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Magnetic properties of permanent magnets for magnetic sensors working in wide range of temperature

***Abstract**. Permanent magnets are used in many sorts of devices. They are applied in many electromagnetic transducers – like, for example, electric machines and measurement instruments. Nowadays a new generation of sensors, especially position sensors, are fitted with permanent magnets. Different types of sensors and different working environments require the application of permanent magnets with parameters adapted to working conditions, such as, among other things, the temperature of operation. This paper presents a review of permanent magnets, their magnetic properties and their properties in different temperatures.*

***Streszczenie.** Magnesy trwałe znajdują zastosowanie w wielu rodzajach urządzeń, przykładowo w maszynach elektrycznych i przyrządach pomiarowych. Nowe generacje sensorów , w szczególności czujniki położenia, zawierają również magnesy trwałe. Sensory pracujące w różnych warunkach wymagają doboru właściwych parametrów magnesów, między innymi, do pracy w różnych temperaturach. W artykule dokonano przeglądu magnesów trwałych oraz ich właściwości w szerokim zakresie zmian temperatury (**Właściwości magnetyczne magnesów trwałych dla sensorów pracujących w szerokim zakresie temperatur**).*

Keywords: permanent magnets, Alnico magnets, ferrite magnets, bonded magnets.
Słowa kluczowe: magnesy trwałe, magnesy Alnico, magnesy ferrytowe, magnesy proszkowe.

Introduction

The development of soft and hard magnetic materials is one of the main factors decisive for the development of a new generation of equipment, among other things, sensors. Magnetic materials are divided into two main groups, namely soft and hard magnetic materials. The criterion of dividing is the value of coercivity. Standard IEC Standard 404-1 proposed 1 kA/m as a borderline value of coercivity. As soft magnetic materials we consider magnetic materials with coercivity lower than 1 kA/m. As hard magnetic materials we consider materials with coercivity higher than 1 kA/m. Between soft and hard magnetic materials there is the group of magnetic materials called semi-hard magnetic materials. Coercivity of these kinds of magnetic materials is 1 to 100 kA/m [1,2]. All magnetic materials are characterized by different forms of hysteresis loop (Figure 1). The most important values are: remanence B_r, coercivities H_{cJ}, H_{cB} and maximum energy product $(BH)_{max}$ which determines the point of maximum magnet utilization. Electric machines, instruments and sensors with permanent magnets, according to magnetic circuit-characteristics, work on reverse part of the loop between values of B_r, H_{cJ} or H_{cB}. This is the main difference in comparison with devices excited electromagnetically by excitation currents. The working point depends on magnetic circuit change or deformation, on load current reaction, ambient or work temperatures and changes of parameters with time. Some very important parameters for permanent magnets are Curie temperature and coefficient of temperature. One of the main limitations for the application of permanent magnets is the deterioration of magnetic properties in elevated temperature. Magnetic parameters of permanent magnets are as a rule measured in room temperature. With changes of temperature properties of materials also change; this includes magnetic materials. In the case of permanent magnets these changes are either reversible or irreversible. Reversible changes are those which disappear after the temperature returns to room temperature. Irreversible changes are the result of changes in microstructure of materials and changes of domain structure. Losses stemming from changes of domain structure can be reversed by remagnetization. Changes stemming from shifts in microstructure of materials permanently alter the magnetic properties of permanent magnets. Thus, two very important factors, ones indeed decisive for the magnet's applicability, are Curie temperature and temperature coefficient of coercivity and remanence. Curie temperature is a temperature above which the material's magnetic properties are gone. Temperature coefficient of coercivity and remanence reflects reversible changes of magnetic properties of permanent magnets. Curie temperature and temperature coefficient are features of material, dependent on the kind of hard magnetic materials.

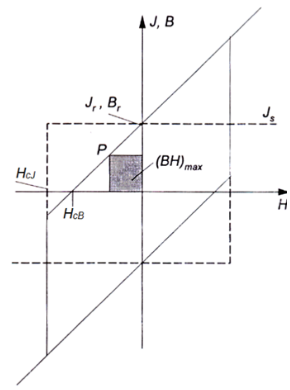

Fig. 1. Example of hysteresis loop, J_r – remanence of magnetic polarization, B_r – remanence of magnetic flux density, H_{cJ} – coercivity of magnetic polarization, H_{cB} – coercivity of magnetic flux density, $(BH)_{max}$ – maximum energy product, maximum density of magnetic energy [3]

Permanent magnets are used in many devices. The main recipient of permanent magnets is the electric machines and instruments industry. They are used not only in electric motors, but also in various types of electromagnetic transducers, analogue measurement devices with magnetic circuits. Nowadays the development of various sensors with permanent magnets can be observed. Magnetic sensors find a wide range of application in industrial automatics – in electric drives designed for specific purposes, in automotive technology, in the increasingly developing technology of the so-called "intelligent buildings", in medical technology, etc. [4]. Some examples of magnetic sensors:

- proximity magnetic sensors,
- magnetic encoders,
- linear position sensors,
- precise position sensors,
- read relay.

This type of sensors requires the application of permanent magnets that display stability of magnetic induction, and are relatively insensitive to fluctuations of temperature, humidity and vibrations. Sensor technologies can be divided to "macro" sensors, in which permanent magnets whose dimensions range from several millimetres to several centimetres, and "micro", whose magnetic elements are produced in the thin layer technology. The following paper cites the results related to forming, magnetizing and testing the properties of magnetic materials applicable in sensors technology.

Permanent magnets

Permanent magnets can be divided into three main groups depending on the technology of production: cast, sintered or bonded magnets. Bonded permanent magnets are very often referred to as dielectromagnets or ferroplast. The powder metallurgy methods have many advantages such as, e.g., low losses of materials, and low consumption of labour and energy. Another division of permanent magnets depends on the type of magnetic materials used. In this group are Alnico magnets, ferrite magnets, Sm-Co or Nd-Fe-B magnets.

Alnico permanent magnets

The widespread development of devices with permanent magnets starts with the introduction of Alnico cast magnets and ferrite sintered magnets. The most widespread of cast permanent magnets are Alnico type permanent magnets. The first investigations of this type of permanent magnets had been started by the Japanese scientist Mishima on Fe_2NiAl. This alloy is a basic material for the production of permanent magnets of types such as Alni, Alnico, Alcomax, Ticonal [1, 2, 5, 6]. The technology of production consists in casting alloys to mould. One very important parameter of technology is thermal or thermal-magnetic treatment. This treatment improves magnetic properties and temperature stability of ready-made permanent magnets. Alnico magnets are characterized by a high value of remanence and low value of coercivity. Thus it is possible to easily demagnetize permanent magnets of this type. The main advantages of Alnico type of magnets are: high value of remanence and Curie temperature as high as 850°C. They show the best thermal stability and can work in up to 550°C. The disadvantages of Alnico permanents magnets are, beside their low value of coercivity, brittleness and high hardness. They require machining after casting.

Additional disadvantage of these magnets is their high price resulting from the high price of cobalt. Permanent magnets from Alnico alloys can be manufactured either by powdering and sintering, or by powdering and bonding, but due to their very poor magnetic properties and high price, permanent magnets of this kind are produced in low volumes. Table 1 shown, as an example, magnetic properties of Alnico magnets.

Table 1. Properties of examples of Alnico permanent magnets, $TK(H_{cJ})$-thermal coefficient of magnetic polarization coercivity [3,4]

Tape of Alnico	B_r	H_{cB}	$(BH)_{max}$	$TK(H_{cJ})$	$TK(B_r)$
	[T]	[kA/m]	[kJ/m^3]	[%/°C]	[%/°C]
Cast	1,30	60	55,5	-0,02	-0,02
Sintered	0,85-0,90	115-127	35,8-63-3	-0,02	-0,02

Ferrite magnets

In 1950 Philips laboratories elaborated and patented a conception of an oxide mixture: PbO, BaO, SrO with Fe_2O_3 as a material for production of permanent magnets. These compounds, called ferrites, are distinguished by their high magnetocrystalline anisotropic energy. Ferrite magnets are manufactured by powder metallurgy technology. The most widespread application of ferrite magnets is in strontium and barium ferrite magnets. Ferrite powders can be used for production of sintered and resin-bonded magnets in isotropic and anisotropic version. Magnetic properties of ferrite magnets are not very high, but – their coercivity being higher than coercivity of Alnico magnets – they are less sensitive to demagnetization. High resistivity allows ferrite magnets to work in a variable magnetic field with high frequency. Curie temperature of ferrite magnets is 450°C. The behaviour of ferrite magnets in different temperatures is different than that of other kinds of permanent magnets. With elevated temperature coercivity increases but remanence decreases. Temperature coefficient of coercivity has positive value. In temperatures below 0°C the remanence of ferrite magnets increases while coercivity decreases. Ferrite magnets can work in up to 250°C. The disadvantages of ferrite magnets are their brittleness and high shrinkage after sintering. They need machining after sintering process. Ferrite magnets can be prepared as sintered or bonded magnets and isotropic or anisotropic in character. Permanent magnets of this type are the most popular, mainly due to their low price. Table 2 shows examples of ferrite magnets [1, 2, 6].

Table 2. Magnetic properties of selected ferrite magnets, $TK(H_{cJ})$-thermal coefficient of magnetic polarization coercivity, $TK(B_r)$-thermal coefficient of magnetic remanence [5, 6]

Type of ferrite magnets	B_r	H_{cJ}	H_{cB}	$(BH)_{max}$	$TK(H_{cJ})$	$TK(B_r)$
	[T]	[kA/m]	[kA/m]	[kJ/m^3]	[%/°C]	[%/°C]
Barium ferrite-sintered	0,38	180	155	27,0	+0,3	-0,2
Strontium ferrite-sintered	0,40	275	265	30,0	+0,3	-0,2
Compression moulded	0,26	225	180	15,5	+0,3	-0,2

Permanent magnets type R – Co

Investigation shows that RCo_5 and R_2Co_{17} (R rare earth elements) are characterized by a significant magnetocrystalline anisotropy and saturation induction. Sintered magnets are prepared by powder metallurgy – powder with grain size about 5 μm is pressed in the presence of magnetic field, then sintered in about 1150^{o}C; sometimes heat treatment in lower temperatures is necessary. Sintering and heat treatment must be conducted in protective atmosphere such as argon, or in a vacuum. This type of permanent magnets is characterized by a high value of magnetic properties. The maximum energy product $(BH)_{max}$ reaches values ranging from about 150 kJ/m^3 up to 400 kJ/m^3. Curie temperature R-Co magnets is about 825°C. Temperature coefficient of remanence and coercivity has a negative value; it means that magnetic properties decrease with increasing temperature. Samarium – cobalt permanent magnets can work in temperatures up to about 350°C. This type of powders can be used for preparing bonded magnets by compression or injection moulding technology. The method of manufacturing bonded magnets consist in preparing a mixture of magnetic powder with bonding agent, and then injecting the mixture (injection moulding) or pressing and curing (compression moulding). Magnetic properties of permanent magnets made by injection or compression moulding are lower than those of sintered magnets – in the range of 180°C – 300°C. One of the disadvantages of R-Co permanent magnets is their high cost related to the market price of samarium and cobalt [1, 2, 6].

Table 3. shows examples of R-Co permanent magnets [8, 14]

Type of magnets	B_r	H_{cJ}	H_{cB}	$(BH)_{max}$	$TK(H_{cJ})$	$TK(B_r)$
	[T]	[kA/m]	[kA/m]	[kJ/m^3]	[%/°C]	[%/°C]
Sm_2Co_{17}	0,96	1600	700	175	-0,19	-0,03
$SmCo_5$	0,85	1750	640	155	-0,25	-0,04
Sm_2Co_{17}	0,96	1600	700	175	-0,15	-0,03

Nd-Fe-B permanent magnets

Permanent magnets from the R-Co group have very good magnetic properties, but their disadvantage is a high price – researchers were looking for permanent magnets with comparable magnetic properties but less expensive. The next stage of development in the technology of manufacturing hard magnetic materials was the creation of hard magnetic materials from Nd-Fe-B alloys. This type of permanent magnets was first developed in 1984 by Sumitomo Special Materials in Japan and General Motors in USA. The good magnetic properties of intermetallic phase $Nd_2Fe_{14}B$ are caused by ferromagnetic coupling of magnetic moments in sublattice of the rare earth group and iron [1, 2, 3, 6]. Among the advantages of the Nd-Fe-B compound is its lower price and easier access to components. The content neodymium in ore is several times higher than that of samarium; iron is, of course, cheaper then cobalt. It is the reason why this type of permanent magnets has been more widely applied. The main advantages of Nd-Fe-B are their magnetic properties, high remanence and coercivity. Their disadvantage, however, is low Curie temperature 310˚C and maximum working temperature of about 110˚C [1, 2, 6, 13]. Nd-Fe-B is a basic material for preparing different types of permanent magnets – sintered, resin-bonded, hot pressed and die upsetted (Figure 2).

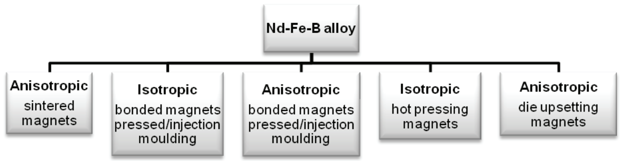

Fig. 2 Permanent magnets prepared from Nd-Fe-B alloys

All of these types of permanent magnets are prepared from Nd-Fe-B alloy powder, but since powders are prepared by different methods, their properties, as well as structure, size etc., vary (Figure 3).

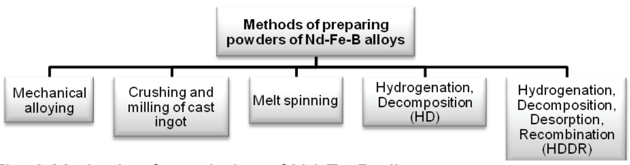

Fig. 3 Methods of powdering of Nd-Fe-B alloy

Sintered and bonded types of Nd-Fe-B permanent magnets are ones that are used most frequently. Sintered Nd-Fe-B magnets are manufactured by classic powder metallurgy method. In the first stage alloy is powdered and then powder with grain size about 3 µm is pressed in the presence of magnetic field. Green compact is sintered and heat treated in protection atmosphere in temperature 1000 °C. These types of Nd-Fe-B permanent magnets are anisotropic in character and have to be magnetized in the same direction as the direction of magnetic field during pressing. Due to high shrinkage during sintering, process magnets have to be machined before magnetization. Rapid growth of application of Nd-Fe-B permanent magnets has been observed; of the sintered type as well as the bonded Nd-Fe-B permanent magnets. It is connected with many advantages of bonded magnets. The technology of preparing bonded magnets, called ferriplast or dielectromagnets, is simpler than sintering technology, as the process requires lower temperatures, without protective atmosphere. Nd-Fe-B dielectromagnets can be made by compression or injection moulding. Nd-Fe-B powder for both methods is prepared by melt spinning method, and the melt-spun ribbon is powdered into grain size about 250 µm. One very important virtue of such technology is the possibility of tailoring physical properties of magnets, not only magnetic properties but mechanical, electric or thermal properties, too. The disadvantage of magnets, including dielectromagnets, made from Nd-Fe-B alloys is their thermal properties, mainly the high negative value of temperature coefficient of coercivity. This parameter in many cases makes use of such magnets impossible. One advantage of ferrite magnets is their positive value of temperature coefficient of coercivity. Studies have shown that making dielectromagnets from the mixture of Nd-Fe-B powder and strontium ferrite powder allows us to improve the temperature coefficient of coercivity-table 4 [15].

Table 4. Magnetic properties of bonded magnets from mixture of powders

Magnets type	$TK(H_{cJ})$ [%/˚C]
Nd-Fe-B	-0,3 ÷ -0,5
Nd-Fe-B + 25 wt. % of ferrite	-0,31
Nd-Fe-B + 50 wt. % of ferrite	-0,27

Thus, tailoring physical properties of this type of permanent magnet makes it possible to produce magnets suited exactly to the requirements of those who design devices with permanent magnets. It is the reason why the area of application for these types of permanent magnets has been growing. Of course, magnetic properties of bonded Nd-Fe-B permanent magnets are lower than magnetic properties of sintered magnets. It is connected with lower content of magnetic powder in bonded magnets. Such properties are, however, sufficient for many applications. Table 5 shows magnetic properties of different type of Nd-Fe-B permanent magnets.

Table 5. Magnetic properties of different types of Nd-Fe-B permanent magnets [8, 9, 17]

Type of Nd-Fe-B magnets	B_r [T]	H_{cJ} [kA/m]	H_{cB} [kA/m]	$(BH)_{max}$ [kJ/m^3]	$TK(H_{cJ})$ [%/˚C]	$TK(B_r)$ [%/˚C]
Sintered	1,43	950	915	398	-0,56 ÷ -0,57	-0,12
Compression moulded	0,63	1194	446	72	-0,4	-0,16
Injection moulded	0,45	1000	300	37	-0,4	-0,13
Die upset	1,31	1280	980	334	-0,45	-0,16

Bonded Nd-Fe-B magnets are manufactured mainly in the isotropic version. Isotropic magnets can be magnetized in all direction and multipole. It is very important for many applications, particularly in sensors, such as permanent magnets for position sensors or read relay. Fig. 4 shows examples of multipole magnetization.

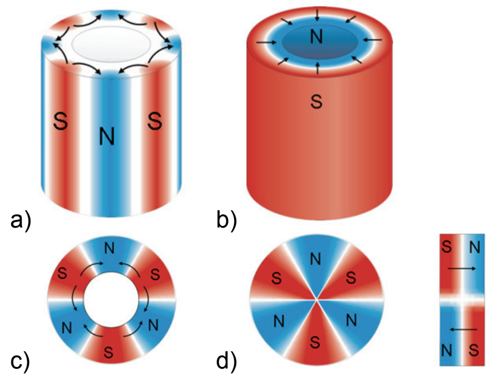

Fig. 4 Methods of magnetization (a) multipole on outside circumference, (b) radialy oriented, (c) multipole on inside circumference, (d) magnetized axially in segment with alternating poles

Conclusions

The review shows that a broad range of permanent magnets with different magnetic, thermal, electric and mechanical properties is available on the market. The choice of magnets for particular sensors depends on the design of sensor and environmental conditions in the workplace. Magnetic properties are, of course, the main factor decisive for application of permanent magnets, but sometimes corrosion resistance is very important as well. In high humidity ferrite magnets are preferred. Ferrite magnets are oxide materials with high resistance to corrosion. Sintered magnets very often require a special layer of coating for anti-corrosive protection. Sensors with permanent magnets can work in temperatures from below zero Celsius to room temperature to elevated temperatures. The behavior of permanent magnets with changes of temperature depends on the type of hard magnetic materials. Designers of sensors have to take into consideration changes of properties of magnets in different temperatures of operation.

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