Investigation of the influence chemical and fractional compositions on the magnetic properties of the gas atomization powder of the Fe-Nd-B system

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Abstract. The authors explore the magnetic properties, macro- and microstructure of the powder material of the Fe-Nd-B alloys obtained by spraying a melt stream with an inert gas flow. Compositions of gas atomization powder (GAP) alloys: Fe77,6Nd14,8B7,6; Fe74Nd16,5B8,5(Bi, Al, Co); Fe76Nd15B(Dy, Tb).

GAS ATOMIZATION POWDER MATERIALS OF THE SYSTEM Fe-Nd-B

The authors explore powder alloys of the system Fe-Nd-B, obtained by melt quenching from the liquid state (MQ) by gas atomization of the melt in a flow of inert gas (1,2).

Two fundamental points make the work relevant and practically significant. Firstly, the very high corrosion resistance of the investigated gas atomization powders to storage under natural conditions without loss of consumer properties when processing them into sintered anisotropic magnets by standard technology (3). Secondly, the presence of an effective residual magnetic moment (effective magnetic anisotropy) in the fracturing of Fe-Nd-B system. It is for the solution of the second problem that the structural-phase state of hydraulic fracturing was studied depending on their chemical and fractional composition. The chemical compositions were chosen in a special way to influence the magnetic properties of the main magnetic phase - Fe14Nd2B (cobalt doping and heavy REM) and the structure of the fast-solidifying melt in MQ by the GA method at a fixed fractional size: surface active elements-Al and Bi. In the latter case, when the effect of grinding the grain structure with the introduction of surfactants at a fixed rate of cooling of the melt at MQ was predictable, to improve the thermal stability of the magnetic properties, the gas atomization alloy was doped with cobalt.

To solve this problem, the following methods of research, analysis and testing were used:
1. sieve analysis of the fractional composition of GAP;
2. metallographic analysis of the structure and phase composition of the GAP alloy;
3. calorimetric analysis of the structural phase transitions in the GAP alloy during heating at a given speed in a protective atmosphere;
4. magnetometric analysis of plastic bonded and sintered magnets;
5. modeling of the magnetic field of a magnetic system from spherical powders of a GAP alloy containing grains of the Fe14Nd2B phase, which crystallize from the melt in the liquid crystal by the GA method.
Metallographic analysis of the GAP alloy Fe-Nd-B system

The results of the metallographic analysis prove the effect of additional doping by the PM and REM components on the fracturing of different fractions. The results of the metallographic analysis prove the effect of additional doping by the PM and REM components on the fracturing of different fractions. The effect of such doping on the morphology of the Fe_{14}Nd_{16.5}B_{8.5} grains and, in general, on the structure of the alloy, as a function of its dispersion, is demonstrated by the metallographic structures of the "FIGURE 1" hump. For comparison, "FIGURE 1" presents analogous structures of the three-component alloy of the Fe-Nd-B system. Reducing the size of the powders reduces the size of the grains of the main phase, while their shape remains.

![FIGURE 1](image1.png)

**FIGURE 1.** Influence of the fractional composition of the MQ GAP alloy Fe_{77.6}Nd_{14.8}B_{7.6} on the morphology of grains of the phase Fe_{14}Nd_{16.5}B_{8.5}

In a number of powders, clear boundaries are revealed between the structural components of different dispersity, which can be located both inside and on the surface of the powder. Their occurrence, as before, can be associated with concentration supercooling, formed on the front of a growing array of small grains of the phase (2:14:1) and a change in the mechanism of their crystallization. Doping, especially PM = Co, increases the number of such boundaries (4, 5). Their shape has spherical symmetry. Consequently, the growth of the structural components bounded by such a boundary is determined by a factor characterized by spherical symmetry, for example by the heat sink to the "FIGURE 2" volume.

![FIGURE 2](image2.png)

**FIGURE 2.** Influence of the fractional composition of the MQ fracturing alloy Fe_{77.6}Nd_{16.8}B_{8.5} (Bi, Al, Co) on the morphology of the grains of the Fe_{14}Nd_{16.5}B_{8.5} phase

The realization of such a scheme is possible when in the supercooled melt (in its separate parts) the crystallization centers occur randomly, that is, heterogeneous crystallization is realized. In this case, refractory
inclusions can appear as these centers, the number of which increases substantially when modifying components, especially Al, are introduced into the alloy. Specifically, in fracturing-alloys containing such PM separated by a boundary, the number of structural constituents is increased.

**Calorimetric analysis of the GAP alloy Fe-Nd-B system**

Differential thermal analysis (DTA) was carried out using the classical method of investigation on the NETZSCH 204 F1 Phoenix instrument. Samples of a gas atomization powder were poured into a quartz crucible, heated to 850 K, and then cooled at the same rate of 5 K/s.

According to the data obtained on "FIGURE 3", the following conclusion can be drawn. The Curie temperature ($T_C$) for each chemical composition of the gas atomization powder alloy is different:

- Fe$_{77.4}$Nd$_{14.8}$B$_{7.6}$ (T$_C$~550 K);
- Fe$_{74}$Nd$_{16.5}$B$_{8.5}$ (Bi, Al, Co)$_1$ (T$_C$~575 K);
- Fe$_{70}$Nd$_{16.5}$B$_{8.5}$ (T$_C$~530 K).

The obtained data confirm that the fracturing, above the listed compositions of alloys, are ferromagnets. After $T_C$, the energy of thermal chaotic motion overcomes the energy of the exchange interaction of electrons and the spontaneous magnetization disappears. The ferromagnet loses its magnetic properties and becomes a paramagnet. For further research, we choose fracturing of the composition Fe$_{72}$Nd$_{16.5}$B$_{8.5}$ (Bi, Al, Co)$_1$(6).

**Magnetometric analysis of sintered anisotropic magnets from gas atomization powder alloys of the Fe-Nd-B system**

To study the magnetic properties, plastic bonded and a sintered magnet from the fracturing system Fe$_{72}$Nd$_{16.5}$B$_{8.5}$ (Bi, Al, Co)$_1$ were fabricated. Plastic bonded were obtained from a gas atomization powder of Fe$_{72}$Nd$_{16.5}$B$_{8.5}$ (Bi, Al, Co)$_1$. The filler of the plastic bonded is an epoxy resin (30% by volume) and a powder (70% by volume). Pressing of fracturing specimens occurred in a magnetic field with strength of 12.5 kOe. The direction of the pressing coincided with the direction of the magnetic field. The resulting compacts were sealed in a quartz ampoule in an argon atmosphere and sintered for one hour at a temperature of 1020 °C. The magnetic properties were studied in a coecimeter. The results of magnetic measurements are presented on the "FIGURE 4" curves for magnetization and demagnetization of plastic bonded from fracturing (1 and 1') (d <0.08 μm) and an anisotropic magnet Fe$_{72}$Nd$_{16.5}$B$_{8.5}$ (Bi, Al, Co)$_1$ (2 and 2').
The similarity of magnetizing branches for plastic bonded and anisotropic magnets from fracturing is revealed, which indicates that at the initial stage of magnetization of magnets from the fracturing the mechanism of braking of the motion of domain walls does not work. The nature of demagnetizing branches indicates a mixed mechanism for the formation of magnetic rigidity.

**Modeling of the magnetic field created by spherical particles of the Fe-Nd-B alloy**

On the basis of the metallographic analysis, a sample of single-domain, two-domain and multidomain particles was made to evaluate the confirmation of the results obtained by theoretical calculations. We selected particles in which the growth of the grains coincides with the direction of the magnetic moment. The direction of the magnetic induction vector coincides with the domain of the particle, so an algorithm was compiled analytically to calculate the magnetization. In the Origin 8 program, there were crystallization centers and the coordinates of the points that were needed for calculations. The direction of the growth of the largest grains determined the direction of the domain of the particle *FIGURE 5*.

"FIGURE 6" shows the graph of the module $\vec{B}$, obtained by the program Ansys Maxwell. According to the graph, the magnetic field of a single-domain particle is $B = 1.07 \, T$, which is comparable to the result of the analytical solution method according to formula 1, where $B = 1.072 \, T$. 

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**FIGURE 4.** Magnetization curves (1 and 2) and demagnetization (1’ and 2’)

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**FIGURE 5.** Direction of the magnetic moment (indicated by an arrow) of a single-domain particle
\[ B(z) = \frac{\mu_0}{2\pi} \left( \frac{x^2}{z^5} - \frac{1}{2z} \right) = \frac{\mu_0 IV}{2\pi z^3} \]  

(1)

**FIGURE 6.** The module for induction of the magnetic field of a single-domain particle (Z axis)

Ansys Maxwell was modeled for the plastic bonded. The shape of the plastic bonded is a cube, the number of spherical single-domain particles is 125 pieces. The simulation schedule is presented on "FIGURE 7". According to the schedule, \( B \approx 0.2 \, \text{T} \).

**FIGURE 7.** The magnetic field of the plastic bonded model

The result of the magnetometric analysis is \( B \approx 0.28 \, \text{T} \) "FIGURE 8". The best magnetic characteristics are Fe\(_{74}\)Nd\(_{16.5}\)B\(_{8.5}\) \((\text{Bi, Al, Co})_1\) fractions with a fractional composition of 0.0-0.08 mm.
The difference can be explained by a number of reasons, such as the number of particles, the fractional composition, and their distribution in space and the type of particles. According to the results of the sieve analysis, fractions (+0.08 - 0.14) mm predominate for fracturing the Fe77.6Nd14.8B7.6 alloy. In the alloy Fe74Nd16.5B8.5 (Bi, Al, Co)1, the maximum distribution of the fracturing is shifted to the increased powder dimensions: (+0.14 - 0.2) mm. Alloying of the alloy with heavy REM atoms (for example, an alloy of the composition Fe76Nd15B8 (Dy, Tb)1) leads to a reverse displacement of the distribution of powders in size: the largest amount of powder in the mixture corresponds to the fraction (+0.0-0.08) mm. The obtained results agree satisfactorily with the nature of the effect of alloying components on the viscosity and surface tension of the melt (at a fixed temperature). Elements that increase the viscosity (Al) and reduce the surface tension of the melt (Bi), favor the predominant formation of large particles during gas spraying of the melt stream by an inert gas stream.

The results of the metallographic analysis of the structure of the fracturing alloy prove that additional doping affects not only the fractional composition of the fracturing, but also the grain size of the main magnetic phase (for a fixed size of the powders).

Thus, the doping of fracturing with bismuth and aluminum increases the amount of fine grains of the Fe14Nd2B phase. The metallographic analysis of the fracturing shows that the powders of a triple alloy with a diameter less than 80 μm have an equiaxial grain structure with a crystallite size of the order of 0.5 μm (7). In powders with a larger diameter, the dendritic morphology of the Fe14Nd2B phase grains is predominantly realized, with an average size of up to 4 μm.

The results of calorimetric analysis show that the Curie temperature (Tc) for the corresponding chemical composition of the gas atomization powder alloy differs, exceeding the experimental accuracy (± 10 K):

Fe77.6Nd14.8B7.6 - (Tc·550 K);
Fe74Nd16.5B8.5 (Bi, Al, Co)1 - (Tc·575 K);
Fe76Nd15B8 (Dy, Tb)1 - (Tc·530 K).

According to the results of the magnetometric analysis, the similarity of magnetizing branches for plastic bonded and sintered antisatropic magnets from the fracturing is revealed, which indicates that at the initial stage of magnetization of magnets from the fracturing the mechanism of braking of the motion of the domain walls does not work.

The nature of demagnetizing branches indicates a mixed mechanism for the formation of magnetic rigidity. The best magnetic characteristics are Fe74Nd16.5B8.5 (Bi, Al, Co)1 fractions of fractional composition (+0.0-0.08) mm.
Characteristics of magnetic properties (coercive force, residual induction, rectangular shape of the hysteresis loop) of manufactured and investigated sintered anisotropic magnets prove the applicability of fracturing alloys for the production of magnets of the iron-neodymium-boron system in powder technology without loss of properties. This opens the prospect of reducing the cost of production of magnets by combining two technological cycles: melting and grinding.

The simulation results for the magnetic field produced by the spherical particles of the Fe-Nd-B system alloy are numerical calculations using the Ansys Maxwell program and an analytical method for single-domain, bipartite and multidomain particles.

A model for the formation of the magnetic anisotropy of a single powder is proposed. The average effective magnetic anisotropy of a spherical particle is formed because of the average effective grain anisotropy: the total average number of grain lengths in the powder (with allowance for the vector nature of the chosen direction) is always on the average nonzero. This result is due to the probabilistic displacement of the center of the onset of heterogeneous crystallization from the center of the sphere of the powder to the periphery.

For the plastic bonded (multidomain particle system), the magnetic field was simulated and quantitative estimates of the magnetic characteristics (residual induction Br) were made. A satisfactory quantitative agreement of the simulation results (Br ≈ 0.3 T) and experimental measurements for a system of single-domain powders (plastic bonded, B, ≈ 0.28 T) was obtained.

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