PROPERTIES, OPTIONS AND LIMITATIONS OF PRFEB-MAGNETS FOR CRYOGENIC UNDULATORS

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Abstract

The gap induction and thus the K-factor of permanent magnet undulators may be increased by cooling them to cryogenic temperatures. The use of NdFeB-magnets in cryogenic undulators, however, is limited to temperatures above 140 K due to the spin-reorientation transition (SRT) which leads to a reduction of the magnetization level.

A further increase of the gap induction in undulators may be achieved by use of PrFeB-magnets at even lower temperatures, as this alloy does not show the SRT phenomenon.

Although the effects are well known, up to now only a few undulator prototypes were built using this class of material since the coercivity of ternary PrFeB-magnets is not sufficient to minimize the risk of partial demagnetization when the undulator structure is kept at room temperature.

This problem can be solved by applying actual technologies like grain-boundary diffusion in order to achieve coercivities exceeding 1600 kA/m at RT without sacrificing the high remanence Br of about 1.6 T at 77 K.

We will provide actual data of the magnet performance achieved and show up the technological limitations in building PrFeB-based CPMU's.

INTRODUCTION

In the search for increased K-factors of permanent magnet undulators, an increase of the gap induction may be achieved by use of permanent magnets with increased remanence. The natural increase of Br with falling temperatures has been used in several cryogenic NdFeB-based devices already, but is limited to temperatures above 140 K due to the spin-reorientation in these alloys. As cryogenic technologies are efficiently available and approved for liquid nitrogen temperature around 77 K, a few successful trials have been reported on basis of PrFeB-magnets (most of them with Hitachi's CR53 grade) [2, 3] or mixed $(Nd_xPr_{1-x})_2Fe_{14}B$-alloys (an individual VAC grade) [1, 4]. In these, the spin-reorientation does not occur.

A specific limitation in the use of these high remanent alloys is the limited coercivity, which requires special precautions already during assembly at room temperature (e.g. assembly in cooled chambers, [4]) and also limits the options of bakeability for UHV use [3]. Specific alloys like Hitachi's CR50 and CR47 exhibit increased coercivity at the expense of reduced remanence and thus are a compromise between stability throughout assembly and / or bakeout and the aim for higher gap induction at low temperatures.

In the need of dedicated magnet materials for specific scientific applications, Vacuumschmelze has created a new, PrFeB-based magnet grade (VD131TP) and also successfully applied the grain-boundary diffusion process to those magnets in order to gain improved coercivities. Magnets with these properties are indicated as VD131DTP in their grade name.

In the development of these new grades, some limitations in the applicability of the diffusion process have been found, which will limit the full usability to some restrictions in the magnet geometry.

RESULTS ON TERNARY PRFEB-MAGNETS

Whereas the first magnets containing Pr produced for HMI in 2008 still were a mixed alloy with the composition of $(Nd_{0.2}Pr_{0.8})_2Fe_{14}B$, the new VD131-alloy series is based on pure ternary $Pr_2Fe_{14}B$.

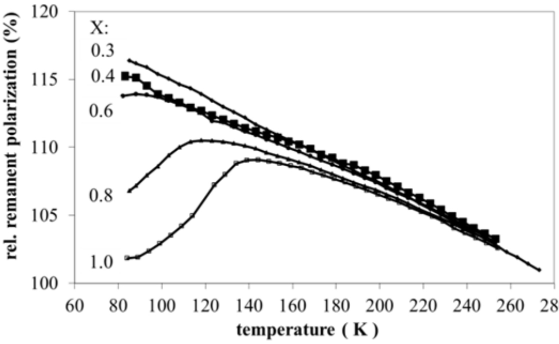

Figure 1: relative change of polarization with temperature for $(Nd_xPr_{1-x})_2Fe_{14}B$-magnets [1].

The relative remanent polarization of $(Nd_XPr_{1-X})_2Fe_{14}B$-alloys in Figure 1 does not show a spin-reorientation with the typical cusp for Nd-contents X of less than 0.3% down to liquid nitrogen temperature.

For the new alloy VD131TP, typical remanence and coercivity values are given in Figure 2. This figure also includes results of VD131DTP-magnets, which were produced from VD131TP by subsequent application of the grain-boundary diffusion process.

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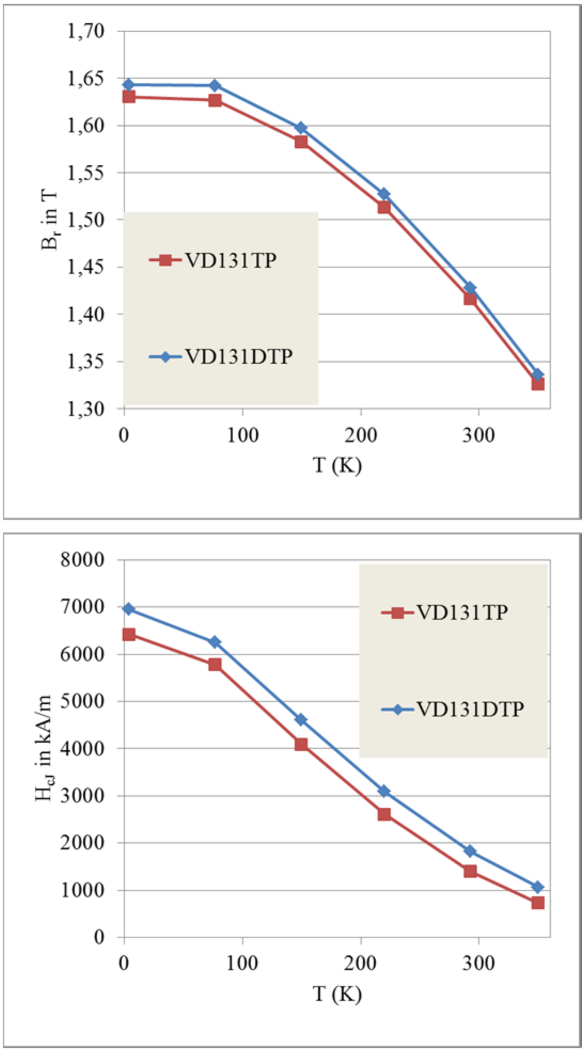

Figure 2: Remanence and coercivity of VD131TP and VD131DTP-magnets versus temperature.

Table 1: Specifications of VD131 TP and DTP

Characteristic	VD131TP	VD131DTP
Remanence B_r (min)	1.38 T	1.38 T
Coercivity H_{cJ} at 293 K (min)	1230 kA/m	1640 kA/m
Max. thickness	20 mm (0.79 in)	5 mm (0.20 in)
Coercivity H_{cJ} at 77 K	>3185 kA/m	

GRAIN-BOUNDARY-DIFFUSION

An increase of coercivity without significant loss of remanence may be achieved by the grain-boundary diffusion process. In this process - compared to conventional implementation by alloying method - the heavy rare-earth elements (Dy, Tb) which are required for effective decoupling of the magnetic grains are transported to the dedicated location inside the magnets microstructure where they operate most effectively: the grain boundaries. Regardless of the technical options (application from the gas phase or application in direct contact to the surface), the heavy rare-earth elements need to penetrate the already sintered and mechanical dense permanent magnet from the external (macroscopic) surface. A schematic of this process is shown in Figure 3.

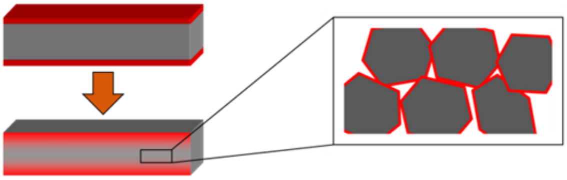

Figure 3: Schematic description of the Grain-boundary diffusion process: macroscopic view (with Heavy RE-Elements (red) on top of a sintered magnet (grey)) and microscopic view.

This transport mechanism is most effective along the existing, Nd-rich grain boundary phase in the alloy and should be stopped, before the heavy rare-earth elements significantly enter into the grain's bulk consisting of the main phase $Pr_2Fe_{14}B$. Therefore, it becomes clear, that there will be a geometric profile of the local coercivity achieved with highest values at the outer surface of the magnet and dropping towards negligible increases after a few mm.

LIMITATIONS

The effective use of the grain-boundary diffusion is limited by the thickness of the magnet exposed to the diffusion process. This is caused by the finite diffusion length of the heavy rare-earth material at a given process temperature and by the loss of effectivity towards an increase in coercivity as soon as the heavy rare-earth element starts to penetrate the main $RE_2Fe_{14}B$ grains.

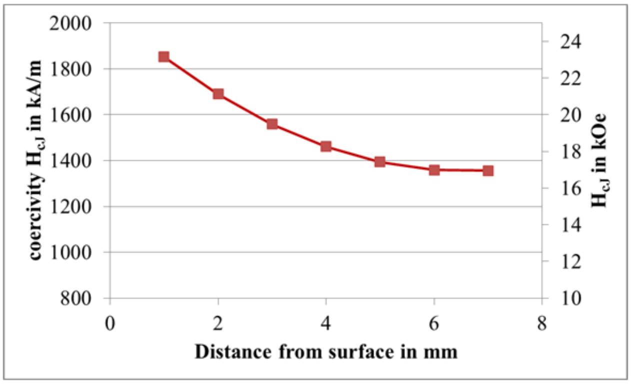

Figure 4: Depth profile of coercivity enhancement by grain-boundary diffusion for VD131DTP.

The coercivity enhancement exhibits a local variation with the maximum at the surface of the magnet and a steep decrease with increasing depth into the magnet.

Thus, for thin magnets, most of the coercivity gain may be conserved, whereas with increasing thickness the coercivity locally drops down to the original value without diffusion.

A typical diffusion profile is shown in Figure 4.

As an example, the magnetization reversal on a large magnet is shown in Figure 5. This large magnet with preferred direction normal to the paper plane has been exposed to grain-boundary-diffusion from the top side surface only. After application of a magnetic field in opposite direction to the original magnetization direction, the green pole-indicator sheet shows the transition between reversed polarization and non-reversed area with a white line. Thus, it can be indicated, that at a given field the dominant part of the magnet has reversed the magnetization, whereas the narrow top section, in which the grain-boundary-diffusion has been effective, is not reversed yet.

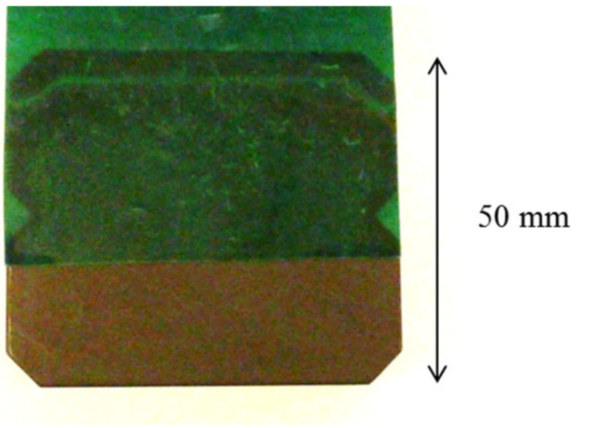

Figure 5: Large magnet with partial use of grain-boundary diffusion after exposition to a knock-down field. The magnetization direction within the top few millimetres is not reversed yet as indicated by the white line on the green pole-indicator foil.

However, this local increase of the coercivity can be used advantageously in applications where the highest demagnetizing fields are restricted to the regions close to the surface of the magnets like in hybrid undulators.

CONCLUSIONS

With the development of VD131TP and VD131DTP, a new alloy series based on PrFeB is available for the construction of cryogenic permanent magnet assemblies – especially undulators – to be driven at liquid nitrogen temperature or even lower temperatures.

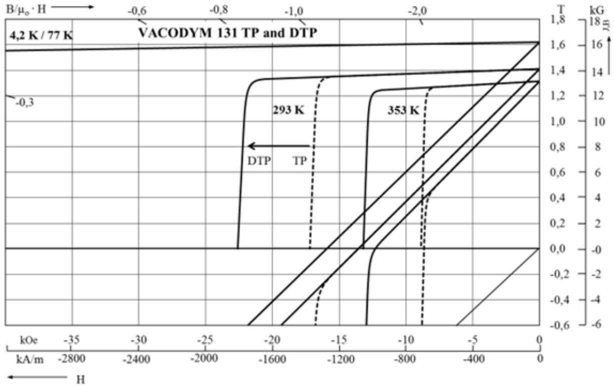

Figure 6: Magnetic characteristics of VD131TP and VD131DTP-magnets.

The permanent magnet properties in Figure 6 propose an increase in gap induction for low temperatures whereas the increased coercivity at room temperature for the DTP variant exhibits sufficient resistivity against demagnetization during assembly at room temperature or even slightly elevated temperatures.

For the application of the GBD-process on undulator magnets, a proper choice of the magnet thickness and / or the surface, from which the diffusion is started, is required.

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