Nd-Fe-B Magnets, Properties and Applications

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Abstract

Permanent magnets based on Rare Earth components have become more and more important in today's technology. This publication gives an overview of new Nd-Fe-B magnet grades with improved corrosion resistance and special coating possibilities. In addition, a detailed analysis is given of the magnetic orientation of axial field die pressed magnets and their optimised use in a rotor system of embedded magnets.

1. Magnetic properties of Nd-Fe-B permanent magnets

1.1 Overview of some soft and hard magnetic material

Magnetic alloys are typically described with their characteristically properties such as Remanence B_r for permanent magnets and Saturation Polarisation J_s for soft magnetic materials, each given in [T] or in [Vs/m^2], and Coercivity H_c given in [A/cm] or [kOe]. Where as in soft magnetic materials the Coercivity is kept as low as possible in the range of some 1x10^{-3} A/cm to reduce the hysteresis losses, the Coercivity of permanent magnets may be as high as 2650 kA/m to assure stability against opposing fields occurring in e.g. electrical machines. **Fig. 1** gives an overview of characteristic magnetic materials.

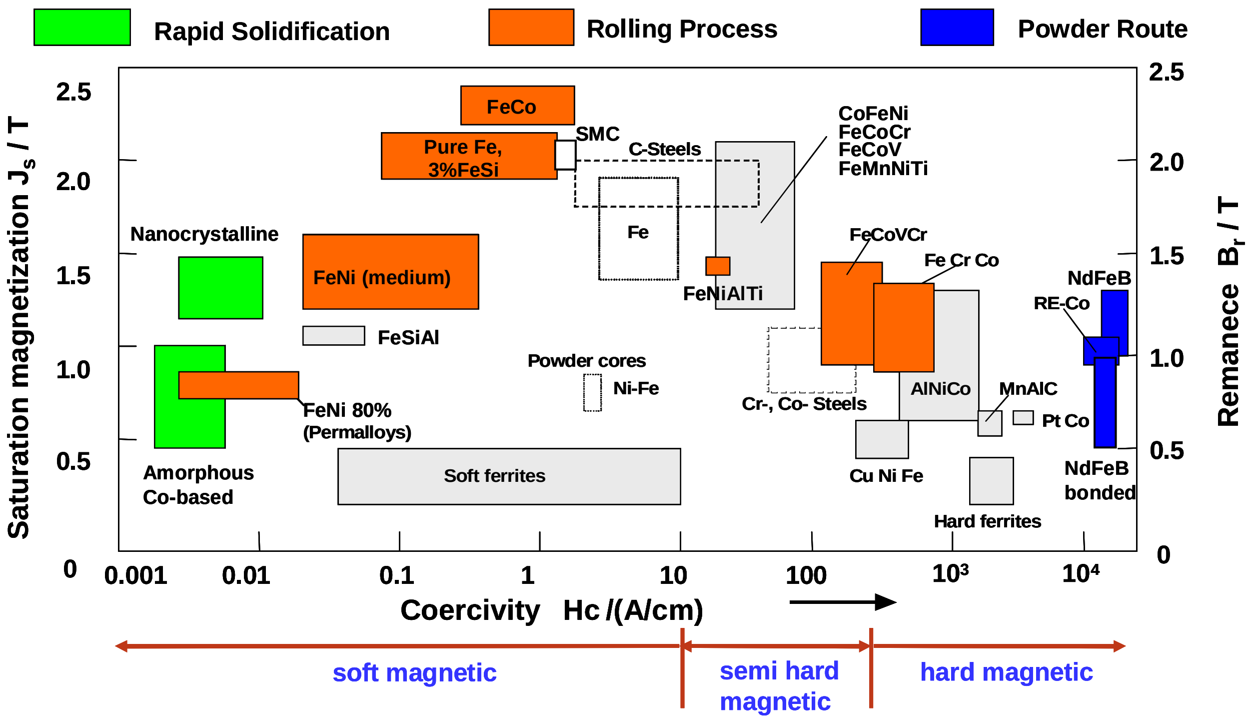

Fig. 1 Overview of magnetic materials and alloys

1.2 Maximum Energy density $(BH)_{max}$

The maximum energy density or energy product is an important property to characterise a permanent magnet. It depends on the Remanence B_r, $[Vs/m^2]$, the Coercivity H_{cB} [kA/m] which best describes the stability of demagnetisation, the permeability μ_p as well as the rectangular shape of the hysteresis curve. Research and development is being focussed to increase the Coercivity by adjusting the alloy composition (not neglecting J_s) and by producing a fine microstructure (since H_{cJ} is reciprocal proportional to the grain size). A high residual induction may be achieved by producing small crystallites and aligning them perfectly parallel to gain the best anisotropy. The development of the energy density $(BH)_{max}$ $[kJ/m^3]$ over the time is depicted in **Fig. 2**.

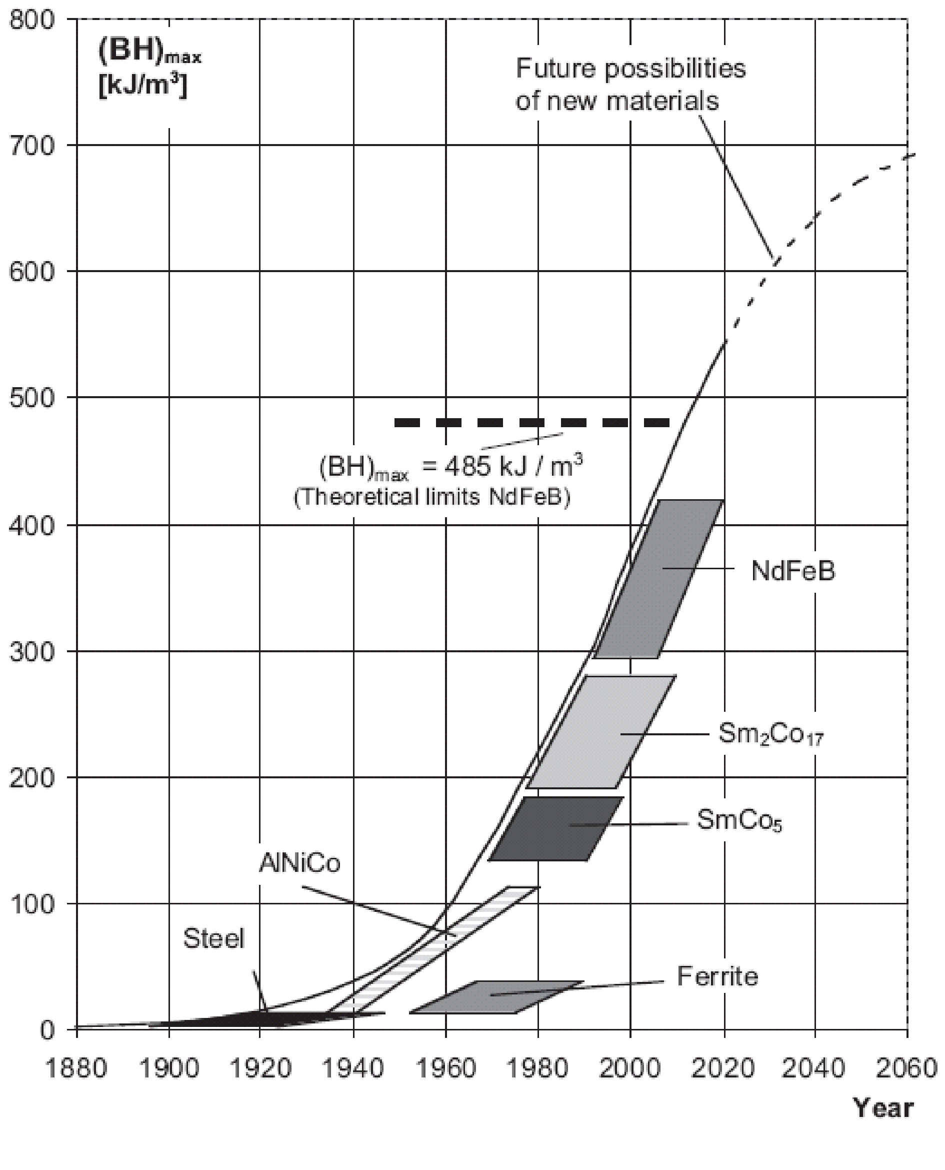

Fig. 2 Development of permanent magnets and energy density

1.3 Magnetic properties and production process of Nd-Fe-B magnets

By observing various permanent magnetic materials in detail, it may be shown that Rare Earth based magnets possess the highest energy density available today, with a Remanence of up to 1.45 T and a maximum Coercivity of 2650 kA/m, while ferrite, for example, possesses a Remanence of only 0.45 T and a Coercivity of about 300 kA/m; bearing in mind, that both intrinsic properties are interacting, so that the highest Remanence can not be achieved at the highest Coercivity.

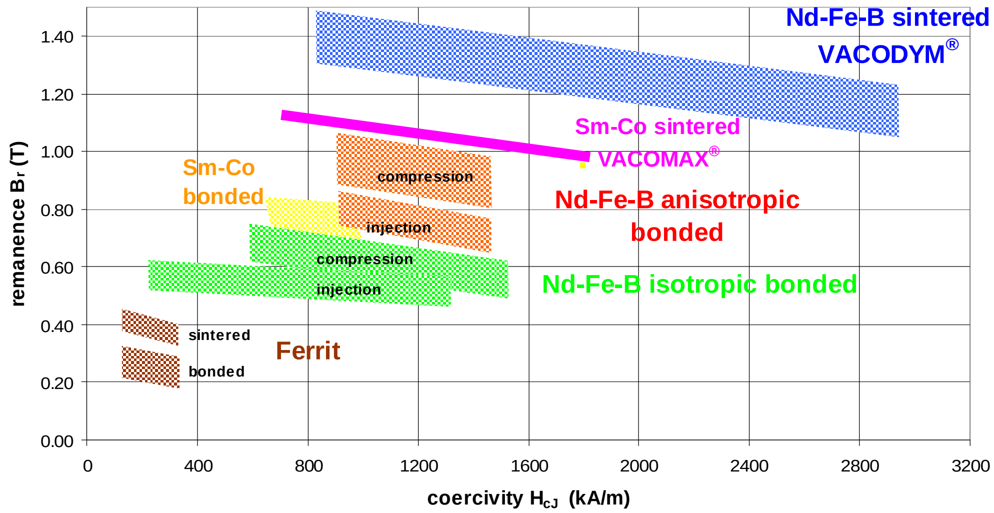

Fig. 3 Overview of permanent magnetic materials as a function of Remanence vs. Coercivity

The following **Fig. 4** displays the schematic manufacturing and sintering process of Rare Earth based permanent magnets. In mass production, typically there are two ways of die pressing which are common in industry: **A**xial field die-**P**ressing called AP and **T**ransverse field die-**P**ressing called TP. The TP method involves more manufacturing steps by first pressing blocks and then slicing them to the desired shape, which is more expensive than AP pressing, where the die press speed is much higher, thus reducing the costs significantly.

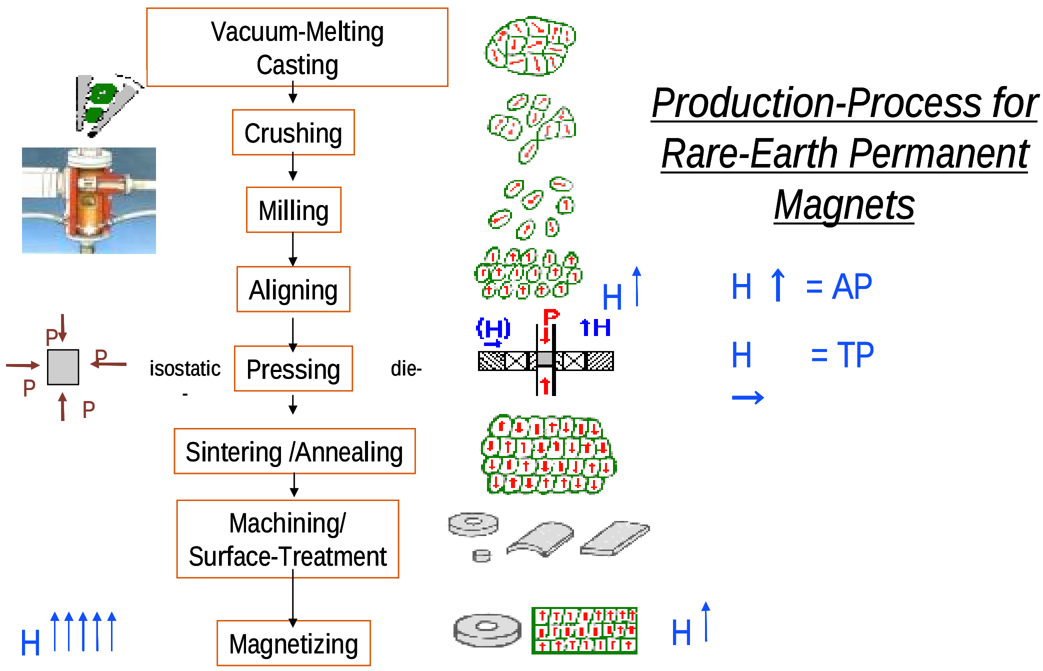

Fig. 4 Manufacturing process of Rare Earth based magnets

1.4 Magnetic properties depending on the pressing process AP or TP

The outer axial or transverse field H influences the degree of magnetic orientation within the pressed magnet (green body), thus the crystallite grain aligns itself into the direction of the outer applied field. The degree of orientation is significantly influenced by the according pressing technique AP or TP, resulting in a difference in Remanence of roughly 4% between AP and TP.

Fig. 5a and 5b displays the Remanence and Coercivity of various alloys and compares the AP or TP processing techniques respectively.

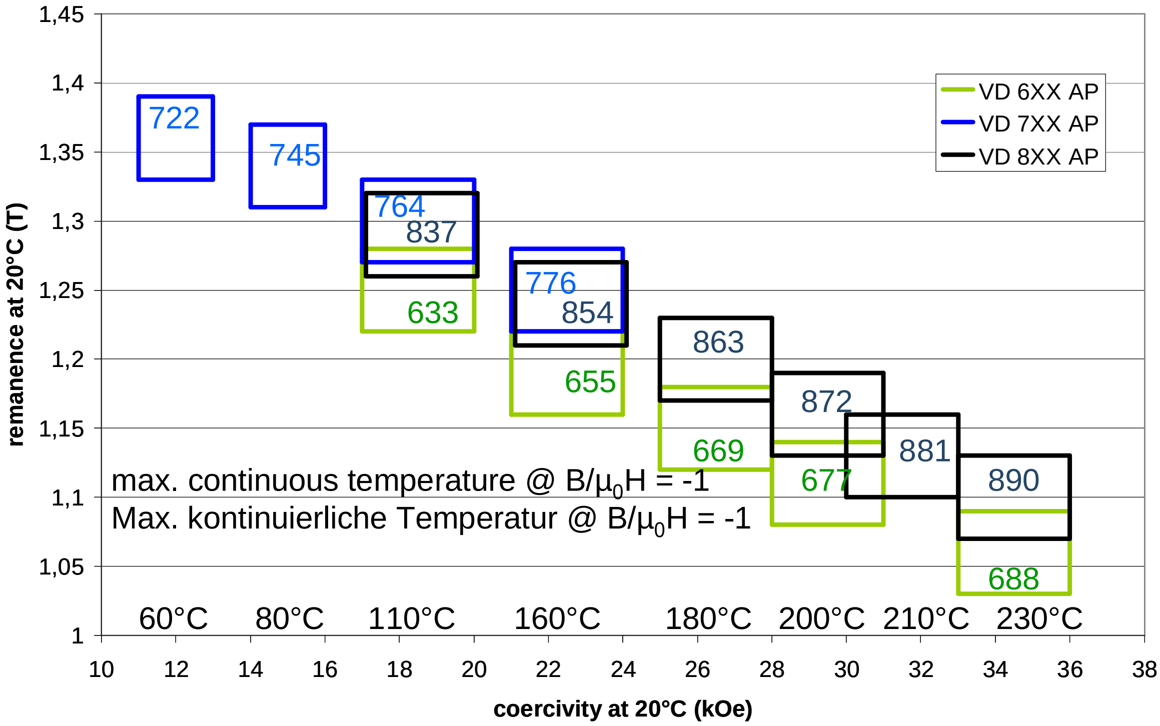

Fig. 5a Remanence and Coercivity of AP die-pressed alloys

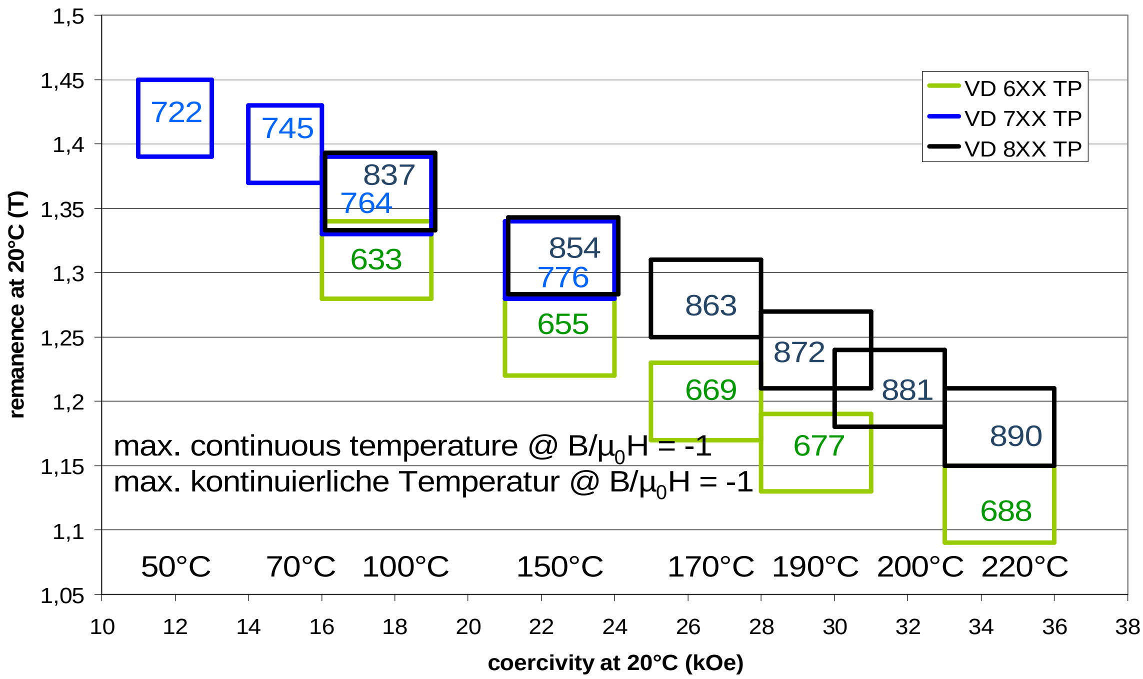

Fig. 5b Remanence and Coercivity of TP die-pressed alloys

2.0 Corrosion resistance of Nd-Fe-B permanent magnets

Apart from the magnetic properties, the corrosion resistance is an important focus for applications such as electrical machines in Hybrid vehicles. Special coatings such as VACCOAT® 20011 have been developed, which are electrically isolating, i.e. non conductive.
To test the corrosion resistance of the basic alloy, uncoated magnets are exposed in a pressure cooker test at 130°C, 2.6 bar (2.6 x 10^5 Pa) pressure and 95% relative humidity. By determining the mass prior to exposure, it is possible to set up a weight loss versus time diagram by removing the oxides on the surface of the magnets at different time intervals and determining its bulk mass. This test is commonly known as a HAST Test (Highly Accelerated Stress Test). The weight loss per surface area in [g/cm^2] of magnet (since corrosion always takes place at the surface of the magnet) over the exposure time t in [days] may be plotted according **Fig. 6**. While (old) traditional magnets show a specific weight loss of more than 1000 mg/cm^2 after 14 days of exposure, new alloys such VACODYM®© 6xx and 8xx show a specific weight loss of up to 1 mg/cm^2 after 10 days of exposure. This behaviour is comparable to SiFe laminated electric steel sheet, although its morphology is different.

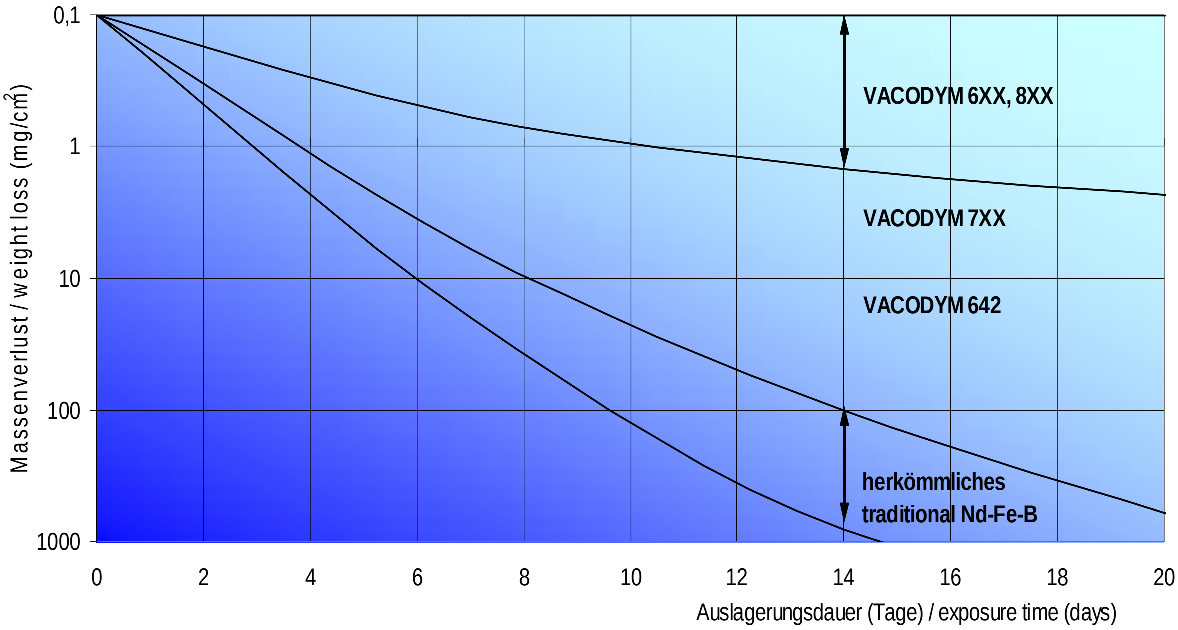

Fig. 6 HAST Test analogous to IEC 68-2-66 (130°C; 95% moisture; 2.6 bar pressure)

2.1 Corrosion resistance and salt-spray resistance of VACCOAT® 10047 und 20011 coating.

Special electric insulating coatings, such as VACCOAT® 10047 and 20011 were optimised during the last years, so that an excellent salt-spray-resistance according ASTM B 117 or DIN 50021 and temperature resistance of up to 200°C are achieved. **Fig. 7a and Fig. 7b** show different magnets after exposure of up to 500 hours under Salt-Spray or 12 days after HAST.

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VACODYM® 677 Magnets with Al-Spray-Coating VACCOAT® 10047

Fig. 7a Salt-spray test DIN 50021 and HAST (130°C; 2,7 bar 100% moisture)

Edge Protection VACCOAT® 20011 – barrel coating process

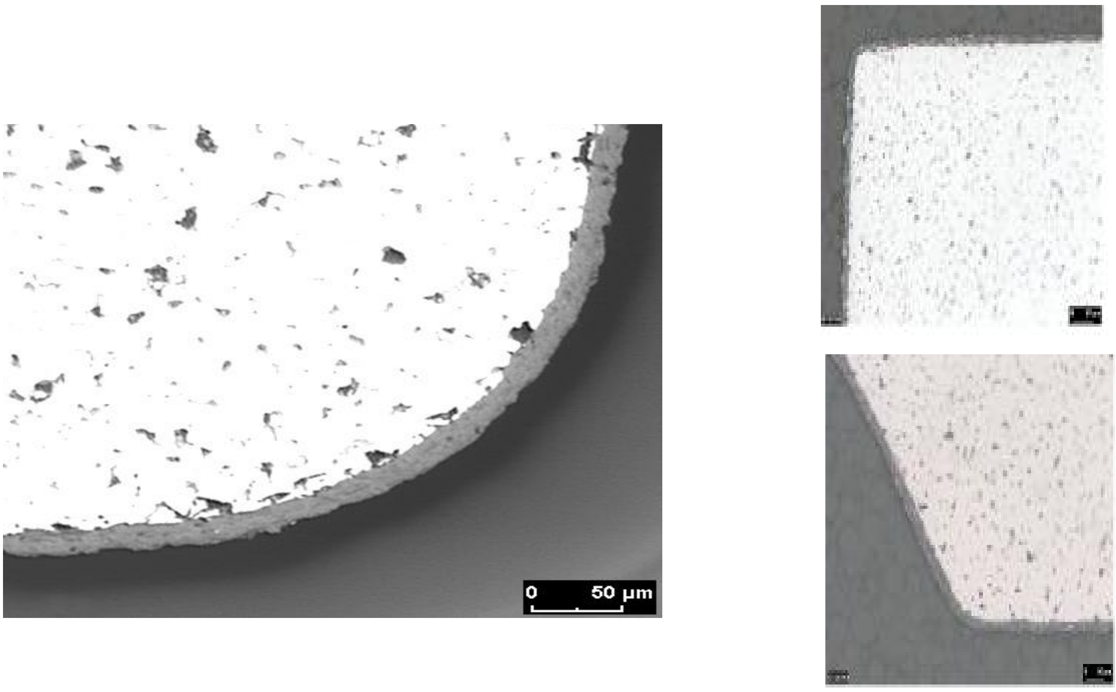


Fig. 7b Micrograph of VACCOAT® 20011 coated magnet with homogeneous coating even around sharp edges

3.0 Hot / Cold Side effect and field profile on AP die pressed magnets

A detailed analysis of **A**xial-field die-**P**ressed magnets reveals a different field distribution on the upper and lower side caused by the position of the pressing mould within the die, thus a divergence of the orientation field towards the upper punch. **Fig. 8** shows a schematic setup of the pressing tool with the field distribution within the mould.

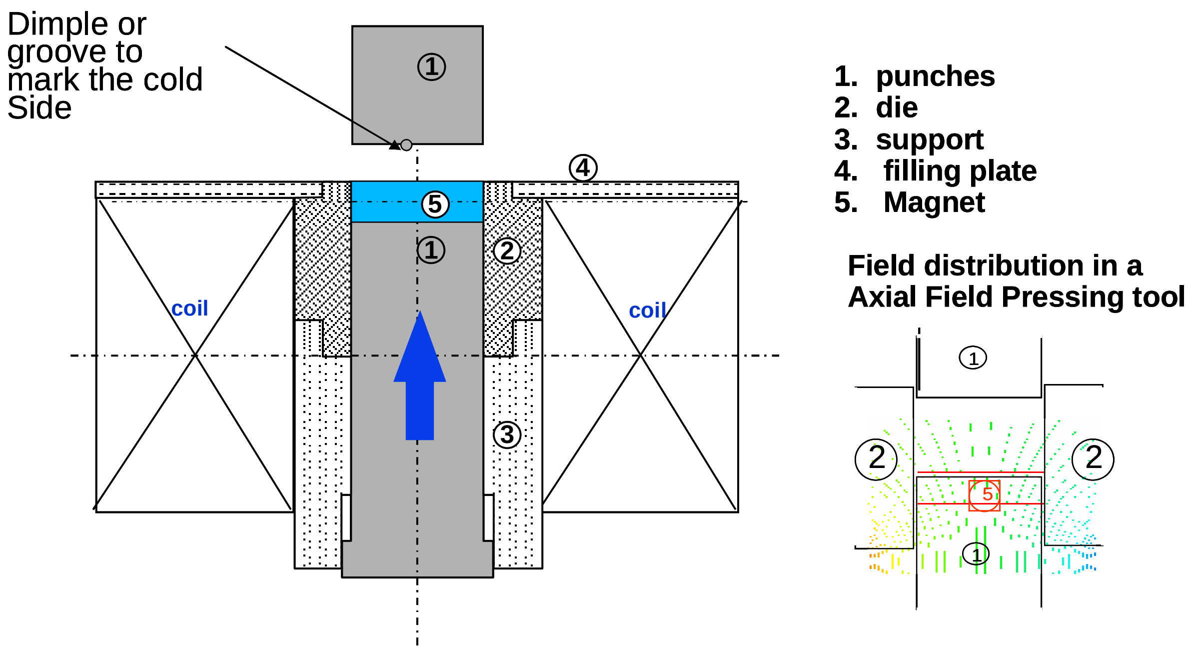


Fig. 8 Schematic setup of a pressing tool and magnetic orientation-coil

The divergence of field orientation within the magnet may adequately be simulated using a FEA (Finite Element Analysis) model, by subdividing the entire magnet in six sub-magnets, where the left and right sub-magnets positioned near to the upper punch have an inclination of magnetic orientation of 20° respectively.

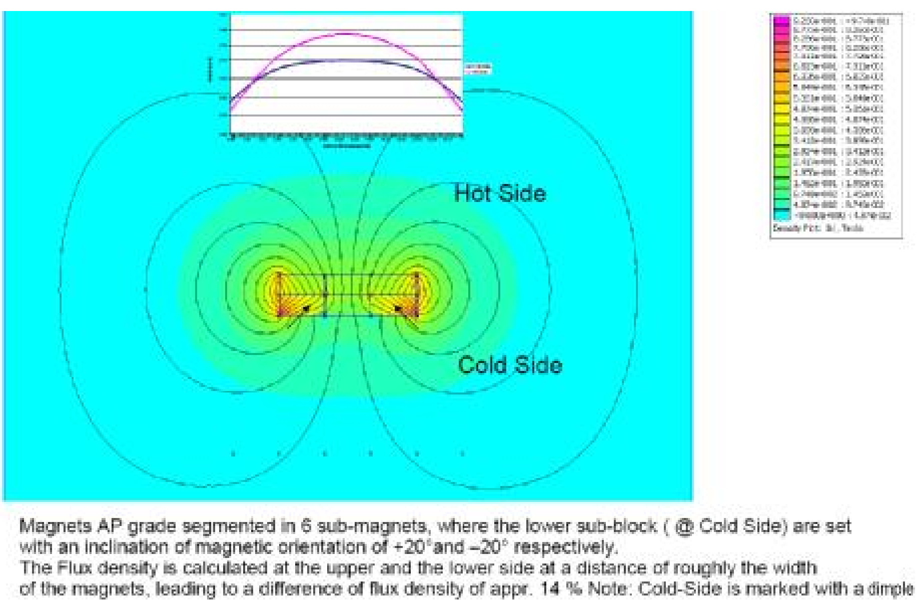


Fig. 9 FEA model simulating the field-profile of the upper and lower side of a magnet.

Evaluating the field profile at a distance of the width of a magnet above the upper side (Cold-side upper punch) of the magnet and the lower side (Hot-side lower punch) of the magnet respectively, we obtain a difference of induction of up to 14% as shown in **Fig. 9**. The following **Fig. 10** renders a field profile of AP die pressed magnets versus a strict diametrical parallel oriented magnet, cut out of block material at the same Remanence level.

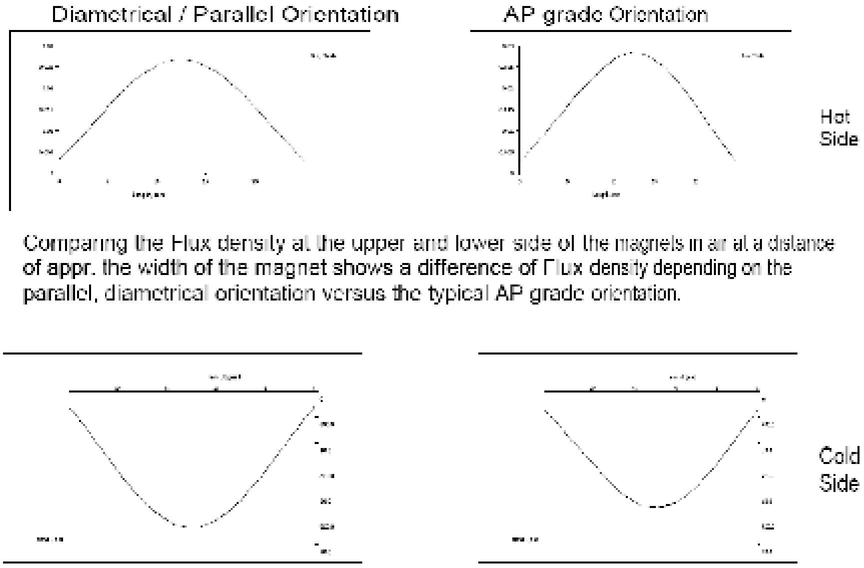
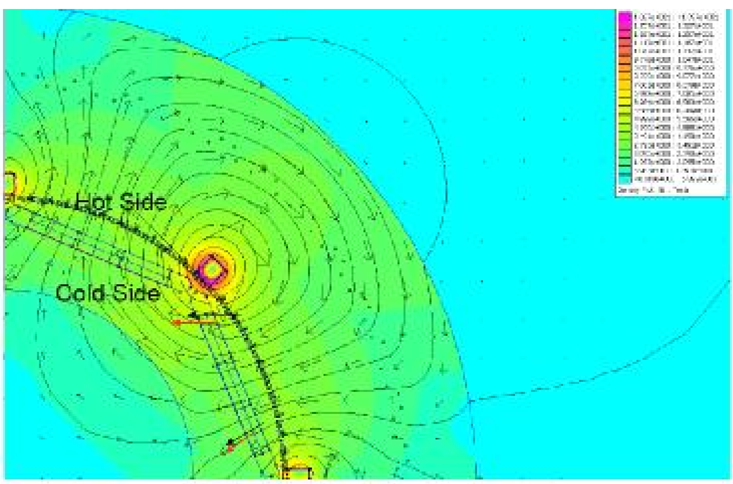


Fig. 10 Typical field distribution of upper and lower side of AP die pressed magnet versus a strict diametrical parallel oriented magnet cut out of a block.

3.1 Hot- / Cold Side effect on AP die pressed magnets while magnetising

When magnetising embedded magnets in a rotor using a magnetisation head, the field distribution of the head which co-aligns with the impregnated orientation of an AP die pressed magnet can be observed. The orientation of the left or right subsection of the magnet obeys the same direction respectively. To saturate the magnet fully, the magnitude of the outer flux need to be at least 2500 kA/m at every position within the magnet, which is shown in **Fig. 11** by arrows.

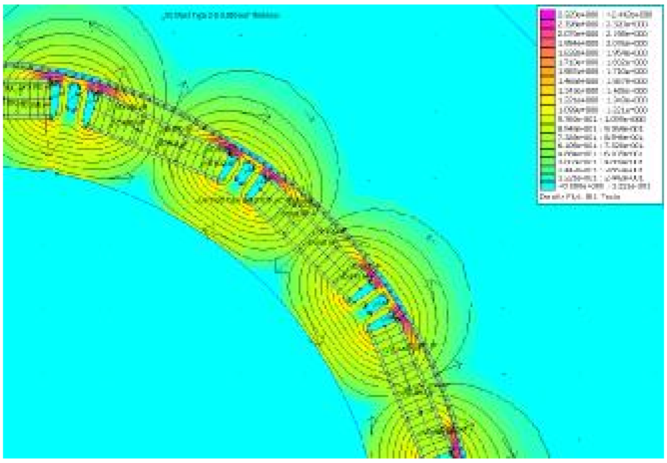


Tangential arrangement of embedded magnets in a rotor. The field of magnetisation diverges at the lower left and right hand side of the magnets. If the intrinsic orientation of the magnet co-aligns with the outer H field, the saturation can be achieved at every part of the magnet, if the Hot Side is placed towards the air gap. The H field should be at 2500 kA/m to saturate the magnet.

Fig. 11 Field profile using a magnetisation head for embedded magnets.

3.2 Hot / Cold Side effect on AP die pressed magnets in a motor application

Using a FEA model of a rotor with embedded magnets and a slot-less stator, one is able to analyse the air gap induction and compare an AP magnet with a strictly diametrical parallel oriented magnet cut out of a block material at the same Remanence level. The difference of air gap induction may be up to 2%, which is almost the same achieved with TP transverse die-pressed magnets. **Fig. 12 a,b,c** show this analysis in detail.



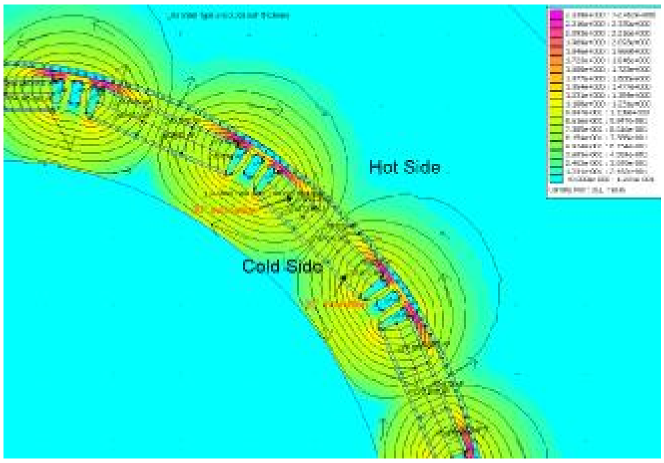
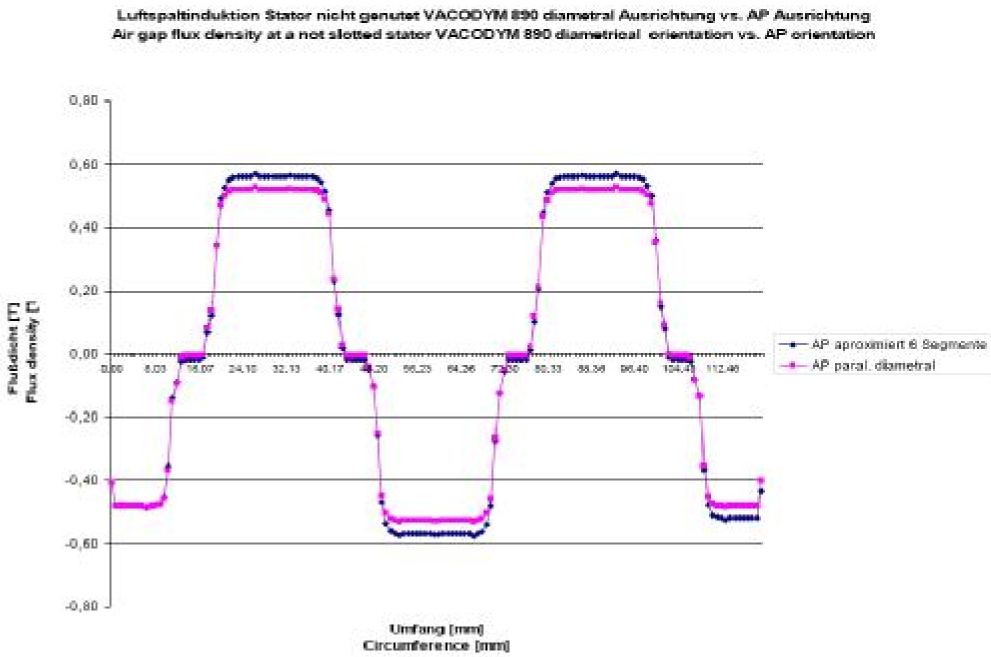


Fig. 12 a Magnet strictly parallel oriented

Fig.12 b AP orientation with Hot / Cold Side effect



Flux density in the air gap comparing parallel diametrical orientation vs. Hot / Cold Side effect of AP Grade (this can be illustrated by using a stator without slots).

Fig. 12 c Comparison of air gap induction

4.0 Summary

New Nd-Fe-B alloys and appropriate coatings may help to improve the performance of e.g. permanent electric synchronous machines in respect of all environmental conditions i.e. moisture or even oily conditions, as well as mounting magnets in such a way, that its intrinsic field distribution due to the axial field die-pressing technique is being exploited to increase the air gap flux density significantly at reasonable costs.