physics, 70(10), 6339–6344.
[47] Withey, P. A., Kennett, H. M., Bowen, P., & Harris, I. R. (2002). The magnetic and mechanical properties of NdFeB type permanent magnets and the effect of quenching. IEEE transactions on magnetics, 26(5), 2619–2621.
[48] Hirosawa, S. (2018). Permanent magnets beyond Nd–Dy–Fe–B. IEEE Transactions on Magnetics, 55(2), 1–6.
[49] Skomski, R., Manchanda, P., Kumar, P., Balamurugan, B., Kashyap, A., & Sellmyer, D. J. (2013). Predicting the future of permanent–magnet materials. IEEE Transactions on Magnetics, 49(7), 3215–3220.
[50] Kuz'Min, M. D., Skokov, K. P., Jian, H., Radulov, I., & Gutfleisch, O. (2014). Towards high–performance permanent magnets without rare earths. Journal of Physics: Condensed Matter, 26(6), 064205.
[51] Kuz'Min, M. D., Skokov, K. P., Jian, H., Radulov, I., & Gutfleisch, O. (2014). Towards high–performance permanent magnets without rare earths. Journal of Physics: Condensed Matter, 26(6), 064205.
[52] Hirosawa, S., Nishino, M., & Miyashita, S. (2017). Perspectives for high–performance permanent magnets: applications, coercivity, and new materials. Advances in Natural Sciences: Nanoscience and Nanotechnology, 8(1), 013002.
[53] Sekine, N., Daigo, I., & Goto, Y. (2017). Dynamic substance flow analysis of neodymium and dysprosium associated with neodymium magnets in Japan. Journal of Industrial Ecology, 21(2), 356–367.
[54] Hirosawa, S. (2015). Current status of research and development toward permanent magnets free from critical elements. Journal of the Magnetics Society of Japan, 39(3), 85–95.
[55] Croat, J. J. (1988). Neodymium—iron—boron permanent magnets prepared by rapid solidification. Journal of materials engineering, 10(1), 7–13.
[56] Orlova, S., & Rassõlkin, A. (2024). Permanent Magnets in Sustainable Energy: Comparative Life Cycle Analysis. Energies, 17(24), 6384.
[57] Croat, J. J., Herbst, J. F., Lee, R. W., & Pinkerton, F. E. (1984). Pr-Fe and Nd-Fe-based materials: A new class of high-performance permanent magnets. Journal of Applied Physics, 55(6), 2078–2082.
[58] Cui, J., Ormerod, J., Parker, D., Ott, R., Palasyuk, A., Mccall, S., Lograsso, T. (2022). Manufacturing processes for permanent magnets: Part I—sintering and casting. Jom, 74(4), 1279–1295.

ISSN: 2067–3809