

History and Development of Permanent Magnets

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ABSTRACT: *The history of development of permanent magnets has been reviewed. The magnet began with the mineral magnetite (Fe₃O₄) or lodestone, was the first hard magnet known to man with Energy Product of about 1kJ/m³. The steps of development have been classified due to the type of materials used in the manufacturing of permanent magnets. The first type of steel magnets are those which were developed to reach (BH)_{max} of about 8kJ/m³. A big jump in the energy product and coercivity occurred after the discovery of Rare Earth magnets. A (BH)_{max} of around 474 kJ/m³ has been achieved. A theoretical value of (BH)_{max} of about 512kJ/m³ for Nd₂Fe₁₄B hard Phase has been reported. A 93% of this theoretical value has been achieved so far. In addition, an idea about large scale applications of Nd-Fe-B magnets has been mentioned in this work. Furthermore, some recent developments in the field of permanent magnets have been summarized in this article.*

Keywords: Permanent Magnets, Magnetic Properties, Rare Earth Magnets, Hydrogen Hecepitation, Energy Product.

HIGHLIGHTS:

Historical background of permanent magnets has been given. Ferromagnetic materials played a vital role in the discovery of the new world and development of many topics. The revolution in the production of magnets has begun when magnetic alignment process started to be used. Permanent magnets based on Rare Earths have been reported.

1. General Introduction:

Materials with ferro or ferrimagnetic behavior are an important group in our daily life. They played a vital role in the discovery of the New World and in the development of modern technology. Without compass Christopher Columbus would not have made his discoveries. The outstanding magnetic properties, low cost and availability of iron has made it possible to generate massive amounts of electricity since 1886 when Westinghouse Electric Company built the first

commercial AC generating station. The use of permanent magnets to perform vital function is not limited to power stations, but other industries such as communications, computers, electric machines and home appliances, etc. Usually, electrical machines are a tremendously important in industry. Electrical machines generate electrical power, and convert electric power to mechanical power which is extremely essential in industrial applications during our life. During recent, highly developments in magnet materials, of which the demagnetization curve almost a straight line from the **B_r** to the coercive field **H_c**, i.e. with an ideal squareness curve of demagnetization. The maximum energy product is directly proportional to these values of **B_r** and **H_c**. The larger the energy product the less permanent magnet material is required, unless otherwise specified according to a certain application, and the smaller the electrical machine can be produced. Within the past two decades, important developments and improvements have been achieved in the magnetic remnant flux density, maximum energy product, sintering density, thermal stability, and enhancing the coercivity of permanent magnets.

This article is not intended to be a complete literature survey about permanent magnets, but to give a general background about them and their developments with different types of materials.

2. Classification of permanent magnets:

The history of the development of magnetic materials begins with the mineral magnetite (Fe₃O₄) or lodestone, the first magnetic material known to man. Lodestone was discovered as a natural permanent magnet in *Magnesia* more than 3500 years ago, with an energy product (BH)_{max} of about 1kJ/m³. *Magnesia* is now found in the western of Turkey. These lodestones were called *magnets* after their place of discovery, and magnetism is derived from the word of *Magnesia* [1, 2]. In fact it is very hard to follow the development steps of permanent magnets starting from magnetite, but it is useful to begin with modern developments. These can be classified as follows:

(i) Magnetic steels

Around the 1770's, the first development was made by Gowin Knight (1713-72), an English gentleman who stirred continuously a large amount of iron in water until he got a suspension of divided of finely iron oxide. This was mixed

with linseed oil, the paste moulded into shape and baked hard. The resulting blocks were then magnetised and formed strong magnets for that time, reputedly [3]. About 1880 hardened carbon steel gave way to low tungsten alloy steels (0.7% C, 6% W), which held the field for many years as permanent magnets [4]. Later, chromium was found to play the same function as tungsten and both 6% tungsten and 6% chromium steel have $B_r = 0.95T$ and $H_c = 4.4kA/m$, with $(BH)_{max}$ of about $2.4kJ/m^3$. In 1917, a considerable improvement was made by the discovery of the Japanese physicists K. Honda and T. Taki [5] that the coercivity could be increased sharply by the addition of cobalt. They found that the addition of 35% cobalt gives the following properties: $B_r = 0.9 T$, $H_c = 20 kA /m$ and $(BH)_{max} = 7.6kJ /m^3$. In 1930, some English Manufacturers combined to form the Cobalt Magnet Association and one of the first actions was to standardise six grades of cobalt steel magnet [6]. Compositions and magnetic properties of some of these steel magnets are given in Table 1.

Table 1 Nominal compositions and magnetic properties for some different types of steel [6].

Nominal Composition, weigh % Balance Fe							
materia	C	Cr	W	M	Co	$B_r(T)$	$(BH)_{max}(kJ/m^3)$
1				o))
1% C	1.0	-	-	-	-	0.9	1.6
6% Cr	1.0	6.	-	-	-	0.98	2.4
	5	0					
3% Co	1.0	9.	-	1.5	3.0	0.72	2.8
	5	0					
9% Co	1.0	9.	-	1.5	9.0	0.78	4
	5	0					
35% Co	0.8	6.	4.	-	35.	9	7.6
	5	0	0		0		

(ii) Al-Ni-Fe

In 1930, a new direction in permanent magnets was opened when an alloy of nickel, aluminum and iron was discovered with a high coercivity magnet, the optimum magnetic properties were $B_r = 0.6T$, $H_c = 40 kA/m$ and $(BH)_{max} = 10kJ/m^3$. Following this, a new generation of permanent magnets was first developed in England at Sheffield based upon the addition of Cu and Co to the Ni-Al-Fe alloy. This subject has been comprehensively reviewed by Smithells [4] and McCaig [6]. The result was a series of alloys which are usually known as Alnico.

(iii) Alnico

At the beginning of development, the magnetic properties were approximately; $B_r = 0.75T$, $H_c = 40kA/m$ and $(BH)_{max} = 12.8kJ/m^3$. After this stage, the development of these alloys

was carried out at Sheffield and in 1938 it was found that heat treatment in a suitable magnetic field could enhance the properties. The properties after this treatment were $B_r = 1.25T$, $H_c = 44kA/m$, and $(BH)_{max} = 36kJ/m^3$, and this stage could be looked upon as **a new revolution in the production of permanent magnets by using magnetic alignment process**. The commercial name of these alloys in the United Kingdom is Alcomax. Further increase of $(BH)_{max}$ to about $60kJ/m^3$ was achieved by producing a columnar grain structure in cast alloys and cooling in a magnetic field, these being named Columax as commercial alloys. Other very high coercivity alloys of the Alnico or Alcomax type have been developed by the addition of titanium or niobium and they are marketed as Hycomax III or IV and Ticonalx. Magnetic properties related to heat treatment and the magnetic alignment are summarised in Table 2 for some Alnico alloys. Information of applications and developments of these alloys have been reported by Luiz *et al.* [7]. As reported by Ormerod [8], energy product of about $103kJ/m^3$ could be achieved for Alnico alloys.

Table 2 Magnetic properties of some Alnicos with heat treatment conditions [4].

The alloy	Magnetic Properties			Heat Treatment
	$(BH)_{max}$	$H_c(kA/m)$	$B_r(T)$	
Alni	7.2-9.6	25-50	0.55-0.75	Quench from $1150^{\circ}C$, temper at about $550^{\circ}C$
Hynico	12.8-16.0	60-80	0.55-0.58	Air cool from $1200^{\circ}C$, temper at about $55^{\circ}C$
Alnico-8	40-48	110-170	0.75-0.90	Quench, followed by reheat to $800^{\circ}C$ and cool in magnetic field

(iv) Ceramic Magnets

During the 1940's, the Philips Organisation (USA) developed many soft magnetic ferrites; these materials which have a cubic structure are sold as Ferroxcube. Probably as a result of their work into soft ferrites, Philips in the 1950's discovered that hard magnetic ferrites could be produced. In general, these ferrites are based on Ba, Sr, Pb and have a formula $MFe_{12}O_{19}$, where M is Ba, Sr, Pb. This subject has been fully discussed by Went *et al.* [9] and McCaig [10]. The representatives of this class of ferrites, which have been given the name of Ferroxdure, have a hexagonal structure (the easy axis being along the c-axis). Their development and properties have been reviewed by Broek *et al.* [11]. Ferroxdure is

manufactured either as a solid permanent magnet or in the form of ferrite particles dispersed in plastic (bonded ferrites). Typical magnetic properties of SrFe₁₂O₁₉ with trade mark of FXD-380 are: Br = 0.39T, Hci = 275kA/m and (BH)_{max} = 28.2kJ/m³ [12].

(v) Rare-Earth magnets

During the 1960's, permanent magnets based upon Rare Earths have been developed. In 1967, Strnat *et al.* [13] investigated several intermetallic phases of the type RCo₅ where R = Y, Ce, Pr, Sm, or Y-rich, Ce-rich mischmetal. Their conclusion was that these alloys were promising candidates for fine particle permanent magnets with extremely high anisotropy. Magnets produced by compacting fine powders of SmCo₅ in a magnetic field gave an energy product (BH)_{max} of about 64kJ/m³ with a corresponding value for H_{CB} of 414kA/m [14]. Later, by using an improved pressing technique, Buschow *et al.* [15] succeeded in producing SmCo₅ with a relative bulk density of about 95% and hence improved (BH)_{max} to around 147kJ/m³. In 1969, Das [16] reported a '**Twenty million Energy Product**' Samarium Cobalt Magnet which is equivalent to (BH)_{max} of about 158 kJ/m³. This result was obtained by improving the magnetic alignment and reducing the particle size below 10µm.

The effect of element additions to SmCo₅ was studied by Nesbitt *et al.* [17] who replaced some of the cobalt by copper, giving an increase in coercivity and a decrease in (BH)_{max}. The preparation and enhanced properties of SmCo₅ produced by liquid phase sintering were reported by Benz *et al.* [18]; their conclusions were that this method gives improved magnetic properties and eliminates porosity. A (BH)_{max} value of more than 156 kJ/m³ was realized.

Shortly after the development of SmCo₅ permanent magnets in the early 1970's, alloys containing copper as well as the rare earths and cobalt emerged. These alloys became known as the **precipitation hardened family** of R(Cu, Co) alloys and eventually led to the development of high energy Sm(Co, Cu, Fe, TM)_{7,8} magnets, where TM ≡ Zr, Ti, or Hf [19, 20].

Sm₂Co₁₇ compounds have emerged as second generation rare earth magnets and these were developed with some addition of Fe to become Sm₂(Co, Fe)₁₇, which appeared to hold the realistic promise of permanent magnets superior even to those based on RCo₅ [21]. The effects of various additive elements on the magnetic properties of the Sm-Co-Fe-Cu system were studied by Ojima *et al.* [22] at TDK Electronics Co. Ltd, Japan. The formula was Sm₂(Co, Cu, Fe, M)₁₇, where M ≡ Nb, V, Ta, or Zr. The result was that the alloys containing Zr or Nb showed good permanent magnetic properties. The best properties were obtained for an alloy of Co with 25.5 wt% Sm, 8 wt% Cu, 15 wt% Fe, 1.5 wt% Zr, the properties were as follows: Br = 1.1T, Hci = 535.3 kA/m, (BH)_{max} = 238 kJ/m³. It was found also that Zr addition to the Sm-Co-Fe-Cu system improves the hard magnetic properties whilst a post-sintering annealing process enhances the effect of Zr on coercivity. Production and development of the

REPMs have been fully reviewed by Strnat [23] and Ormerod [24]. Solidification from the liquid state of samarium-cobalt compounds in a high magnetic has been reported by Legrand *et al.* [25]. Their conclusion was that this route of fabrication can be applied to produce anisotropic permanent magnets of Sm-Co alloys, with no need to the conventional powder metallurgy techniques. Production method and magnetic properties of sintered permanent magnets of Sm-Co 2:17 have been investigated by Fang *et al.* [26]. Table 3 includes the magnetic properties of SmCo₅, Sm (Co, Fe, Cu)₇, and Sm₂(Co, Cu, Fe, M)₁₇.

Table 3 Magnetic data for selected of Sm-Co magnets [23].

Alloy type	Production method	(BH)_{max} kJ/m³	B_r (T)	H_{ci} (kA/m)
SmCo	Sintering wt% 60Sm/40Co	189.6	0.98	955.2
Sm(Co, Fe, Cu) ₇	Sintering precipitation annealing	208.5	1.04	493.5
Sm ₂ (Co, Fe, Zr, Cu) ₁₇	Sintering precipitation annealing	238.5	1.12	533.2

In 1978, Harris *et al.* patented the **Hydrogen Decrepitation (HD)** process as a means of producing powder of SmCo₅ and Sm₂Co₁₇ alloys (British patent 1,554,384, October 1979); large lumps can be crumbled up readily to obtain an extremely friable product which is consequently very amenable to further reduction in particle size. This process was again applied to decrepitate the Sm₂(Co, Fe, Cu, Zr)₁₇ alloys [27, 28]. In the middle of 1983, new rare earth permanent magnets were discovered, and this led to extensive research on these materials in many countries.

(vi) Discovery of Nd-Fe-B magnets and development:

Permanent magnets based upon Nd-Fe-B alloys first emerged in the middle of 1983 and could be looked upon as the third generation of Rare-Earth permanent magnets. This subject has been comprehensively treated by Mitchell [29]. At the beginning, and independently, two routes were developed for fabricating these new magnets, and these have continued to be used. The first is a conventional powder metallurgy route which was developed by Sagawa and his team work in Sumitomo Special Metals Company Ltd (SSMC), Japan [30]. They announced that a new sintered anisotropic permanent magnet had been developed based on Nd, Fe and a small amount of B, and the typical alloy, which had excellent magnetic properties, was Nd₁₅Fe₇₇B₈. The energy product of the magnets produced by this route was about 290kJ/m³. The other route for the production is rapid solidification to give an

isotropic permanent magnet, this method being announced by the General Motors Corp. (GM) USA [31, 32]. The energy product of the magnets produced by this method was about 114kJ/m^3 . From above, we can conclude that most of high performance permanent magnets have been fabricated by employing powder metallurgy technique. Magnetic properties are so dependent on starting materials, microstructures, magnetic alignment, and heat treatment process, therefore powder metallurgy represents an ideal route to control most of these factors. This subject has been recently reported by the present author [33].

Later, Livingston [34] reported that the peak properties occur at an optimum wheel speed, i.e. optimum quenching rate that produces $\text{Nd}_2\text{Fe}_{14}\text{B}$ grains 20- 80 nm in diameter. The isotropic nature of the melt-spun ribbons gives limited remanence and energy product values and the problem which had to be overcome was how to achieve crystallographic alignment. However, Lee (1985) [35] showed that a magnetic anisotropy could be induced by high temperature plastic deformation (hot pressing/die-upsetting or thermomechanical deformation route), and hence well aligned Nd-Fe-B magnets could be produced from rapidly quenched ribbons. An energy product of about 320kJ/m^3 has been obtained by employing this method of production. Magnets prepared by this thermomechanical deformation route have been further improved by Croat [36] who announced values of $(\text{BH})_{\text{max}}$ up to 350kJ/m^3 with $H_{\text{ci}}=1080\text{kA/m}$. Fig.1 shows the anisotropy behavior of $\text{Nd}_{15}\text{Fe}_{77}\text{B}_8$ permanent magnets reported by Sagawa *et al.* [30], and the easy axis is along the c- axes of the tetragonal structure of the hard phase of these magnets. Fig. 2 showing domain walls in the hard magnetic phase parallel to the easy direction [37].

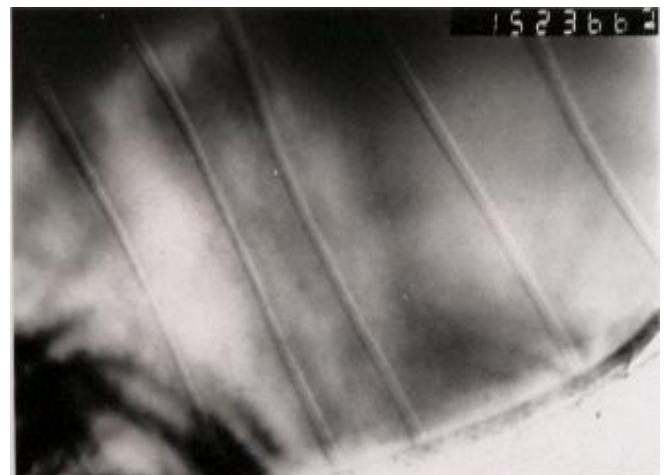


Fig. 2. TEM Lorenz micrograph showing domain walls along the c- axes of Nd-Fe-B magnet [37].

The difference in the processing methods of Nd-Fe-B magnets developed by GM and SSMC enabled each company to file patent applications [38]. The characteristics of magnets fabricated by the conventional route are summarized in Table 4, which can be compared with Table 5 that gives the properties of magnets produced by the rapid solidification route.

Table 4 Characteristics of a magnet made by a conventional powder metallurgy route [30].

Remanence (Br)	1.23T
Intrinsic coercivity (H_{ci})	969 kA/m
Normal coercivity (H_{cB})	880 kA/m
Energy product (BH)max	290 kJ/m^3
Density	7.40 g/cm^3
Vickers Hardness	600 HV
Curie temperature (T_c)	$312\text{ }^\circ\text{C}$

Table 5 Characteristics of a magnet made by a rapid solidification route [31].

Remanence (Br)	0.82T
Intrinsic coercivity (H_{ci})	1194 kA/m
Normal coercivity (H_{cB})	557 kA/m
Energy product (BH)max	114 kJ/m^3
Density	7.55 g/cm^3
Vickers Hardness	600 HV
Curie temperature (T_c)	$327\text{ }^\circ\text{C}$

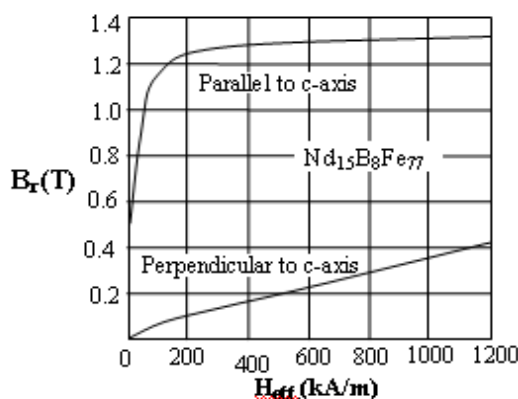


Fig. 1. Magnetisation at room temperature in the easy and hard directions for a $\text{Nd}_{15}\text{Fe}_{77}\text{B}_8$ magnet [30].

Further improvements which gave $(\text{BH})_{\text{max}}$ values as high as 380kJ/m^3 and 360kJ/m^3 were reported by Sagawa *et al.* [39] and Narasimhan [40]. The main problems of these third generation Rare Earth permanent magnets are the corrosion resistance, low Curie point, coercivity and remanence reduce rapidly with heating, and most of researches are concentrated to enhance these properties [41-44]. In 1985, theoretical maximum value of energy product of Nd-Fe-B magnet was determined by Sagawa *et al.* [45]. They reported a value of about 512kJ/m^3 for $\text{Nd}_2\text{Fe}_{14}\text{B}$ Phase which represents the hard

phase in the Nd-Fe- B alloy. Later, practical values of around 405kJ/m³ and 416kJ/m³ were published [46, 47].

As mentioned the (HD) process has been applied in the production of the REPMs since 1979. After the discovery of Nd-Fe-B permanent magnets in 1983, the (HD) process was successfully re-applied to decrepitate as-cast ingots of the Nd₁₅Fe₇₇B₈ alloy and related compositions [48]. This work was carried out at the Metallurgy and Materials Science Department, University of Birmingham. At the beginning they showed that hydrogen could fragment the as-cast alloy if the ingots were exposed to hydrogen at a pressure of 33 bar and ambient temperature, and later it was found that 1 bar of hydrogen pressure is enough to decrepitate the ingots of Nd₁₅Fe₇₇B₈ or near compositions at room temperature [49]. This subject has been fully reviewed by Harris [50, 51], Harris and McGuiness [52].

Hydrides formed which rendered the material extremely friable and therefore made it easy to mill the product to the required particle size. Thus, this route represents an alternative method of preparing the starting powder prior to pressing and sintering in the manufacturing process of Nd-Fe-B magnets. Elsewhere, this method was used to produce a fine powder of Nd₁₅Fe₇₇B₈ starting from as-cast ingots, in an attempt to study the nature of hydrogen adsorption-desorption of R₂Fe₁₄B alloys, where R ≡ Nd, Y, and Ce [53]. The nature of the (HD) process when applied to as-cast Nd₁₅Fe₇₇B₈ alloy was studied by following the microstructural changes on polished surfaces of the material exposed to hydrogen at a pressure of 4 bars at room temperature [54]. A series of SEM micrographs to illustrate the decrepitation process are given in Fig. 3a, b, c, d. Comparison between magnets produced by the (HD) process and the conventional technique has been made by studying the microstructure and the magnetic properties of Nd₁₆ Fe₇₆B₈ alloy [55]. Fig. 4 shows high magnification micrographs of magnets prepared by the two routes. In 2012, combination between the HD and HDDR has been used in the recycling of Nd-Fe-B magnets [56].

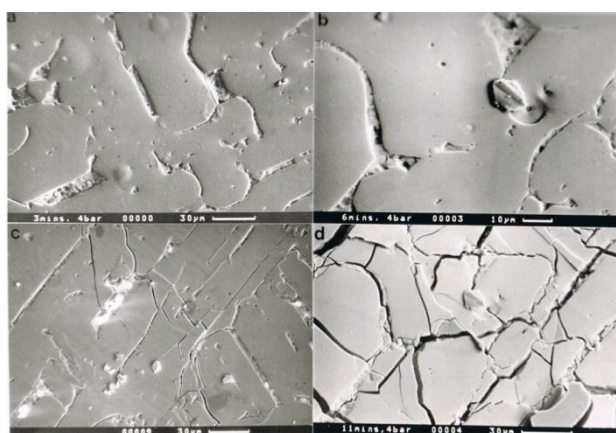


Fig. 3. Stages of the HD process using 4 bar hydrogen pressure, 3, 6, 9, and 11 min [54].

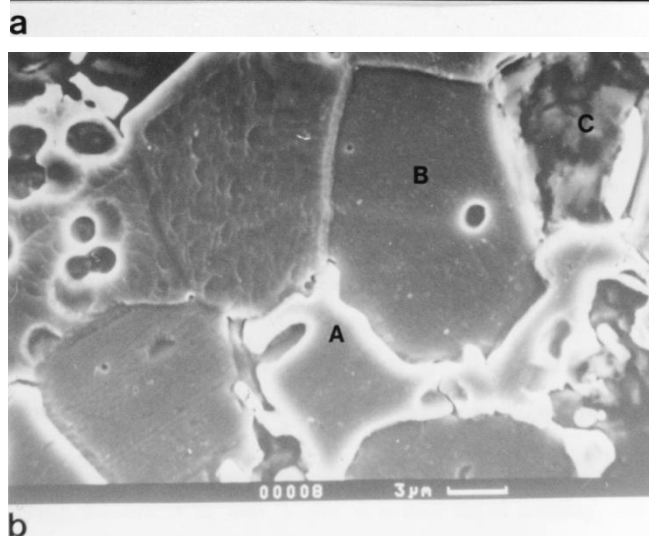
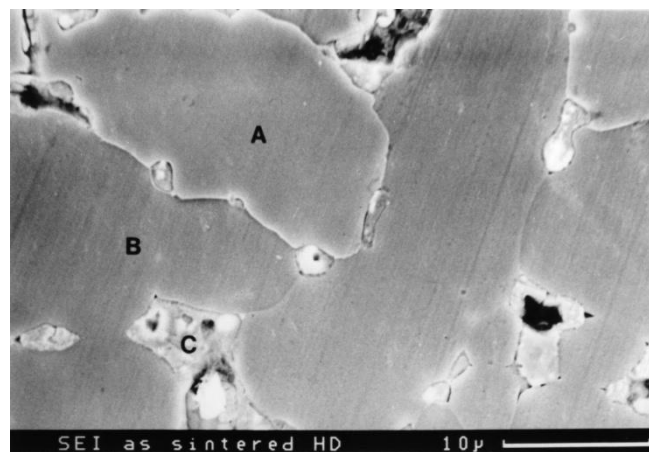


Fig. 4. SEM micrographs showing the phases present in the magnets made by: (a) HD route, (b) conventional method, (A) B-rich phase, (B) Nd₂Fe₁₄B phase, (C) Nd-rich phase [55].

The magnetic and mechanical properties of Nd-Fe-B magnets at different hot deformation temperatures have been investigated [57]. Their results showed that the optimum magnetic and mechanical properties and the highest crystallographic alignment of Nd-Fe-B magnets were obtained at 700 °C. During 2000, Yuji Kaneko has announced “**Highest Performance of Nd-Fe-B Magnet Over 55 MGOe**” energy product [58]. He reported values of (BH)_{max}=444kJ/m³, B_r=1.514, and H_{ci}=691kA/m. Development of Nd-Fe-B sintered magnets has been reviewed by Yutaka Matsuura [59]. He reported that magnetic properties of this type of magnets with B_r=1.55T, (BH)_{max}=474kJ/m³ which is about 93% of the theoretical value, H_{ci}=653kA/m were produced by NEOMAX Co. Ltd in 2005. So many attempts were done to improve corrosion resistance and Curie temperature of Nd-Fe-B magnets [60-63]. The Effect of post-sinter annealing on the coercivity and microstructure of Nd-Fe-B permanent magnets has been studied by Li *et al.* [64]. They showed that the coercivity increase caused by post-sinter annealing at about 600 °C. The highly development of (BH)_{max} of Nd-Fe-B magnets accelerated the era of modern

permanent magnet machines. Currently, these magnets even in the mass production process, energy products of around 400kJ/m^3 and Br with about 1.4T can be achieved [65]. Amazing theoretical and practical work on the use of Nd-Fe-B permanent magnets have been reported by Thompson [66]. He widely discussed the theoretical part in addition of the practical design matters related with the applications of high strength of Neodymium Iron Boron magnets, especially in the transportation systems, such as Maglev, bearings, and eddy current breaks. Some examples of different types of permanent magnet magnets are summarized in Table 6.

Table 6 The Development of permanent magnets. Today, energy products over 400kJ/m^3 can be reached [65, p.14].

Year	Energy product [kJ/m^3]	Summary
1966	143	Dr. Karl J. Strnat discovers the high energy product of the Samarium-Cobalt (Sm-Co) compound. (U.S. Patent 4063971, 1966)
1972	239	Dr. Karl J. Strnat and Dr. Alden Ray develop a higher energy product Samarium-Cobalt (Sm-Co) compound.
1983	279	General Motors, Sumitomo Special Metals and the Chinese Academy of Sciences develop a high energy product Neodymium-Iron-Boron (Nd-Fe-B) Compound (U.S. Patent 4601875, 1986). 290 kJ/m^3 was discovered by Sagawa et al. in 1984.
1993	308	A rubber isostatic processing was developed, including apparatus to implement this technology (Sagawa et. al. 1993). 308 kJ/m^3 for Nd-Fe-B compound was found.
2000	400	Kaneko (2000) devised high energy product magnets in the laboratory conditions. 444 kJ/m^3 was obtained, which started the mass production of 400 kJ/m^3 Nd-Fe-B magnets.
2001	409	Tokoro et al. (2001) studied wet compacting process. As a result, Nd-Fe-B magnets with 409 kJ/m^3 were obtained in mass production.
2007	415	Nd-Fe-B compound, commercial name BM 53 (Bakkermagnetics 2007).

Within the 1990's a new magnetic compound of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ was discovered by Coey and Sun [67], employing mechanical alloying method at Trinity College, Dublin University. They showed that the magnetic properties of these permanent magnets are excellent and the Curie temperature is in the range of 450°C , with $(\text{BH})_{\text{max}}$ of about 400 kJ/m^3 . The main drawback of these magnets is the sintering process at high temperature, because $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ compound is not stable at high temperature and decomposes into αFe and SmN phases above 600°C . After the discovery of the $\text{Sm}_2\text{Fe}_{17}\text{N}_3$ permanent magnets, they used as bounded magnets so as to avoid the sintering process. The effect of niobium on the microstructure and Curie temperature of $\text{Sm}_2\text{Fe}_{17}$ based cast alloys were studied by Sinan *et al.* [68]. They found that some enhancement in Curie temperature occurs with addition of 4at. % Nb. In 1995, Platts, Harris, and Coey [69] used a technique for producing $\text{Sm}_2\text{Fe}_{17}$ ingots without free iron phase by addition of Nb, and the free iron phase replaced by paramagnetic NbFe_2 with addition of Nb between 4 and %5 at. The process was followed by nitriding procedure to produce permanent magnet of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$.

Further information about mechanical alloying of these magnets has been reported [70, 71]. Effect of some additives was studied by Sinan *et al.* [72] to enhance the magnetic properties of $\text{Sm}_2\text{Fe}_{17}\text{N}_3$. Later, Sm-Fe-N bulk magnets have been produced using nonconventional consolidation techniques such as deformation- shearing process and shock compression route [73-75]. They produced anisotropic Sm-Fe-N bulk magnets with maximum energy product of 228kJ/m^3 and corectivity of 0.88MA/m [74]. Fig. 5 shows the historical development of permanent magnets starting from 1917, from which we can see that the Nd-Fe-B magnets still at the top of the permanent magnets at the present time. This curve does not mean that we are prefer to use the Nd-Fe-B magnets, as they have the highest energy product, but that depends upon what sort of magnets we are looking for according to the aim of their use.

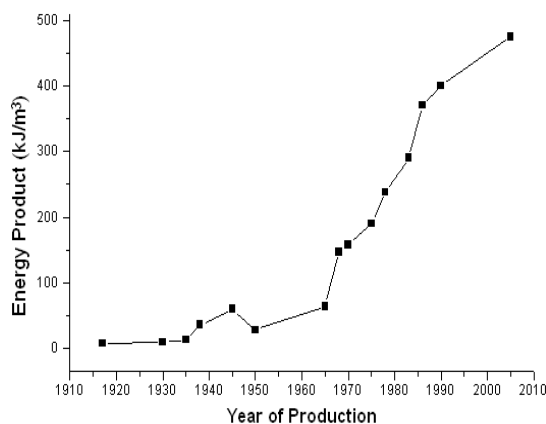


Fig. 5. Historical development of permanent magnets

(vii) Sm - F e - N magnets:

3. Large scale application:

In the present time, Nd-Fe- B permanent magnets are very strong and thermally stable enough to be employed in the large scale such as Maglev system, motors, MRI (Magnetic Resonance Imaging) for medical application and in high energy physics filed to produce charged particle beams. This subject has been discussed by Stekly *et al.* [76] and [66]. They confirmed that Nd-Fe-B permanent magnets can be used in large scale because of their low price and more abundant compared with Sm-Co magnets, but for high temperature applications, magnets of Sm-Co are still preferable on Nd-Fe-B magnets. This subject is very important from energy resources point of view in order to face the lack of energy sources in the future, as the Maglev system depends on magnetic energy.

4. Some recent work on Nd-Fe-B magnets:

Nano crystalline Nd-Fe-B powder was produced by mechanical milling under hydrogen atmosphere with pressure of around 0.5MPa at room temperature [77]. The best magnetic properties were H_{ci} , B_r , and $(BH)_{max}$, 635.3kA/m, 0.8T, and $106.3kJ/m^3$ receptively, at sintering temperature of about $780^{\circ}C$ under vacuum of 5×10^3 Pa. Comparison between magnetic properties of HDDR powder and ultrafine particles was done in this article. Effect of hot extrusion on magnetic and microstructure on $Nd_2Fe_{14}B/\alpha Fe$ nanocomposite has been studied by Jiang *et al.* [78]. They were following the effect of the first extrusion temperature on the properties of the second extrusion. On the basis of their results, the best magnetic properties were achieved when the first extrusion temperature was about $950^{\circ}C$.

The coercive force of sintered Nd-Fe-B magnets decreases when the degree of alignment of $Nd_2Fe_{14}B$ hard phase particle increases. This subject has been treated by Yutaka *et al.*; their result showed that the experimental data can be explained on the magnetic domain wall motion to clarify the relation between the grains alignment and the coercive force of this type of magnets [79]. In 2013, magnetic property and microstructure of single crystalline $Nd_2Fe_{14}B$ ultrafine particles ball milled from HDDR powders were investigated [80]. They showed very nice TEM and SEM microstructure work upon $Nd_2Fe_{14}B$ alloy, and they confirmed that the produced powder was single crystal with almost about 280nm particle size as an average particle value.

In 2104, Comparison between spark plasma sintering (SPS) and conventional route of production of Nd-Fe-B magnets was reported by Wang *et al.* [81]. They showed that the specimens produced by SPS method better mechanical properties, so that values of bending strength of 402.3MPa and Vickers hardness of 778.1MPa were achieved. In general, their conclusion was that the experimental results of SPS samples have the same excellent magnetic properties and better mechanical properties than that fabricated by the conventional route. Also during 2014, improvements on HDDR were made by Sheridan *et al.* in the School of Metallurgy and Materials, University of Birmingham to produce anisotropic powder

starting from sintered magnets of Nd-Fe-B [82]. The result of this work showed that the magnetic properties can be enhanced due to decrease of the oxidation of the Nd-rich phase at the grain boundaries.

5. Conclusion:

The Permanent magnets play a vital role in the development of modern technology. Most of research groups in this field focus their work on improving the magnetic properties, such as energy product, coercivity, remanence, and Curie temperature. Heat treatment and magnetic alignment are found to be extremely important factors in controlling magnetic properties. More attention has to be given to the study of microstructures of permanent magnets, in order to obtain a complete understanding of the magnetic properties. Since the discovery of Nd-Fe-B permanent magnets, the corrosion resistance has been recognised as an area where improvements would be of great practical value. Many workers in this field are focusing their researches to find new magnetic materials with excellent magnetic properties, availability and with low cost.

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