RARE EARTH PERMANENT MAGNETS

VACODYM · VACOMAX

ADVANCED MAGNETIC SOLUTIONS

VACUUMSCHMELZE

THE COMPANY
VACUUMSCHMELZE

ADVANCED MAGNETIC SOLUTIONS

VAC is a leading manufacturer of magnetic alloys and the solutions derived from them. We drive today's and tomorrow's technologies with passion. As a trusted partner, we work with our customers to develop application solutions that enable them to meet ever-increasing demands. With groundbreaking solutions, we push the limits of technology. The use of our materials and their unique magnetic properties is the key to making our customers' solutions smaller, lighter, more efficient, and, above all, safer. In doing so, we make a significant contribution to conserving resources and protecting our environment.

TABLE OF CONTENTS

RARE EARTH PERMANENT MAGNETS
VACODYM AND VACOMAX

Together with permanent magnets, VAC's product range also includes soft magnetic semi-finished products and parts, inductive components, magnetic shielding, magneto-caloric and other materials with special physical properties. Apart from rare earth permanent magnets, the range of magnets also includes ductile permanent magnets and magnetically semi-hard materials. The latter are mainly characterized by low-cost shaping options and adjustable permanent magnet properties.

We have been developing and optimizing the magnetic properties of specialized metallic materials and their applications for 100 years. In 1973, we started producing rare earth (RE) and cobalt-based permanent magnets using powder metallurgical processes which to this day are produced and sold under the trade name VACOMAX®.

In 1986, industrial-scale production of VACODYM® magnets began. They are manufactured based on neodymium-iron-boron alloys. From manufacturing the powder to coating the finished parts, we can carry out all steps in-house and can thus ensure optimized material properties over the entire production process. As the European market leader, we are today one of the world's top-rated producers of rare earth permanent magnets.

We continuously pursue intensive development to align our range of VACODYM alloys to market demands, for example, for medical applications, sensor technologies, and electro-mobility. The single-pressing processes established at VAC are resource-efficient and are characterized by a high level of reproducibility of the magnetic properties.

If required, VAC has the option to use pre-alloys produced in Europe. Further information is available from our staff upon request.

Efficient production facilities, modern testing technologies, and a certified quality management system are as standard for us as the continuous training of our employees and active workplace and environmental protection. With these principles guiding our business policy, we are your reliable and competent partner.

The following chapters provide a more detailed description of our products. Further information is available on our website.

PRODUCT RANGE

The product range of our rare earth magnets includes balanced sets of materials with different magnetic properties. They enable an easy material selection adapted to individual operating conditions.

VACODYM is the permanent magnet material offering the highest energy densities among the highest energy densities currently available. The excellent magnetic properties of this material group can be traced to the strongly magnetic matrix phase $Nd_2Fe_{14}B$ with very high saturation polarization and high magnetic anisotropy. A rare earth-rich phase between grains gives these magnets good opposing field stability. Depending on the operating temperature, part of the neodymium contained in the VACODYM alloys is replaced by other rare earths such as dysprosium, terbium or praseo-dymium, enabling us to always provide the right material for temperatures between -270 °C and +240 °C.

VACOMAX is a permanent magnet material made from rare earths and cobalt. These magnets have excellent temperature and corrosion stability, allowing for magnetic performance up to +350 °C. Thanks to a low remanence loss under higher temperatures, VACOMAX provides higher energy densities than VACODYM for applications above 150 °C.

Fig. 1 shows an overview of the achievable energy densities $(BH)_{max}$ of selected permanent magnet alloys as a function of the operating temperature.

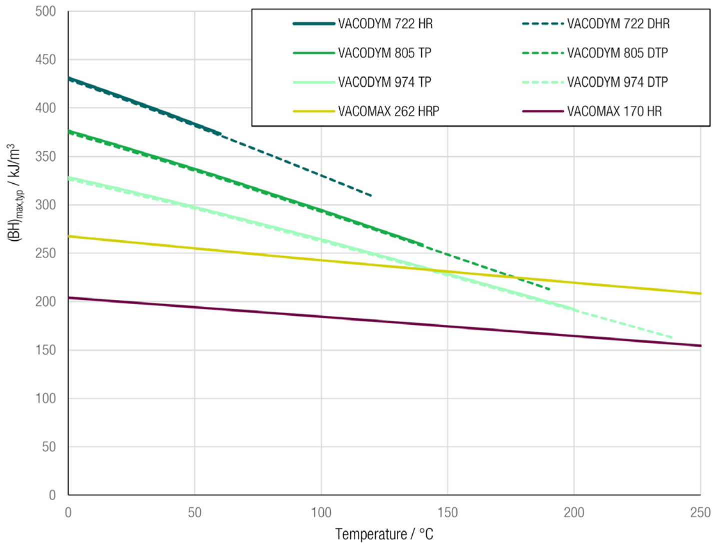


Fig. 1: Typical energy densities $(BH)_{max}$ of selected VACODYM and VACOMAX permanent magnet alloys depending on the temperature

Magnets made of VACODYM and VACOMAX are produced by sintering using powder metallurgical processes. The main steps of the production process are illustrated in Fig. 2. The magnetic properties vary depending on the composition of the alloy and the pressing process. At VAC, we use three different pressing processes. These three processes are reflected in the alloy name with the letters HR, TP or AP. HR (High Remanence) refers to isostatically pressed magnets.

In die-pressed designs, we differentiate between TP (Transverse-Pressed) and AP (Axial-Pressed). During TP-processes, the powder particles are aligned by strong magnetic fields perpendicular to the direction of pressing, while they are aligned parallel to the direction of pressing for the AP process. Isostatically and transverse-field pressed parts have approximately 5-8 % higher remanence values when compared to axial-field pressed magnets.

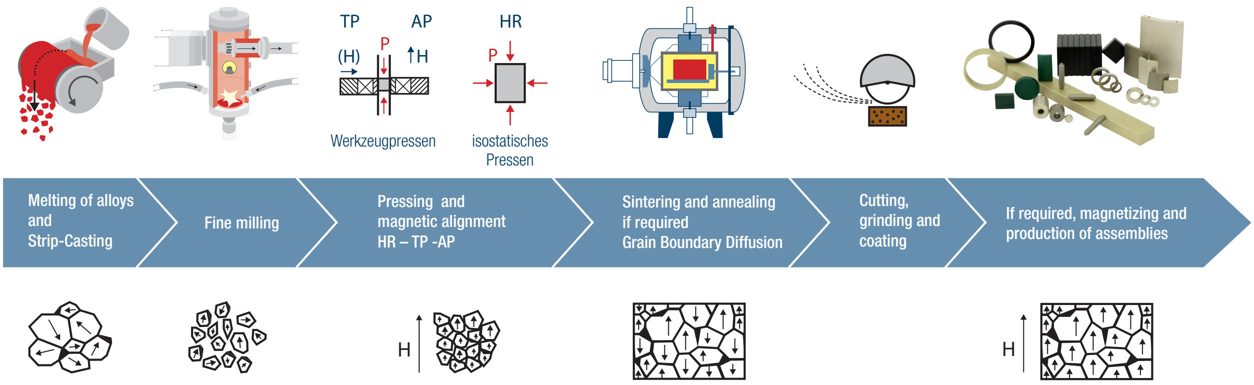


Fig. 2: Schematic illustration of the powder metallurgical production processes for VACODYM and VACOMAX sintered magnets

One of VAC's unique expertise is the single part pressing process. Contrary to the widely used die pressing of large magnet blocks, this process allows for even the smallest magnets to be manufactured as closely to the dimensions specified by the customer. This way, some of the usual mechanical processing steps can be omitted, which significantly increases resource efficiency. In addition, this process enables highly replicable magnetic properties, which can be further combined with specific magnetization directions depending on customer requirements. (Fig. 3). In the single part pressing process, for example, it is possible to produce magnets that exhibit a one-sided increase in magnetic flux, thereby enabling higher air-gap inductions. Another advantage of the single part pressing technology is the precise adjustment of the magnetization direction with minimal part-specific deviations. Upon customer request, VAC can also produce magnets with special magnetization directions - for example, with a magnetization axis tilted from the mechanical symmetry axis - in large quantities (Fig. 3c).

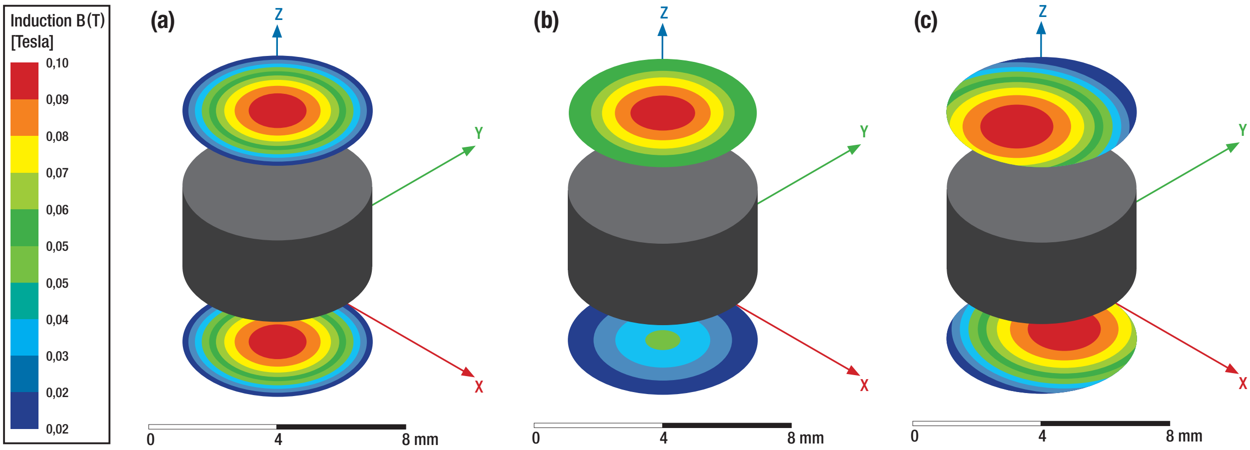


Fig.3: Micromagnetic simulations of a (a) homogeneous magnet, (b) magnet with a one-sided flux increase and (c) magnet with special magnetization direction

Regarding resource efficiency, in addition to the single part pressing technology, a process step known as grain boundary diffusion has been established. This process not only increases the coercivity of VACODYM but also enables a reduction in the use of heavy rare earth metals, which are limited in global availability. Using a patented method, terbium or dysprosium is enriched in a thin layer that coats the individual neodymium-iron-boron grains within the magnet (Fig. 4). This process step can, in principle, be applied to all fully ground VACODYM sintered magnets and is indicated by the suffix “D” in the alloy designation. Depending on the selected base alloy, an increase in coercivity of more than 520 kA/m (6.5 kOe) can be achieved for part thicknesses up to 3 mm. The diffusion process is also applied to a wide range of parts with significantly greater thicknesses and can be selectively applied to specific surfaces upon customer request.

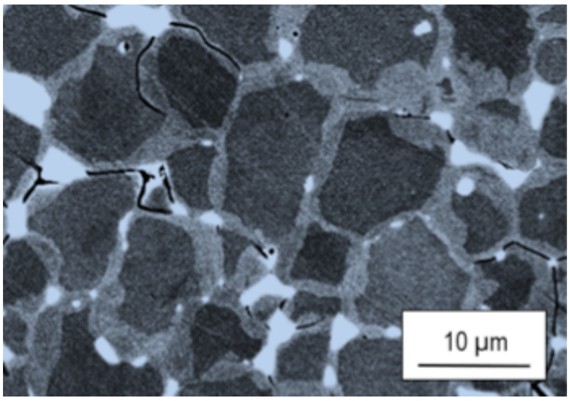


Fig. 4: Microstructure of a VACODYM magnet after grain boundary diffusion. Terbium-rich grain shells are visible as brighter contrast

However, due to the characteristic diffusion length of only a few millimeters, certain limitations apply, and consultation with our specialists is recommended.

With many years of experience in the production of permanent magnets, we are also able to rapidly develop and reliably manufacture special alloys tailored to customer requirements on an industrial scale. In addition, the continuous development of our own production processes allows the introduction of increasingly optimized alloys. In the VACOMAX product range in particular, the trend is moving toward new material grades with energy densities exceeding 270 kJ/m³.

In addition to individual magnets, a steadily growing number of magnetic assemblies are also part of our production portfolio. Detailed information on this topic can be found on pages 24 and following.

As a European manufacturer of rare earth permanent magnets, resource efficiency and the sustainable availability of raw materials are naturally essential elements of VACUUMSCHMELZE’s corporate philosophy. Regarding the sustainable supply of raw materials, we rely on long-established and qualified supply chains.

APPLICATIONS

Due to their high energy density and stability against demagnetizing fields, rare earth permanent magnets are used in a wide range of applications.

MOTORS AND GENERATORS

In servo drives for automation technology, DC machines, linear drives, and large-scale machines (e.g., motors for rail and ship propulsion or wind and hydroelectric generators), VACODYM magnets are predominantly employed. Our Finnish subsidiary NEOREM Magnets Oy specializes in the production of large magnets and further refined systems (see also www.neorem.fi).

Another important application area is that of small and micro motors, e.g dental motors. For special requirements, particularly in high-temperature environments, VACOMAX magnets are preferably used.

AUTOMOTIVE ENGINEERING AND SENSORS

Contactless sensors for capturing a wide range of operational data - such as motor, gearbox, and wheel speeds (ABS systems), accelerations (ESP, airbags), or positions (throttle valve, injection system, camshaft, crankshaft, fuel gauge) are built using VACOMAX or VACODYM magnets depending on the required temperature and corrosion resistance.

In electric and hybrid vehicles, permanently excited synchronous machines are primarily used as main drives. These motors are predominantly equipped with VACODYM magnets. For motorsport applications, VACOMAX magnets are also available to meet the highest thermal requirements.

VACODYM magnets are used for actuators in engine management, transmission, auxiliary motors (e.g., power steering) and generators.

With a high level of automation, large-scale production can be carried out cost-effectively while maintaining consistently excellent quality.

HIGH-SPEED ROTORS

For high-speed rotors, such as those used in motorsport or electric turbochargers, we offer complete rotors fully equipped with VACODYM or VACOMAX magnets, including banding and balancing (see pages 24 and following). For the soft-magnetic components, we use high-strength cobalt-iron materials like VACODUR®. All required hard- and soft-magnetic materials are part of VAC's comprehensive product range. This wide selection allows us to deliver solutions precisely tailored to your individual requirements.

AEROSPACE AND AVIATION

Optimized VACOMAX or VACODYM magnets are used in the development of electric drives for aviation. To increase power density, segmented Halbach arrangements are typically combined with our soft magnetic alloys VACOFLUX® or VACODUR. This enables the construction of lightweight drives. VAC supports this future-oriented trend through collaborative development projects, some of which are publicly funded, together with partners from industry and academia.

For other applications, such as auxiliary drives, actuators, and gyroscopes in aerospace technology, we supply magnets made from VACODYM or VACOMAX, depending on the specific requirements.

SCIENTIFIC APPLICATIONS

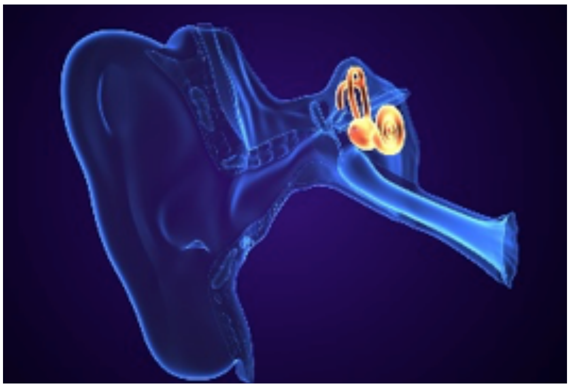
Permanent magnet beam guides are practically maintenance-free and require no energy supply. Systems with VACODYM or VACOMAX magnets have therefore established themselves in all cases where high field strengths must be achieved within a limited space, e.g. in wigglers, undulators, multipoles and particle detectors.

For these applications, precisely matched and coordinated magnet sets can be manufactured with tight tolerances in terms of mechanical and magnetic properties. The single part pressing technology ensures particularly tight distributions with respect to homogeneity and the angular alignment between the magnetic easy axis and the part geometry.

Renowned scientific institutions rely on VAC's expertise, reliability, and quality - for example, when it comes to the design and construction of complex undulator structures or sophisticated Halbach systems.

For low-temperature applications, the specially developed VACODYM 131 alloy is available.

MEDICAL TECHNOLOGY



In miniature systems such as heart pumps, blood pumps, or cochlear implants, VACODYM magnets and sophisticated magnetic assemblies are used due to their high remanence flux density. Other applications include drives for dental and surgical technology, for which micro-motors equipped with VACODYM magnets are manufactured.

For imaging techniques such as magnetic resonance imaging (MRI), components are typically produced as individual magnets, but increasingly also as complex permanent magnet systems in Halbach configuration, made from VACODYM according to customer specifications.
These systems operate without potentially harmful, ionizing X-rays. Another advantage is that they allow for improved visualization of organs and tissue types.

PERMANENT MAGNET BEARINGS

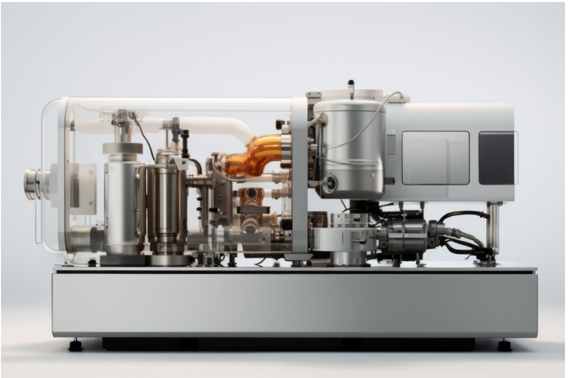
For turbomolecular pumps, centrifuges, and similar applications, various magnetic bearing concepts are available. In passive magnetic bearings, axially magnetized ring magnets are preferably used. The choice of magnet material depends on the specific customer requirements, so either VACODYM or VACOMAX can be applied.

In vacuum technology applications, VACOMAX is typically used due to its superior resistance to environmental influences.

MAGNET COUPLINGS

Magnetic couplings are preferred in automation technology and chemical process engineering as they ensure permanent hermetic separation between different media. Due to increased temperature requirements, VACOMAX magnets are used for many applications. For lower operating temperatures we recommend VACODYM magnets.

MEASURING INSTRUMENTS



The range of the applications extends from electronic scales to pulse counting meters to mass spectrometers and NMR measuring systems (Nuclear Magnetic Resonance). Depending on the chosen design principle, systems, armatures, or rotors with VACODYM or VACOMAX magnets are used.

MATERIALS AND MAGNETIC PROPERTIES

The alloys listed below only represent a selection of all available alloys.
The complete range can be found on our website.

TABLE 1: CHARACTERISTIC PROPERTIES OF VACODYM AT ROOM TEMPERATURE (20 °C)

	REMANENCE		COERCIVITY						ENERGY DENSITY	
	$B_{r\ typ.}$	$B_{r\ min.}$	$H_{cB\ typ}$		$H_{cB\ min.}$		$H_{cJ\ min.}$		$(BH)_{max\ typ.}$	
	T	T	kA/m	kOe	kA/m	kOe	kA/m	kOe	kJ/m^3	MGOe
VACODYM 633 HR	1.35	1.29	1040	13.1	980	12.3	1275	16	350	44
VACODYM 655 HR	1.28	1.22	990	12.4	925	11.6	1670	21	315	40
VACODYM 722 HR	1.47	1.42	915	11.5	835	10.5	875	11	415	53
VACODYM 745 HR	1.44	1.40	1115	14.0	1065	13.4	1115	14	400	50
VACODYM 238 TP	1.37	1.33	1058	13.3	1008	12.7	1275	16	360	46
VACODYM 633 TP	1.32	1.28	1020	12.8	970	12.2	1275	16	335	42
VACODYM 688 TP	1.14	1.09	885	11.1	830	10.4	2625	33	250	32
VACODYM 745 TP	1.41	1.37	1090	13.7	1035	13.0	1115	14	385	48
VACODYM 776 TP	1.32	1.28	1020	12.8	970	12.2	1670	21	335	42
VACODYM 837 TP	1.37	1.33	1060	13.3	1010	12.7	1275	16	360	46
VACODYM 890 TP	1.19	1.15	915	11.5	865	10.9	2625	33	270	34
VACODYM 956 TP	1.35	1.32	1030	13.0	995	12.5	1670	21	350	44
VACODYM 992 TP	1.22	1.19	940	11.8	900	11.3	2385	30	285	36
VACODYM 801 TP	1.42	1.40	1060	13.3	980	12.3	1035	13	390	49
VACODYM 805 TP	1.37	1.35	1050	13.2	1020	12.8	1670	21	360	45
VACODYM 809 TP	1.24	1.22	965	12.1	930	11.7	2625	33	295	37
VACODYM 238 AP	1.30	1.26	995	12.5	946	11.9	1355	17	325	41
VACODYM 633 AP	1.26	1.22	965	12.1	915	11.5	1355	17	305	38
VACODYM 688 AP	1.08	1.03	830	10.4	770	9.7	2625	33	225	28
VACODYM 745 AP	1.34	1.31	1025	12.9	970	12.2	1115	14	340	43
VACODYM 776 AP	1.26	1.22	965	12.1	915	11.5	1670	21	305	38
VACODYM 837 AP	1.30	1.26	995	12.5	950	11.9	1355	17	325	41
VACODYM 890 AP	1.11	1.07	845	10.6	795	10.0	2625	33	235	29
VACODYM 956 AP	1.29	1.26	975	12.3	940	11.8	1670	21	315	40
VACODYM 992 AP	1.16	1.13	885	11.1	850	10.7	2385	30	255	32

At a glance

HRE free alloys

	REMANENCE		COERCIVITY						ENERGY DENSITY	
	$B_{r\ typ.}$	$B_{r\ min.}$	$H_{cB\ typ}$		$H_{cB\ min.}$		$H_{cJ\ min.}$		$(BH)_{max\ typ.}$	
	T	T	kA/m	kOe	kA/m	kOe	kA/m	kOe	kJ/m^3	MGOe
VACODYM 722 DHR	1.47	1.41	1120	14.1	1060	13.3	1395	18	410	51
VACODYM 801 DTP	1.42	1.39	1090	13.7	1050	13.2	1550	20	390	49
VACODYM 805 DTP	1.37	1.34	1050	13.2	1015	12.7	2190	28	360	45
VACODYM 807 DTP	1.30	1.27	1005	12.6	965	12.1	2745	35	325	41
VACODYM 890 DTP	1.19	1.14	925	11.6	870	10.9	3145	40	275	35
VACODYM 902 TP	1.42	1.40	1088	13.6	1055	13.2	1190	15	386	49
VACODYM 909 TP *	1.24	1.22	962	12.1	933	11.7	2620	33	299	38
VACODYM 913 TP	1.41	1.39	1082	13.6	1051	13.2	1350	17	381	48
VACODYM 919 TP *	1.27	1.25	986	12.3	956	12.0	2620	33	312	39

* preliminary values

TYPICAL DEMAGNETIZATION CURVES AND TEMPERATURE DEPENDENCE OF COERCIVE FIELD STRENGTHS

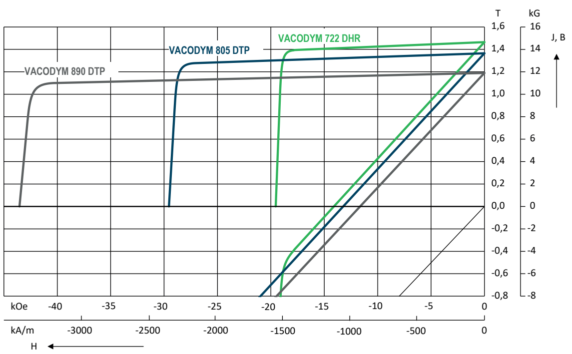


Fig.5: Typical demagnetization curves of representative VACODYM alloys at 20 °C

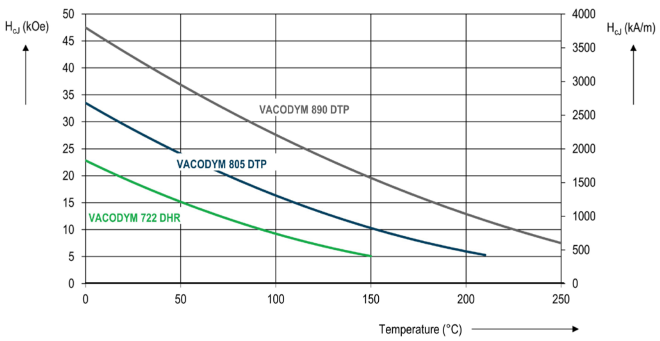


Fig. 6: Typical temperature dependence of the coercive field strengths of representative VACODYM alloys

At a glance

TABLE 2: CHARACTERISTIC PROPERTIES OF VACOMAX AT ROOM TEMPERATURE (20 °C)

	REMANENCE		COERCIVITY						ENERGY DENSITY	
	$B_{r\ typ.}$	$B_{r\ min.}$	$H_{cB\ typ}$		$H_{cB\ min.}$		$H_{cJ\ min.}$		$(BH)_{max\ typ.}$	
	T	T	kA/m	kOe	kA/m	kOe	kA/m	kOe	kJ/m^3	MGOe
VACOMAX 262 HRP	1.19	1.17	880	11.1	860	10.8	1710	21.5	265	33
VACOMAX 262 HR	1.19	1.15	875	11.0	845	10.6	1750	22.0	262	33
VACOMAX 262 TP	1.17	1.12	865	10.9	780	9.8	1590	20.0	254	32
VACOMAX 240 HR	1.12	1.05	730	9.2	600	7.5	640	8.0	240	30
VACOMAX 225 HR	1.10	1.03	820	10.3	720	9.0	1590	20.0	225	28
VACOMAX 225 TP	1.07	1.03	790	9.9	720	9.0	1590	20.0	215	27
VACOMAX 225 AP	1.04	0.97	760	9.6	680	8.5	1590	20.0	200	25
VACOMAX 190 HR	1.06	1.01	830	10.4	755	9.5	1195	15.0	215	27
VACOMAX 170 HR	1.01	0.95	755	9.5	710	8.9	1195	15.0	200	25
VACOMAX 175 AP	1.00	0.95	780	9.8	680	8.5	1990	25.0	195	24.5
VACOMAX 145 S	0.90	0.85	660	8.3	600	7.5	1990	25.0	160	20

VACOMAX Sm_2Co_{17}

VACOMAX $SmCo_5$

TYPICAL DEMAGNETIZATION CURVES AND TEMPERATURE DEPENDENCE OF COERCIVE FIELD STRENGHTS

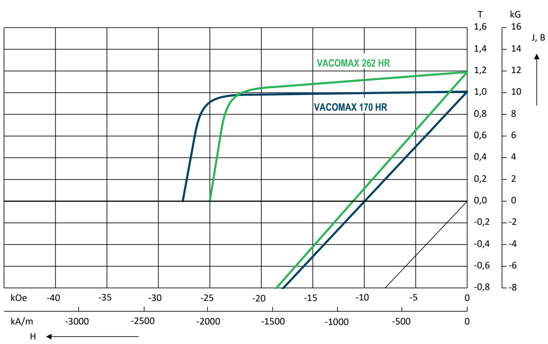


Fig. 7: Typical demagnetization curves of representative VACOMAX alloys at 20°C

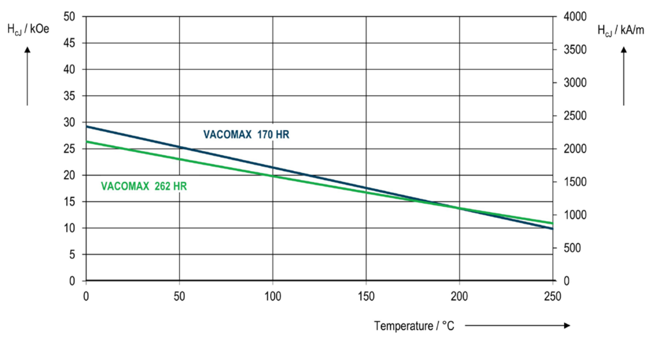


Fig. 8: Typical temperature dependencies of the coercive field strenth of representative VACOMAX alloys

The prerequisite for achieving the magnetic properties specified for each material in the tables above is the complete magnetization of the magnets. The magnetization behavior largely depends on the material used, the installation configuration, and the prior history of the magnets.

TABLE 3: INNER MAGNETIZING FIELD STRENGTH FOR VACODYM AND VACOMAX

MATERIAL	$H_{mag\ min.}$	
	kA/m	kOe
VACODYM	2500	31
VACOMAX 225/262	3650	46
VACOMAX 240	2000	25
VACOMAX 145/170	2000	25

Further information on magnetizing behavior can be found in Hilzinger and Rodewald's publication, "Magnetic Materials" (ISBN 978-3-89578-352-4) or in IEC/TR 62517 "Magnetizing Behaviour of Permanent Magnets".

Before magnetizing our VACODYM and VACOMAX materials, we recommend contacting our experts.

IRREVERSIBLE LOSSES

A completely magnetized permanent magnet loses a part of its magnetic moment when it is exposed to an opposing magnetic field. Here it is necessary to differentiate between reversible and irreversible losses. The reversible losses disappear when the magnet is no longer exposed to the opposing field. They are, in the first place, due to the reversible permeability of the magnet, which is in the range of μ_{rev}=1.05 for NdFeB-based magnets. In the case of the irreversible losses, parts of the magnet are reversed, and losses remain after the removal of the opposing field.

In order to specify and measure the irreversible losses, the following three methods can be used.

• Aging of the magnet at increased temperatures and determination of the irreversible losses. This method is highly time- and labor-intensive and is therefore only very rarely used.

• Measurement of the J(H) curve and determination of the field strength, at the point at which J has reduced by 10 %. This field strength is referred to as knee field strength $H_{K,90}$. $H_{K,90}$ is therefore the field strength at which the J(H) curve intersects the line parallel to the H-axis defined by J = 0.9 x B_r intersect (see Fig. 9). The disadvantage of this method is that due to the reversible permeability of NdFeB-magnets at high coercivities H_{cJ}, only the reversible losses are taken.

• According to IEC 60404-8-1 Ed. 3, the irreversible losses for NdFeB magnets are characterized by the measurement parameter H_{D5}.

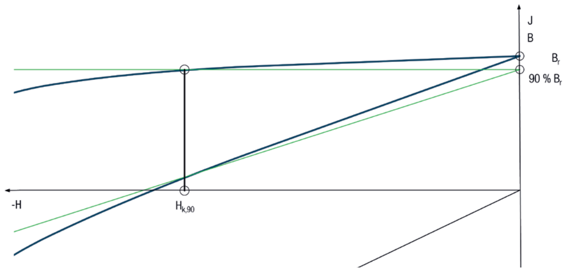


Fig. 9: B(H) and J(H) demagnetization curves with $H_{K,90}$ evaluation

The measurement is based on the determination of the J(H) curve with a hysteresis graph (see Fig. 10). In order to eliminate the effects of the surface processing, the reversible permeability μ_{rev} is determined in the H field range of 20 - 70 %, where H_{cJ} has a linear fit on the J(H) curve. The point of intersection with the J/B axis is then $B_{r,lin}$. This value can then be below the remanence B_r of the magnet due to the surface effects. This straight line is shifted by 5 % to lower J values (point of intersection B_p with the J/B axis at 95 % of $B_{r,lin}$). The intersection of these straight lines is then determined with the J(H) curve, and the corresponding H field is read. This field is named H_{D5} and represents the field strength at which the magnet shows an irreversible loss of 5 % of its magnetic moment. Upon request, for all VACODYM alloys VACUUMSCHMELZE will provide the H_{D5} values at 20 °C, as well as at higher operating temperatures.

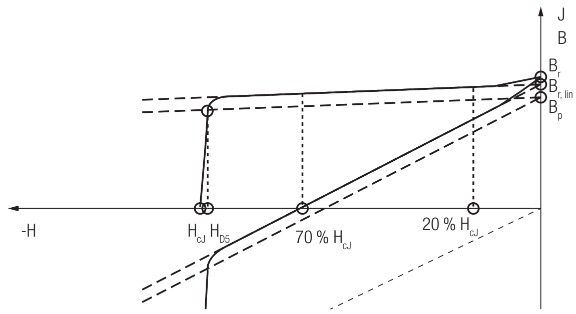


Fig. 10: B(H) and J(H) demagnetization curves with H_{D5} evaluation

CORROSION BEHAVIOR AND COATINGS

CORROSION BEHAVIOR

Rare Earth (RE) elements are considered non-noble and thus highly reactive due to their strongly negative standard electrochemical potential (E^0 = -2.2 to -2.5 V).

Their chemical reactivity is similar to that of alkaline earth metals such as magnesium. Under normal conditions, the RE metals react slowly. Under conditions at higher temperatures and in the presence of water or humidity, the reaction is more rapid releasing hydrogen and RE hydroxide. The released hydrogen can then react with the free RE metal forming RE metal hydrides.

This can lead to intergranular decay in NdFeB magnets. This reaction with water vapor can be significantly suppressed by adding sufficient quantities of more noble elements such as cobalt.

The situation is different when it comes to red rust formation. In the presence of condensed moisture, all VACODYM materials gradually begin to rust on the surface. The use of cobalt has no effect on this. The resulting corrosion products are primarily non-magnetic metal oxides and hydroxides.

Since VACOMAX ($SmCo_5$ or Sm_2Co_{17}) inherently contains a high cobalt content, even after prolonged exposure (e.g. > 1,000 h) to high humidity (e.g., > 80 % relative humidity) and elevated temperatures (e.g. > 80 °C), no significant loss of corrosion products can be detected.

SURFACE PASSIVATION

To protect uncoated magnets temporarily, e.g. during transport or storage, we have developed a passivation method that effectively protects RE permanent magnet materials against environmental influences, such as temporarily increased humidity. The standard passivation involves the application of an ultra-thin Nd/Fe phosphate layer onto the magnet surface.

The thickness of the phosphate layer lies in the sub-µm range (typically < 0.5 µm). This is sufficient to protect the magnets against rust in case of prolonged storage under normal Central European ambient conditions (T ≤ 30 °C, rel. humidity < 70 %).

The thickness of the phosphate layer is within the spectrum of visible light wavelengths, which is why color variations on the surface are completely normal and harmless.

SURFACE PROTECTION

In many applications, the phosphate layer applied is too thin to provide reliable long-term protection for VACODYM magnets. For effective corrosion protection of magnets under complex application conditions, an additional coating is often necessary.

The type and thickness of the coating depends on the prevalent environmental influences in the application. Corrosion-proof coatings can be applied to magnets directly after production and cleaning.

Users may also choose to apply a surface protection to magnets in the finished system. Proven methods are e.g. bandaging with subsequent treatment, grouting or coating of the assembled magnets with synthetic resin or thick enclosure of the magnets, e.g. in a stainless steel casing as well as coating of the finished magnet systems with corrosion-proof layers, e.g. paints.

Depending on the application, surface coatings may also serve other purposes besides corrosion protection.

PROTECTION AGAINST MAGNETIC PARTICLES

VACODYM and VACOMAX are sintered materials, where the occurrence of loose magnetic particles and magnet dust on the surface cannot be ruled out. In certain applications (e.g. systems with small working air gaps), loose magnetic particles may affect the function or destroy the magnet system. The coating process must therefore ensure that the magnets can be cleaned thoroughly and are free of all deposits.

HANDLING PROTECTION

Magnets are often mechanically stressed during assembly or when used in systems. Under certain circumstances, this can lead to separation of magnetic particles, particularly at sharp edges. Each application of VACODYM and VACOMAX must therefore be evaluated to ascertain whether and how the surface should be protected. We have tested the behavior of our permanent magnets under widely varying operating conditions and will be pleased to advise you on the selection of the appropriate surface protection for your application.

TYPES OF COATING

The coatings can be divided into metallic and organic coatings. To meet special requirements and on request, double coatings of metal/metal and metal/organic, and a number of special coatings are available. In addition, special coatings such as nickel/gold for medical applications are available on request.

The majority of applications can be covered by our VACCOAT spray coatings as well as the ”galvanic tin” coating. The coatings feature complementary properties.

VAC carries out all galvanic and spray coating processes in-house using state-of-the-art automation technology to ensure cost-effective production and high reproducibility of coating quality. The described properties can only be achieved through the carefully coordinated interaction of the magnetic microstructure, its mechanical processing, as well as cleaning and coating.

Special coatings, such as titanium-nitride, are provided by subcontractors carefully selected and qualified by VAC. Appropriate quality assurance measures ensure consistent high-quality levels in series production.

EPOXY SPRAY COATING VACCOAT

This coating is an in-house development that sets standards regarding the combination of corrosion protection, temperature resistance, coating application and the subsequent further processing of the coated magnets into systems.

When cured, VACCOAT 20011 provides high-grade corrosion protection for VACODYM. At the same time, the coating film can also serve as a high-strength adhesive before curing.

During the baking of the coating, a high-strength adhesive bond forms giving a typical shear strength of > 15 N / mm^2. At the same time, the coating effectively protects the system against corrosion. The baked coating has a pencil hardness of at least 4H and can be thermally stressed to approx. 200 °C.

In a single operation, visually high-quality layers of between 10-20 µm can be applied (measured at the center of the pole surface). The color of the coating is adjustable (standard color: black). The coating is abrasion-resistant and exhibits excellent electrical insulation behavior. The layers are applied to the magnets in an automatic batch-process.

VACCOAT 20021 is applied with a cost-efficient barrel coating process. This type of coating is only suitable for magnets within certain aspect ratios and with a weight of less than 8 grams. For further information, please contact our team of experts.

Depending on the size of the magnet, radii on the edges are to be expected to achieve full coverage.

For the highest level of corrosion protection, we offer VACCOAT 30033. In a salt spray test according to DIN EN ISO 9227, as well as in the autoclave test at 130 °C / 100 % humidity / 2.7 bar, VACODYM magnets protected with this baked coating achieve corrosion-free aging times of over 1,000 hours. The other properties (mechanical parameters, temperature and chemical resistance) are comparable with VACCOAT 20011.

Both, VACCOAT 30033 and VACCOAT 20011 can only be applied using the automatic batch process. This process also allows coating of flat or otherwise challenging geometries that are not possible using the barrel coating processes. The minimum part weight is 1 g.

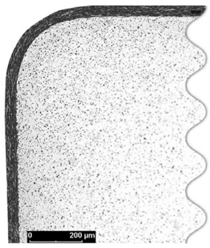


Fig. 11: Micrograph of edge coverage with VACCOAT

ALUMINUM SPRAY COATINGS VACCOAT 10047

The stove-enamel filled with aluminium flakes exhibits good resistance to climatic and salt spray tests similar to the epoxy spray coating VACCOAT 200XX. Even from a thickness of 10 µm onwards, the magnets withstand long-term autoclave and salt spray tests without any problems

This coating is suitable for applications with operating temperatures of up to 200 °C and exhibits very good chemical resistance.

Thanks to its excellent hardness (typically 6-8 H pencil hardness), the coating is not sensitive to mechanical damage.

This coating is particularly beneficial for barrel-coating of small parts. The built-in aluminum flakes provide very good edge coverage. In connection with excellent substrate adherence, edge damage is effectively prevented during the coating process.

GALVANIC TIN

Galvanic tin plating provides good corrosion protection against atmospheric influences, humidity and weak acids and alkaline solutions. The tin plating is dense and free of interconnected pores. The typical plating thickness range for magnets is 15 - 30 µm. The finish of the tin plating is silvery-white and slightly glossy.

No phase transitions occur in the temperature range from -40 °C to tin's melting point (+232 °C). The deposition process is optimized by VAC for RE magnets, especially to prevent hydrogen damage to the surface of the magnet during plating, which often happens with nickel plating, for example.

Small parts can be plated economically in a barrel. Larger parts are galvanized in a rack. The decision whether to use barrel or rack method is governed by the weight of the part or the part geometry (typical guide value: < 25 g barrel; > 25 g rack).

Galvanic tin plating is characterized particularly by its high resistance to environmental influences in a humid and warm climate (e.g. 85 °C / 85 % rel. humidity), as generally specified for electronic applications. Tin is highly ductile and is almost free of internal stress over a wide range of plating thickness and can be deposited with high process reliability. There is no risk of cracking or flaking of the plating. Mechanical stress does not lead to chipping but merely to deformation of the tin plating, so that the magnetic material is still protected safely.

Tin plating is free of all residues when cleaned thoroughly and thus provides an ideal surface for many adhesives.

TITANIUM-NITRIDE

For UHV applications, where the shortest pumping times are important, the titanium nitride coating (TiN) is ideally suited. This coating is deposited in a thin layer (2 µm - 6 µm) on the magnet using a sputtering process based on a VAC-patented process. The TiN coating enables the production of magnets with extremely tight tolerances. The process, which was developed specifically for VACODYM magnets and soft magnetic flux conductors, e.g., made of VACOFLUX, results in adherent, dense protective layers with high wear resistance. Upon request, we clean and package the parts in an additional process to make them UHV-compatible.

CHARACTERISTICS OF DIFFERENT COATINGS

Table 4 compares the properties of the most important coatings and should be used as a guideline when selecting surface protection for a certain application. It specifies the usual layer thickness of the coatings and ensures adequate corrosion protection in most applications. To meet more stringent requirements on corrosion protection, the layer thickness must be adjusted accordingly. It should also be noted that improper handling can compromise the integrity of the coating.

TABLE 4: TYPICAL PROPERTIES OF DIFFERENT COATINGS

Surface	Method	minimum layer thickness	Color	Hardness	Resistance to				Operating temperature
					Humidity	Salt spray test	Toxic gas test	Electrical in-sulating effect	
VACCOAT 20011	Automatic spray coating	> 10 µm	black	> 4H[1]	+	+	+	++	< 200 °C
VACCOAT 20021	Automatic spray coating	> 10 µm	black	> 4H[1]	0	+	+	++	< 200 °C
VACCOAT 30033	Automatic spray coating	> 10 µm	green	> 4H[1]	++	++	+	++	< 200 °C
VACCOAT 10047	Automatic spray coating	> 10 µm	yellow semi-bright	> 4H[1]	+	++	+	0	< 200 °C
Tin (Sn)	Electroplating	> 15 µm	silver bright	HV 10[2]	+	0	0	-	< 160 °C
TiN	Sputtering	> 2 µm	golden	HV > 500[2]	UHV-application				< 200 °C

[1] Pencil hardness

[2] Vickers hardness (guide values)

GLUING OF RARE EARTH MAGNETS

The majority of RE permanent magnets produced by VAC are assembled into magnet systems using adhesives. For a magnet system, the following framework must be considered:

- Static and dynamic load of the adhesive (strength requirements)
- Thermal load of the adhesive
  (time-span / frequency / temperature change)
- Thermal expansion coefficients of the adhesive partners
- Size of adhesive area
- Corrosive load of the adhesive
  (resistance of the adhesive to atmosphere and chemicals)
- Quality of the surfaces
  (coating, roughness, etc.)
- Material matching regarding electrochemical potentials (corrosion due to galvanic element formation)
- Thickness of the adhesive gap

Based on our longstanding experience in assembling RE permanent magnet systems, we can offer the following tips on the gluing of magnets:

a) Adhesives with acid content must not be used with RE magnets, especially not with VACODYM. These products, in connection with humidity, lead to rapid decomposition of the magnet material at the adhesive-magnet interface and can damage the bond. The use of such adhesives is not recommended, even in the case of coated magnets, particularly painted magnets.

b) When bonding large surfaces with iron or other substrates, the thermal expansion coefficients of the RE magnet materials must be taken into account. In particular, in connection with VACODYM, which has a negative thermal expansion coefficient (-1 x 10^{-6}/K) perpendicular to the direction of magnetization (and thus, normally parallel to the gluing surface), stresses build up due to strains resulting from fluctuations in temperature, which the glue must absorb. Our team of experts will be pleased to advise you on this matter.

c) When preparing for the gluing, sand blasting for the pre-treatment of RE magnets should be avoided. This processing step might lead to loosening of the micro-structure on the surface of the sintered magnet.

Our permanent magnets are supplied in a ready-for-gluing state. The passivation applied after cleaning provides a suitable base for most adhesives. However, if a pre-treatment step directly prior to gluing is considered important, we recommend cleaning the gluing surface with a solvent such as acetone or benzene.

d) An adhesive selected for an uncoated magnet is not necessarily suitable for a coated magnet. In the case of coated magnets, it must be ensured that the adhesive does not attack the coating chemically or causes swelling. VAC has in-depth experience with a large number of adhesives and the most commonly used surfaces. We will be pleased to support you in selecting the right adhesive or designing a complete magnet system.

Our particular expertise lies in the joining of magnetized parts, enabling us to comply with the highest requirements, such as the manufacturing of Halbach arrays. Our product quality is ensured by specially trained personnel, including IFAM certified bonding practitioners and bonding specialists. In doing so, we essentially comply with the requirements of DIN 2304.

MAGNET ASSEMBLIES

The manufacturing of magnet assemblies is extremely demanding. Meeting customer-specific requirements, up to the creation of a fully customized magnetic system, involves comprehensive consulting, planning, design, and ultimately the manufacturing of magnets, components, and/or complete assemblies. With our decades of experience in the development and production of both permanent and soft magnetic materials, further refined components of any size and complexity, and certified manufacturing facilities, we are one of the few companies able to provide all steps from a single source. In doing so, we meet the highest standards of precision and reliability, as well as numerous standards.

Based on the customer specification, the requirement profile including the desired function of the magnet assembly, the permitted dimensions, and the thermal, mechanical, climatic, and electrical boundary conditions, we work together to develop solutions for your design. On this basis, we create a basic concept with a rough cost estimate for the implementation of the system.

We support the design process with fundamentals, data, and our expert know-how. We also support our customers' projects with several technical methods, such as:

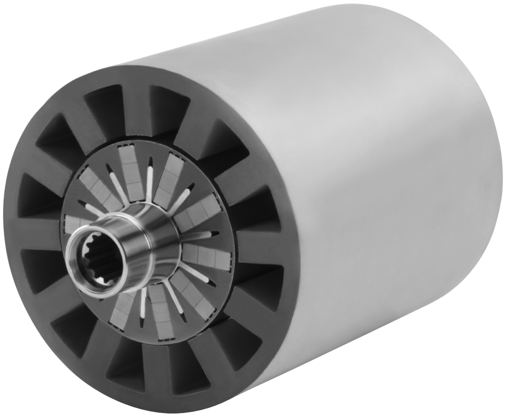
- Numerical and analytical calculation methods to determine field profiles and the forces and torques acting
- Finite element methods in two and three dimensions
- Special testing methods for measuring magnetic properties
- Special electrical and mechanical tests on magnetized assemblies
- Standard CAD systems (STP-, IGES-, DXF-files)

MAGNET ASSEMBLIES IN EVERY SIZE AND LEVEL OF COMPLEXITY

HALBACH ARRAYS FOR HIGH-PERFORMANCE MOTORS

Using our pressing technology and design expertise, we can produce magnets with imprinted special field profiles that form a partial Halbach array. The resulting converging field leads to flux concentration in the air gap, contributing to increased performance of an electrical synchronous machine. Such magnets are also referred to as magnets with a pronounced hot-side/cold-side effect (h-c effect).

Figure 12 shows a rotor with embedded magnets exhibiting a strong hot-side/cold-side effect, which can lead to a 6 % increase in torque.



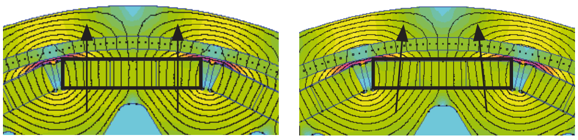
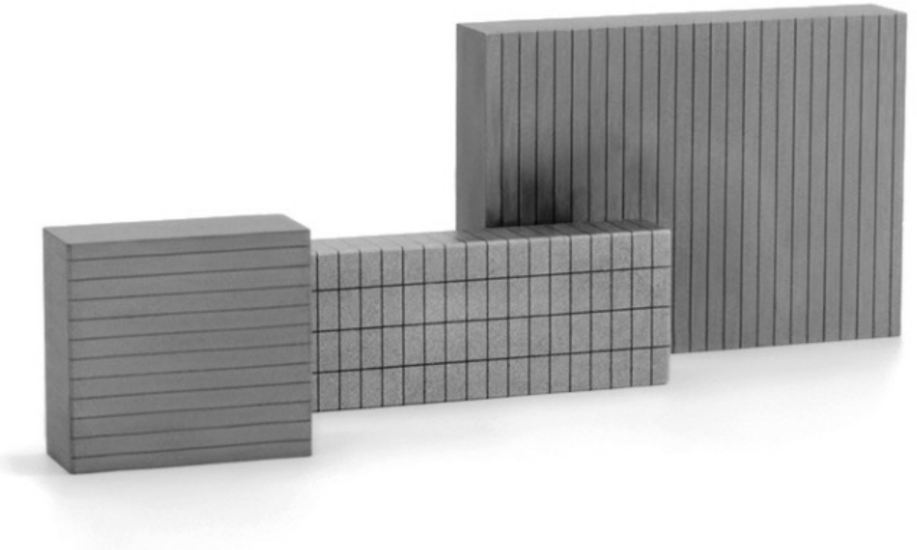


Fig. 12: The air gap flux density can be increased by using embedded, magnetically profiled, and aligned magnets. This can be demonstrated by using magnets with hot-side/cold-side effect.

While a partial Halbach array can be realized using optimized tooling and pressing, a full Halbach array can only be achieved by assembling magnets with different orientations.

The required assembly in the magnetized state is carried out using specially developed equipment and processes.



SEGMENTED MAGNETS

High efficiency and low eddy current losses require segmented magnets that are specially manufactured to be electrically insulating. With segment thicknesses below 1 mm and an adhesive gap below 15 µm, we ensure electrical insulation while maintaining a high packing density.

Bandaged rotor assemblies, consisting of rotors equipped with magnets, are mainly used in aerospace, automotive, motorsports, and industrial applications. Bandages made of composite materials (e.g. CFRP, GFRP) or sleeves made of metal alloys secure the construction of high-speed electrical machines with speeds exceeding 100,000 rpm.

VAC has experience in shrinking-fitting metal sleeves, made of materials such as Inconel 718, as well as in bandaging composite materials. Our services also include shrink-fitting shafts, balancing, and, if required, spin testing of complete rotors.

PRECISION ASSEMBLIES

In scientific applications such as undulators, assemblies consisting of NdFeB (VACODYM) and SmCo (VACOMAX) magnets with flux conductors made of CoFe (VACOFLUX), for example, are used. Manufacturing is carried out with the highest precision, enabling magnet assemblies with less than 1 % deviation in magnetic moment and a magnetic angular deviation of less than 1 °, while simultaneously achieving a north-south effect of less than 1 %.

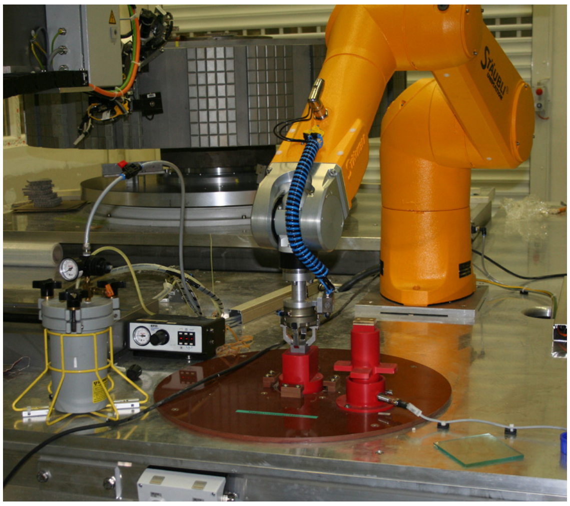
AUTOMATED ASSEMBLY OF COMPONENTS

Magnet assemblies for the automotive or medical industries with high annual production volumes are manufactured in-house on specially developed automated production lines.

The automated assembly of magnetized magnets onto large rotors for generators or electric machines has been fully implemented up to series production readiness.

SMALL-SERIES SPECIAL COMPONENT ASSEMBLY

Magnetic systems with low annual production volumes can be assembled flexibly at individual workstations according to customer requirements. If needed, the final assembly can also be carried out directly at the customer's site.



TECHNICAL TERMS AND CONDITIONS OF SALE

Like most other permanent magnet materials, sintered magnets made of RE alloys are brittle. It is impossible to rule out fine hairline cracks, microscopic pores or chipped edges. These, however, have a negligible effect on the magnetic and mechanical properties of the parts, which still correspond to the technical specifications communicated at an earlier stage.

Unless we have special agreements with our customers, our quality inspection allows mechanical surface damage (flaking, edge and corner chips) up to a total of max. 2 % per pole surface. For small magnets and for magnets whose pole surface is the smallest surface of the part, as well as for diametral disks, the permissible extent of chipping is defined jointly with the customer. For special requirements, the exchange of reference samples has proven effective for testing and determining the visual quality of the magnets. Fine hairline cracks affecting up to one third of the cross-sectional area are not subject to complaint, provided that no restrictions in the mechanical stability of the magnet are to be expected as a result. Slight amounts of magnetic dust and material debris may adhere to uncoated and particularly, to magnetized parts. Where higher cleanliness standards are required, appropriate measures can be provided.

The final inspection of our magnets and magnet systems is normally based on standardized sampling systems. Unless otherwise agreed upon with customers, the sampling scopes for the mechanical and magnetic tests are conducted in accordance with DIN ISO 2859-1 with the acceptance criteria c = 0. By consistently employing the latest quality assurance techniques, we are often able to agree to even higher quality requirements upon request of the customer.

Acceptance conditions relating to special magnetic properties require coordinated test procedures and reference samples. This often requires that the parts be delivered in a magnetized state.

SAFETY GUIDELINES

Magnetized rare earth magnets made of VACODYM and VACOMAX exhibit high magnetic field strengths and exert strong, attractive forces on iron and other magnetic parts in their vicinity. Consequently, they must be handled with care by qualified and trained operators to avoid damage. Owing to their strong magnetic forces, there is a risk of injury when handling larger magnets. They should always be handled individually or with the aid of separators. We recommend wearing suitable personal protective equipment also for handling uncoated VACOMAX and nickel-coated parts. This is applicable particularly for people with allergies to metals.

The high magnetic field strengths can change or damage the calibration of sensitive electronic devices and measuring instruments in the vicinity. In particular, magnetized magnets must be kept at a safe distance (e.g. over 2 m) from computers, monitors and all magnetic data storage media (such as credit cards, audio and video tapes etc.) as well as from pacemakers. RE magnets may generate large sparks on impact. Never handle them in an explosive atmosphere.

Unprotected VACODYM and VACOMAX magnets must not be exposed to hydrogen. Hydrogen deposits destroy the microstructure and lead to disintegration of the magnet. In these cases, the only effective protection is gas-proof encapsulation of the magnets. If magnets must be processed further, special safety precautions must be taken when handling the accumulating grinding debris. For VACOMAX in particular, legal regulations regarding the handling of dust with cobalt content must be observed. Furthermore, the VACOMAX alloys contain Samarium, which exhibits a low level of natural radioactivity.

Further important information on the safe handling of VACODYM and VACOMAX magnets can be found in our alloy-specific material safety data sheets. These can be found in the download area of our website.

QUALITY AND ENVIRONMENTAL MANAGEMENT

Quality is an essential aspect of our corporate policy. In order to reliably realize the high quality of our products and services based on a quality management system certified in accordance with ISO 9001, IATF 16949, and AS/EN 9100, we give priority to close cooperation of all operational divisions.

Our Integrated Management System is based on the following regulations in their current versions:

- **ISO 9001**
- **IATF 16949**
- **EN 9100**
- **ISO 14001**
- **ISO 45001**
- **ISO 50001 / EN 16247**

The most important objective of our quality management measures is fulfilling all customer expectations and achieving high customer satisfaction, both externally as well as internally.

We achieve the product quality demanded by our customers by defining and implementing targeted QM measures in product and process planning, strictly controlling raw material procurement, and integrating test sequences into processes using a statistical process control system.

Compliance with the corresponding process capability indices (cpk values) is as self-evident to us as the documentation of the key magnetic and geometric properties. For complex tasks or particularly high requirements, we define jointly coordinated quality-assurance programs in close collaboration with our customers.

Through qualified technical consulting, we help to design and implement quality-compliant, cost-effective products and services and, at the customers' request, also conclude quality assurance agreements.

Our core expertise lies in producing materials with specialized, high-quality magnetic properties. To ensure the reliability of our magnetic characteristics, we actively engage in national and international standardization of key measurement methods, such as IEC 60404-5 for demagnetization curve measurements in the hysteresis graph.

TECHNICAL BASICS AND TERMS

HYSTERESIS LOOP

The behavior of a magnetic material in the magnetic field is characterized by the correlation between magnetic flux density (induction) B or magnetic polarization J and magnetic field strength H, the B(H) or J(H) hysteresis loop (Fig. 13). The flux density B and the polarization J are given by

$$B = \mu_0 H + J$$

The first quadrant of the hysteresis loop describes the magnetization behavior of the material: when applying a magnetic field H, the flux density B of a non-magnetized material varies along the initial curve (see Fig. 13).

When all magnetic moments are oriented parallel to the external magnetic field, the polarization J is at its maximum value, the saturation polarization J_s ($J = J_s =$ const.). The flux density B, however, continues to increase linearly with the field strength H.

The minimum field strength required to attain the saturation polarization is referred to as the saturation field strength H_s. If – in the magnetized state – the magnetic field strength is reduced, the flux density changes in accordance with the hysteresis loop and attains, at H = 0, the residual flux density (remanence) B_r (intersection of the hysteresis loop with the ordinate).

In the strongly anisotropic RE permanent magnets described here, the remanence B_r is in the same order of magnitude as the saturation polarization J_s :

$$B_r \approx J_s$$

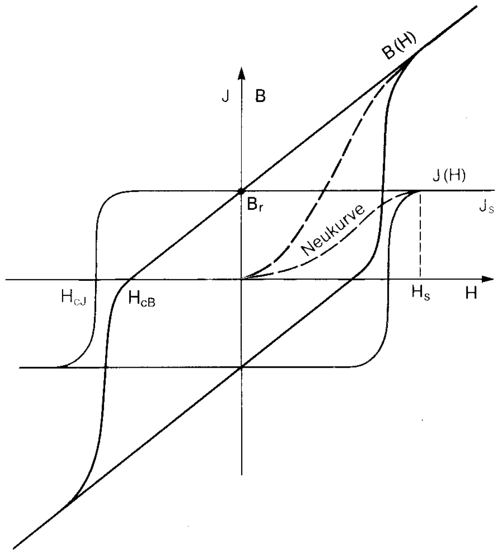


Fig. 13: B(H) and J(H) curve of a permanent magnet

DEMAGNETIZATION CURVE

The second quadrant of the hysteresis loop describes the demagnetization behavior of the material: For permanent magnets, which are operated exclusively in opposing fields (see "working point" for further details), the most important characteristic terms are determined by the demagnetization curve.

The most important characteristic terms of a permanent magnet are:

Remanence

This is obtained, as described above, from the intersection of the hysteresis loop and the ordinate (at H=0, we have $B_r=J_r$).

Coercivity

The field strengths, at which the flux density B or the polarization J reach zero are referred to as coercivities of the flux density H_{cB} or of the polarization H_{cJ} respectively (intersections of the hysteresis loops B(H) and J(H) with the abscissa).

Energy density

The product of the related values from flux density B and field strength H can be attained from any point along the demagnetization curve (see Fig. 14). This product represents the energy density and passes through a maximum value between remanence and coercivity, the maximum energy density $(BH)_{max}$. As a rule, this value is used to grade permanent magnet materials.

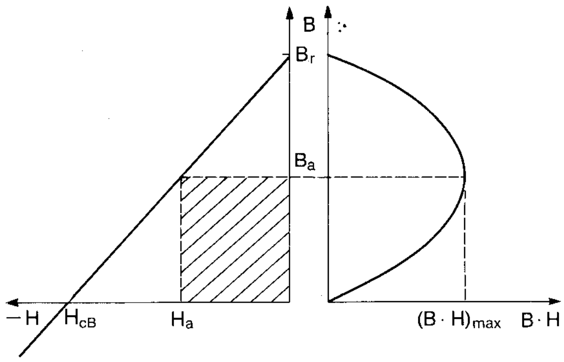


Fig. 14: Schematic illustration of the maximum energy density beneath the B-H curve

Working point

The magnetic field originating from the poles of a permanent magnet has a demagnetizing effect as it is in the opposing direction to the polarization J. The operational state of a permanent magnet is consequently always in the range of the demagnetization curve. The pair of values (B_a, H_a) applying to the relevant operational state is referred to as working point P. The position of P depends on the geometry of the magnet or, in magnetic circuits with soft magnetic flux conductors, on the ratio of air-gap length to magnet length. P is obtained from the intersection of the working or shearing lines with the B(H) curve (see Fig. 15)

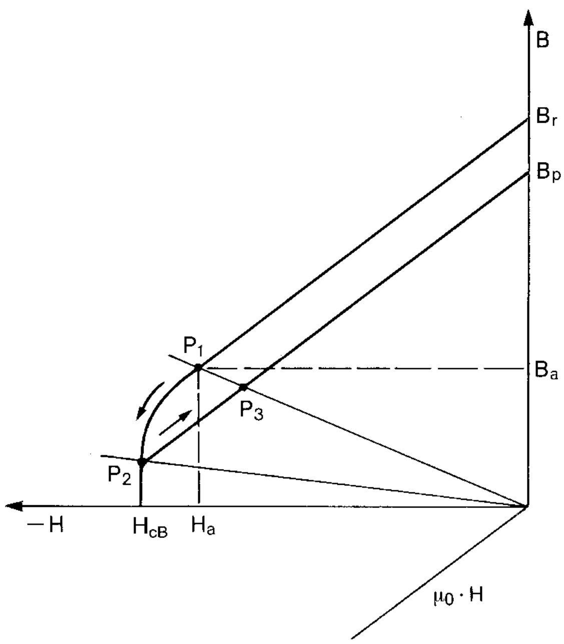


Fig. 15: Illustration of the working point and the irreversible losses in case of excessive shearing

The most effective use of a permanent magnet in static systems is when the working point P lies in the $(BH)_{max}$ point. In practice, shearing in the magnetic circuit should be selected such that the working point is at exactly this position or, preferably, just above it, i.e. is in slightly lower opposing field strengths.

In dynamic systems with changing operating straight lines (e.g. motors), shearing should be selected such that the working point of the permanent magnet always remains within the straight-line range of the demagnetization curve in order to ensure high stability with respect to external field and temperature influences.

If the air gap in a magnet system is increased, the working point shifts to higher opposing field strengths, e.g. from P1 to P2. If the change is reversed, the original working point P1 can only be attained if P2 is within the linear section of the demagnetization curve.

However, if P2 is, as shown in Fig. 15, below the ”knee” of the demagnetization curve, this results in irreversible losses. The working point shifts to P3 on an inner return path with a correspondingly lower flux density. The rise of this return path is referred to as permanent permeability.

INFLUENCE OF TEMPERATURE

The demagnetization curves of permanent magnets are temperature dependent.

This dependency is marked by the temperature coefficients of the remanent flux density TK(B_r) and the coercivity TK(H_{cJ}):

$$TK(B_r) = \frac{1}{B_r} \times \frac{dB_r}{dT} \times 100\ (\%/K)$$

$$TK(H_{cJ}) = \frac{1}{H_{cJ}} \times \frac{dH_{cJ}}{dT} \times 100\ (\%/K)$$

A change in temperature causes the working point to shift on the working line (see Fig. 16). As long as the working point remains within the linear region of the demagnetization curve, the changes in the flux density are reversible, i.e. after cooling, the flux density returns to its original value. In all other cases, any change in the flux density is irreversible (irreversible magnetic losses) and can only be reversed by remagnetization.

To avoid irreversible changes in the flux density through temperature fluctuations, the working point must remain within the linear section of the demagnetization curve over the entire temperature range in which the magnet is used.

A permanent magnet can be completely demagnetized by heating to temperatures above the Curie temperature T_c. After cooling to the initial temperature, the former state of magnetization can be reproduced by remagnetizing provided heating has not caused any changes in the microstructure. We generally recommend that you consult with us before starting thermal demagnetization.

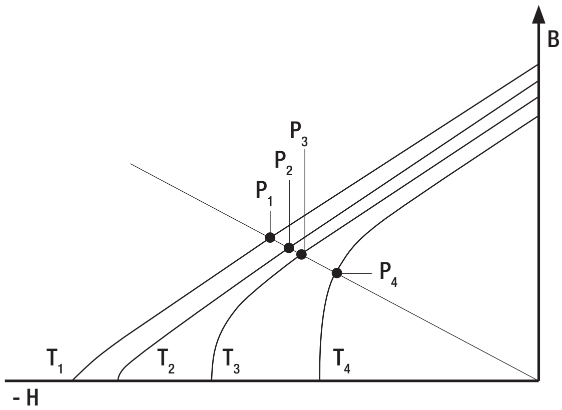


Fig. 16: Influence of the temperature on the B-H curve and the working

MAGNETIC TERMS AND UNITS

The most important magnetic terms, their units, and conversions are given in the following table.

TERM AND SYMBOL	SI units [1]	Conversion table
Flux density B	T (Tesla)	1 T = 1 Vs/m² = 10 kG Induction (Kilogauss)
Polarization J	T (Tesla)	See flux density B
Magnetic field strength H	A/m	1 A/cm =0,4 π Oe ≈ 1.257 Oe (Oersted)
Energy density $(BH)_{max}$ (energy product)	kJ/m^3	1 kJ/m^3 = 0.126 MGOe
Magnetic flux Φ	Wb (Weber)	1 Wb = 1 Vs = 10^8 Mx (Maxwell)

[1] Basic units in SI systems:
meter, kilogram, second, ampere. The units Gauss, Oersted, and Maxwell in the conversion table refer to the cgs or Gaussian system with the basic units centimeter, gram and second.

VACUUMSCHMELZE GMBH & CO. KG
Grüner Weg 37
D 63450 Hanau / Germany
Phone +49 6181 38 0
Fax +49 6181 38 2645
info@vacuumschmelze.com
www.vacuumschmelze.com

VACUUMSCHMELZE CHINA MAGNETICS
Shanghai Sales Office
Room 06, 19F
Zhongrong Hengrui International Plaza
620 Zhangyang Road, Pudong District
Shanghai, PRC 200122
Phone +86 21 58 31 98 37
Fax +86 21 58 31 99 37
vac_china@vacuumschmelze.com

VAC MAGNETICS LLC
2935 Dolphin Drive
Suite 100
Elizabethtown, KY 42701
Phone +1 270 769 1333
Fax +1 270 769 3118
info-usa@vacmagnetics.com

Published by VACUUMSCHMELZE GmbH & Co. KG, Hanau, March 2026

ADVANCED MAGNETIC SOLUTIONS

VACUUMSCHMELZE