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THE COMPARATIVE STUDY OF Nd-Fe-B MAGNETIC MATERIALS WITH DIFFERENT Nd CONTENT

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ABSTRACT
For the purpose of better understanding of the effect of different Nd content on the magnetic properties of three types of commercial Nd-Fe-B alloys with 10-12 wt% Nd (Nd-low), 21-25 wt% (Nd-stoich.), and 26-29 wt% Nd (Nd-rich) were simultaneously analyzed using X-Ray and ^{57}Fe Mössbauer spectroscopy (MS) analysis. The observation was based on correlation of starting chemical composition with phase composition and magnetic properties in optimized magnetic state.
Keywords: rapid quenched Nd-Fe-B alloy, chemical composition, phase composition, magnetic properties

1. INTRODUCTION
Current research in the field of magnetic materials based on Nd-Fe-B is directed in three main directions: increase of magnetic energy, increase of corrosion resistance and reduction of amount of rare earth (Nd) in order to reduce the price of final magnetic material, while keeping high values of magnetic energy [1, 2]. The influence of Nd content on microstructure and magnetic properties of three kinds of commercial Nd-Fe-B alloys was analysed by comparing chemical composition, phase composition, and magnetic properties in optimized magnetic state.

2. EXPERIMENTAL
The chemical composition of the starting Nd-Fe-B powders after quenching and crystallization are presented in table I. The phase composition in optimized magnetic state was determined by X-ray diffraction analysis (XRD) and ^{57}Fe Mössbauer spectroscopy. X-ray diffraction measurements were performed on an X'Pert PRO MPD multi-purpose X-ray diffraction system from PANanalytical using Co K_{α} radiation. For the MS spectra fitting and decomposition the CONFIT software package was used [3].
Magnetic properties of investigated alloys were measured at room temperature on SQUID magnetometer with defined strength of magnetic field $\mu_0 H$ -5 +5 T.

Table 1. The chemical composition (wt. %) of investigated Nd-Fe-B alloys –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	-	-	-

3. RESULTS AND DISCUSSION

The basic magnetic properties measured on VSM (given by producer) are presented in Table 2.

Table 2.

Sample	**Br [T]**	**$H_{c(B)}$ [MA/m]**	**$H_{c(J)}$ [MA/m]**	**$(BH)_{max}$ [kJ/m^3]**
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

The results of phase analysis using XRD are given in Table 3.

Table 3. XRD- phase analysis of the Nd-low (C1), stoich. (C2) and Nd-rich (C3) alloys

Sample	**Phase Composition**			
C1 (Nd-low)	$Nd_2Fe_{14}B$	Fe_3B		
C2 (stoich.)	$Nd_2Fe_{14}B$	Alfa Fe	Nd1.1Fe_4B_4	Fe_2B , ZrB_{12}
C3 (Nd-rich)	$Nd_2Fe_{14}B$	$Fe_{17}Nd_2$	Nd1.1Fe_4B_4	

In optimal magnetic state, the magnetically hard $Nd_2Fe_{14}B$ phase is present in all three investigated alloys. The Nd-Fe-B alloy with Nd low content is multiphase [4, 5]. Beside main hard magnetic phase $Nd_2Fe_{14}B$, soft magnetic phases with high magnetization Fe_3B exist, as well as whole set of phases of Fe-B type. The hard magnetic phase $Nd_2Fe_{14}B$ with magnetically soft Fe_3B phase forms the well known exchange coupled nanocomposite structure [4, 5, 6]. The formed nanocomposite $Fe_3B/Nd_2Fe_{14}B$ is directly responsible for the enhancement of remanence. The results of XRD and MS analysis show that stoichiometric Nd-Fe-B alloy is practically single phase with dominant amount of $Nd_2Fe_{14}B$ hard magnetic phase. The some small amount of other detected phases ($Nd_{1.1}Fe_4B_4$, and limited amount of paramagnetic iron, probably in a phase with Zr) which are probably situated on grain boundaries had negligible influence on the magnetic properties.

On the other side, magnetic properties of Nd-rich Nd-Fe-B alloy are under dominant influence of the magnetically isolated grains of hard magnetic $Nd_2Fe_{14}B$ phase. In the Nd-rich alloy, the phase $Fe_{17}Nd_2$ (determined by XRD) can be understood as a representative for some minor amount of a Fe (Nd) solid solution. In the corresponding Fe (Nd) B Mössbauer component non-magnetic Nd and B atoms are almost undistinguishable. No traces of any thermal or other decomposition α-Fe, Fe_2B, eg. were found. The results of Mössbauer phase analysis are illustrated by MS spectra on Fig 2.

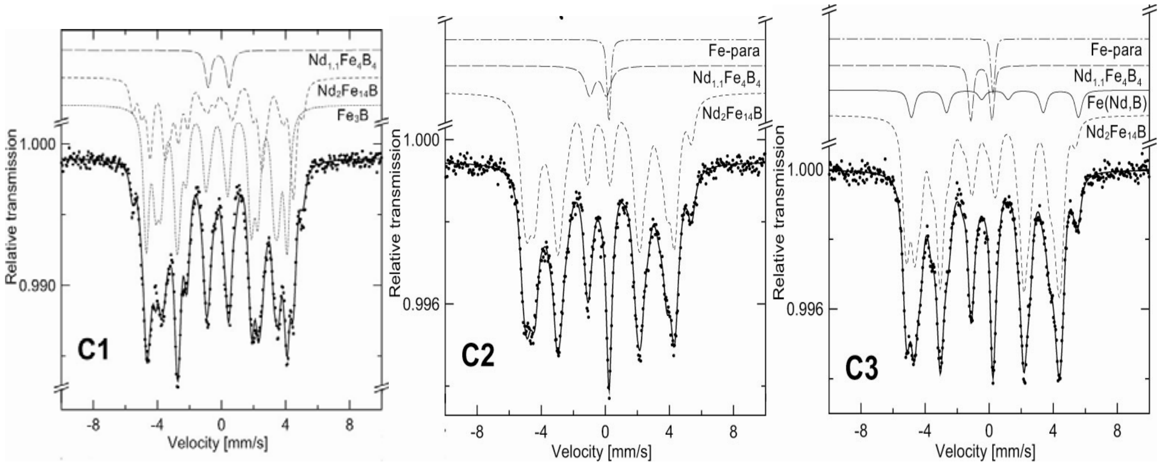

Figure 2. Mossbauer phase analysis of the Nd-low-C_1, stoich-C_2. and Nd-rich –C_3 alloys

The phase composition of investigated NdFeB alloys obtained by analysis of MS spectra is given in Table 4.

Table 4. Eclectic phase analysis; relative fractions as taken from MS spectra

Sample	Fe_3B	$Nd_2Fe_{14}B$	$Nd_{1.1}Fe_4B_4$	Fe(Nd,B)	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)

Hysteresis loops obtained by SQUID magnetometer for all investigated alloys are presented on the Fig 3. The shape of SQUID hysteresis loops corresponds to the chemical and phase composition for Nd-Fe-B alloy with reported Nd content in optimal magnetic state.

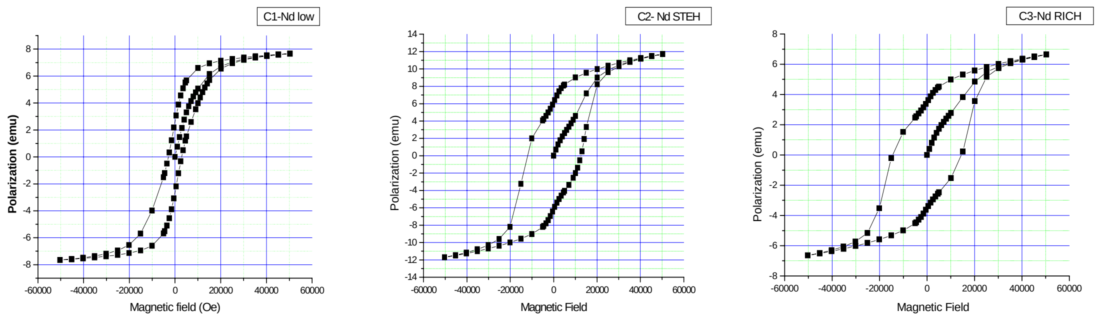

Figure 3. Hysteresis loops for three investigated Nd-Fe-B alloys

4. CONCLUSION

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

From the presented SQUID hysteresis loops it is obvious that investigated Nd-low alloy has higher value of the remanence, which is typical for nanocomposite structures of Nd-Fe-B alloys, despite reduced Nd content.

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