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## NdFeB Permanent Magnets with Various Nd Content

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Three kinds of commercial Nd–Fe–B based materials were compared using  $^{57}\text{Fe}$  Mössbauer spectroscopy and X-ray analysis: near the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  stoichiometry and with both lowered and raised Nd content. Magnetically hard  $\text{Nd}_2\text{Fe}_{14}\text{B}$  is present in all three materials. In the Nd-low material it is accompanied with the magnetically soft  $\text{Fe}_3\text{B}$  phase, building the nanocomposite structure. In the Nd-rich sample the overstoichiometric Nd atoms seem to build separate phase of Fe–Nd solid solution. None of the materials contain significant content of phases degrading magnetic characteristics, with except of minor  $\text{Nd}_{1.1}\text{Fe}_4\text{B}_4$  one.

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### 1. Introduction

The classical  $\text{Nd}_2\text{Fe}_{14}\text{B}$  sintered permanent magnets or just  $\text{Nd}_2\text{Fe}_{14}\text{B}$  based rare-earth hard magnetic materials are known because of their high coercivity and large energy product. The newer nanocrystalline magnetic materials based on Nd–Fe–B alloys prepared by the rapid quenching of the liquid, known as exchange-coupled nanocrystalline composite hard magnetic materials, are almost of the same quality despite reduced amount of expensive rare-earth Nd [1–3]. On the other hand, there are also experiments trying to enhance the qualities of the stoichiometric material adding even more neodymium atoms to the basic structure.

### 2. Results and discussion

Three kinds of commercial materials being of the above-mentioned compositions (see Table I for constitution) were compared using room temperature Mössbauer spectroscopy of  $^{57}\text{Fe}$  and X-ray analysis. Their basic magnetic charac-

teristics are presented in Table II. For illustration, Mössbauer and X-ray diffraction spectra of both non-stoichiometric materials are shown together with their decomposition (Fig. 1 and 2).

TABLE I  
Studied samples and their nominal constitution (wt.%)  
— as given by producer.

Sample	Nd	B	Fe	Co	Zr	Si
C1 (Nd-low)	10–12	< 5	> 80	–	–	1–3
C2 (stoich.)	21–25	< 1.5	> 65	3–5	3–5	–
C3 (Nd-rich)	26–29	< 1.3	> 69	–	–	–

TABLE II  
Basic magnetic characteristics of the materials studied — as given by producer.

Sample	$B_r$ [T]	$H_{c(B)}$ [MA/m]	$H_{c(J)}$ [MA/m]	$(BH)_{max}$ [kJ/m <sup>3</sup> ]
C1 (Nd-low)	0.835	0.203	0.246	52.4
C2 (stoich.)	0.640	0.359	0.682	59.7
C3 (Nd-rich)	0.603	0.374	0.947	57.1

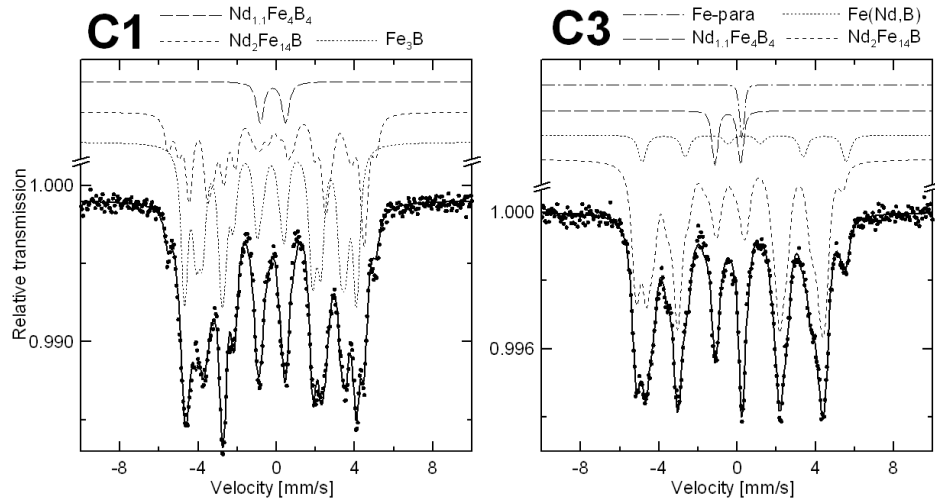


Fig. 1. Mössbauer phase analysis of the Nd-low (C1) and Nd-rich (C3) samples.

Both Mössbauer and X-ray spectra revealed the presence of the magnetically hard  $\text{Nd}_2\text{Fe}_{14}\text{B}$  phase in all three materials. In the material with the lowest neodymium concentration it is accompanied predominantly by the magnetically

soft  $\text{Fe}_3\text{B}$  phase, building the well known exchange coupled nanocomposite structure [4, 5]. The material near the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  stoichiometry contains besides the major phase also some rests of the  $\text{Nd}_{1.1}\text{Fe}_4\text{B}_4$  phase and limited amount of paramagnetic iron, probably in a phase with Zr (X-ray analysis). In the Nd-rich material, the X-ray diffraction component  $\text{Fe}_{17}\text{Nd}_2$  can be understood as a representative for some minor amount of an  $\text{Fe}(\text{Nd})$  solid solution. In the corresponding  $\text{Fe}(\text{Nd},\text{B})$  Mössbauer component, non-magnetic Nd and B atoms are almost undistinguishable in our case. No traces of any thermal or other decomposition ( $\alpha$ - $\text{Fe}$ ,  $\text{Fe}_2\text{B}$ , e.g.) were found.

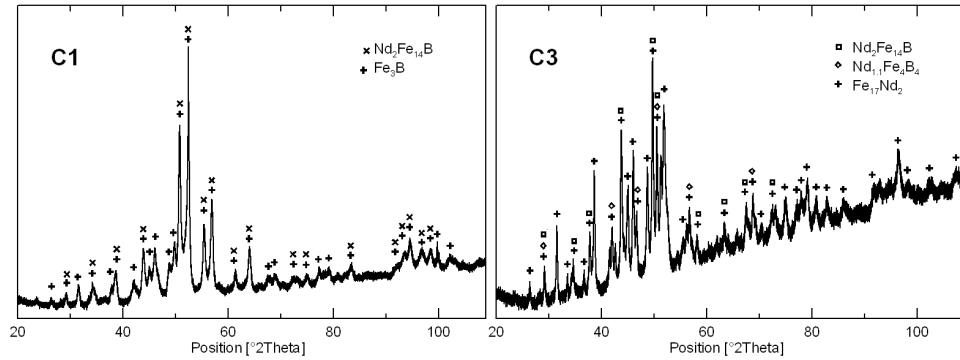


Fig. 2. X-ray diffraction of the Nd-low (C1) and Nd-rich (C3) samples.

Results of the Mössbauer phase analysis — taking into account also the X-ray spectra analysis — are summarized in Table III. For simplicity, proportionality between intensity of the Mössbauer lines and amount of relevant iron atoms is supposed.

TABLE III

Eclectic phase analysis; approximate fractions as taken from the Mössbauer spectra.

Sample	$\text{Fe}_3\text{B}$	$\text{Nd}_2\text{Fe}_{14}\text{B}$	$\text{Nd}_{1.1}\text{Fe}_4\text{B}_4$	$\text{Fe}(\text{Nd},\text{B})$	$\text{Fe-para}$
C1 (Nd-low)	0.58	0.38	0.04	—	—
C2 (stoich.)	—	0.92	0.05	—	0.03
C3 (Nd-rich)	—	0.87	0.05	0.08	( $\ll 0.01$ )

### 3. Conclusion

For low neodymium nanocomposite magnets the large saturation magnetic polarization (and finally also the remanence) is ascribed just to the presence of the prevailing soft magnetic phase  $\text{Fe}_3\text{B}$ , while the coercivity value remains connected

with the hard magnetic phase. In the neodymium rich sample the overstoichiometric Nd atoms seem to build separate phase of Fe(Nd) solid solution, obviously in some combination with an Fe(B) one. The particular material can be chosen according to the preferred characteristics of magnetic hardness.

All the three studied hard magnetic materials are of high quality, as none of the materials contain any significant content of “parasitical” phases (e.g.  $\alpha$ -Fe or other products of thermal decomposition) degrading the most important magnetic characteristics. Also no oxidation products can be seen in the Mössbauer spectra.

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