ON THE STUDY OF THE INFLUENCE OF EXTERNAL PRESSURE AND CARBON ON THE STRUCTURE FORMATION AND PROPERTIES OF COMPACTS BAKED ON THE BASIS OF RAPIDLY COOLED Nd-Fe-(C,B)-Cu-Ti ALLOYS (PART 2)

Objective. Complex study of thermodynamic and physico-chemical conditions of phase formation in ready permanent magnets, manufactured on the basis of Fe-Nd-B systems.

Research methods: metallographic, x-ray, magnetometric.

Result. The influence of external pressure and a small amount of carbon (0.17...0.86 % AO) on the structure and properties of permanent magnets made on the basis of the Nd-Fe-B system doped with copper and titanium. For the manufacture of permanent magnets with high magnetic energy, fast cooling products from the liquid state are used. To do this, the flakes obtained by the LRE method were pressed in a mold and spiked in a vacuum. The mold and bolts that fasten are made of alloys that have different coefficients of linear expansion. This method allows to achieve high pressure (∼1 HPa) during sintering. Sintering was performed in a vacuum under pressure P = 12 MPa and at a temperature of 1013 K.

It is shown that carbon has a dual effect on the properties of alloys Nd$_{15.2}$Fe$_{75.5}$-x C$_x$B$_{6.6}$Cu$_{1.57}$Ti$_{1.38}$, (x: 0.33...0.86 % of the stock.): on the one hand, in the presence of carbon (0.33...0.86 at.%) in the liquid alloy, micro-areas are formed, which are enriched with copper, on the basis of which, when quenched from the liquid state, NdCu$_2$ crystals are born. On the other hand, during crystallization of the amorphous component in alloys Nd$_{15.2}$Fe$_{75.5}$-x C$_x$B$_{6.6}$Cu$_{1.57}$Ti$_{1.38}$ under high pressure conditions, imperfections are formed in which the alloying elements – carbon, copper, titanium, neodymium-are diffused. Micro-areas, reaching critical sizes, become an obstacle to the displacement of domain boundaries. And in the first, and in the second cases actively manifests itself pinning-effect.

Scientific novelty. It is found that the sintering temperature of rapidly cooled alloy flakes decreases Nd$_{15.2}$Fe$_{75.5}$-x C$_x$B$_{6.6}$Cu$_{1.57}$Ti$_{1.38}$ in conditions of high pressure of about 0.9 MPa from the technological 1323 K to the temperature of 1013 K practically does not affect the rate of nucleation of metastable phases NdCu$_2$ and Nd$_3$Fe$_4$B and at the same time reduces the speed of their growth. However, this leads to an increase in the coercive force of the finished magnets from 160 kA/m to 1300 kA/m.

Practical significance. The results obtained in this work are important for the further development of physical material science of magnetically hard materials and modern technology.

Key words: sintering “heat” pressure, annealing, the main hard magnetic phase, the phase with reduced metastability, the coercive force.

Introduction

Today magnetic materials are used in all spheres of life. Permanent magnets are an integral part of various spheres of human life, so improving its magnetic characteristics such as residual induction and coercive force is an important and priority task. As is known, the coercive force of magnets can be increased both by changing the microstructure and phase composition of the magnet material (the structural constant C), and by changing the fundamental characteristics of the magnetorjost phases (saturation magnetization $\mu$, magnetocrystalline anisotropy field $H$). However, in the manufacture of permanent magnets, the size of the main fraction of the powders should not exceed 10...20 μm, after sintering, the particles should be isolated from each other by a non-ferromagnetic layer to suppress the nucleation of the reverse magnetization domains. There are several ways to solve this problem: 1) modification of main hard magnetic phase Nd$_3$Fe$_4$B 3a special introduction to the fusion of elements of a certain concentration; 2) quenching from the liquid state of the initial alloys; 3) HDDR method.

The analysis of literary sources

In 1984, Herbst [1] determined the structure of the compound by x-ray diffraction and neutron diffraction Nd$_3$Fe$_4$B. Connection Nd$_3$Fe$_4$B it has a tetragonal crystal lattice and belongs to the space group P4 /mmm. It consists of 68 atoms in an elementary cell, has six crystallographic positions of iron and two positions of neodymium (Fig. 1). For the analysis of the Mossbauer spectra of the phase Nd$_2$Fe$_{14}$B [1] the Wigner-Seitz cell method was used and...
the number of nearest neighboring atoms for different crystallographic positions of iron atoms was determined: $8_j$, $8_{j_1}16_k$, $16_k$, $4e$, $4c$. Nodes $8_j$ and $8_j$ it has 12 nearest neighboring iron atoms, nodes $16_k$ and $16_k$ have 10 nearest neighbors, node $8_k$, it has 1 boron atom instead of iron as the nearest neighboring atom. Nodes $4e$ and $4c$ respectively, 9 and 8 of the nearest neighboring iron atoms. Lattice parameters: $c = 1.22$ nm and $a = 0.881$ nm. This structure provides a uniaxial magnetic anisotropy of the compound Nd$_2$Fe$_{14}$B. In the center of the trigonal prism formed by three iron atoms, there is a boron atom. Fundamental magnetic characteristics of the phase Nd$_2$Fe$_{14}$B there is a field of magneto-crystalline anisotropy $H_e = 5.4$ kA/m, saturation magnetization $J = 1.6$ T, Curie temperature $T_c = 585$ K, residual induction $B_R = 1.2$ T [2–4]. Magnetic properties of the phase Nd$_2$Fe$_{14}$B(C) determines the exchange interaction between the iron atoms in the iron sublattice, and the optimal distance between the atoms forms the neodymium sublattice (or other heavy REM) due to its size.

However, these mechanisms do not allow to fully interpret the entire range of experimental data [5, 11–14]. A comprehensive analysis was carried out in [9,10], which showed that in the case of the application of the model of the visco coercive state, the greatest correspondence between the theoretical representations and the experimental results obtained at room temperature is obtained. This model is based on the mechanism of delay of formation of reverse magnetization embryos. The authors attribute the discrepancy between the calculated and experimental data to the presence of grains in the samples, which are oriented differently. At temperatures above 423 K is dominated by the delay mechanism of the displacement of domain walls with magnetic inhomogeneities of grain boundaries [15–18]. The authors in these works suggest that there is a ferromagnetic phase with a close Curie temperature and low coercive force in the Micrograin layers, but this phase could not be detected experimentally [19].

All alloying elements can be divided into three large groups:

1. the Introduction of terbium, dispersion, gadolinium into the neodymium sublattice can be an effective method of increasing the magnetic properties of finished products;

2. the replacement of iron atoms into the cobalt (raises the Curie temperature), Nickel (contributes to thermal stability), aluminum, niobium, manganese, molybdenum.

The difficulty lies in the fact that the iron atoms in the elementary cell of the phase Nd$_2$Fe$_{14}$B in they occupy six non-equivalent crystallographic positions [20], so it is almost impossible to predict in which positions the doping element will be replaced and whether such replacement will occur at all;

3. the introduction of surface-active elements, copper, titanium, molybdenum, aluminum, gallium, on the basis of which are formed of non-magnetic phase to isolate the magnetic grains of the hard phase Nd$_2$Fe$_{14}$B(C) and increase its corrosion resistance.

In alloys with iron crystal structure isomorphic to the structure of the compound Nd$_2$Fe$_{14}$B, is formed with most of REE from La to Lu (except for Eu). In the compounds R$_2$Fe$_{14}$B large values of coercive force are possible in the interaction of boundaries with defects:

- the energy density of the boundary is high, so large changes are possible;
- the thickness of the domain boundary had, therefore, these changes in the energy of the boundaries can take place at a small displacement, which will lead to a high value of the energy gradient and the corresponding value $H_c$.

In [21], the authors studied sintered magnets, cast and quickly hardened alloys of composition (in weight. %) Nd$_{10}$Co$_{10}$B$_{15}$Al(Ti)$_{15}$Fe$_{37.7}$ for the behavior of alloying elements (Co, Al, Ti) when introduced into the stoichiometric compound Nd$_2$Fe$_{14}$B. Analysis and comparison of mssbauer spectra showed that for these materials quadrupole splitting, isomeric shifts, the values of effective fields within the experimental error are

![Fig. 1. Phase unit cell Nd$_2$Fe$_{14}$B(C) [6]](image-url)
determined by the chemical composition of the samples and do not depend on their state.

It has also been shown that in nodes 16k₂-like cobalt atoms can replace iron atoms. In the crystal lattice Nd₂Fe₁₄B the distance between the atoms Fe(k₂)–Fe(j₁) the smallest, and it increases the possibility anti ferromagnetic exchange interaction between the magnetic moments of the atoms [22]. The introduction of cobalt atoms reduces the number of negative Fe(k₂)–Fe(j₁) exchange bonds, which leads to an increase in Curie temperature and saturation magnetization [23].

Despite the fact that the addition of cobalt significantly increases the Curie temperature, its use should be in a certain amount – an increase in the concentration of co contributes to a decrease in the coercive force of sintered Nd-Fe-B magnets [24]. In [23], the authors explain this fact by the formation of new soft magnetic phases based on cobalt, which worsens the magnetic isolation of the phase grains Nd₂Fe₁₄B.

Co atoms replace Fe atoms in positions 8j₁ and 16k₂-type’s. In these positions Fe atoms have a magnetocrystalline anisotropy of plane type [21]. It is possible that the introduction of non-magnetic aluminum atoms leads to an increase in the resulting uniaxial magnetocrystalline anisotropy of the phase Nd₂Fe₁₄B.

Analysis of hyperfine scattering fields of muons in samples with addition of titanium and without titanium found no significant difference, that is, titanium spectra in samples with addition of titanium and without titanium are identical, and do not depend on their state. However, more research is needed to determine the optimal ratio between the leguvalnymi elements to achieve the greatest magnetic, temperature and corrosion characteristics of sintered magnets based on the system Nd-Fe-B.

Mathematical modeling vlive sizes of domains of the phase nD₂fE₁₄B and non-magnetic impurities in the nC systems nD-I-E-n

At the first stage, we find out how the size of the inclusions and the distance between them affect the values of the coercive force and the velocity of the domain boundaries of permanent magnets. According to the theory of Kondorsky [27–30], the smaller the size of the inclusions and the thicker they are, the lower the speed of the domain boundaries and, accordingly, the more important the coercive force becomes.

For the Nd-Fe-B System, the values of the magnetic characteristics and the width of the domain wall are shown in table. 1 [28–30]. According to the theory of inclusions [27, 29, 30], the domain boundary in the initial state tries to overturn the maximum possible number of non-magnetic inclusions. This reduces its surface energy. Let the inclusions have the shape of a sphere with diameter d and are located in a cubic crystal with constant S (Fig. 1).

Let the coercive force be found by the following formula:

$$H_c = \frac{1}{I_x} \left( \frac{\partial \sigma}{\partial x} \right)_{\text{max}}.$$  (1)
Table 1 – Magnetic characteristics for Nd-Fe-b system

| Parameter                        | Value          |
|----------------------------------|----------------|
| Became exchange interaction $A$  | $1.25 \times 10^{-11}$ J/m |
| Became anisotropy $K$            | $4.5 \times 10^{6}$ J/m$^3$ |
| Magnetic saturation $I_s$        | $1.61 \times 10^6$ A/m |
| $\gamma_p$                      | 0.03 J/m$^2$   |
| The width of the domain wall $\delta$, nm | 5.24 |

where $I_s$ – magnetic saturation, $K$-became anisotropy;

$\delta$ – the width of the domain boundary for phase Nd$_2$Fe$_{14}$B;

$S$ – distance between inclusions, $d$ is the size of the inclusion.

Formula 4 was used for modeling. The calculation results are shown in Fig. 3. From Fig. 3 it can be seen that by reducing the size of non-magnetic inclusions to $5...10$ nm, which is commensurate with the width of the domain boundary for the phase Fe$_{14}$Nd$_2$B, there is a sharp increase in the values of the coercive force to $5$ MA/m.

Fig. 3. Dependence of the coercive force of the phase Nd$_2$Fe$_{14}$B from the size of non-magnetic phase inclusions NdCu$_2$ and the distance between them

Materials and methods studies

As starting materials for producing sintered compacts of high-energy used quickly hardened tape. Rapidly quenched ribbon was produced by the method of melt spinning is presented to the vacuum setting rapid hardening “Tape-3” (NSC “KIPT”, Kharkiv). The chemical composition of the alloys obtained in the work is shown in table 2.

Table 2 – Chemical composition of the initial alloys of the system Nd-Fe-(B,C)-Cu-Ti

| № sample's | Nd   | Fe   | C    | B    | Cu   | Ti   |
|------------|------|------|------|------|------|------|
| 1          | 15.2 | 75.33| 0.17 | 6.5  | 1.57 | 1.38 |
| 2          | 15.2 | 75.17| 0.33 | 6.5  | 1.57 | 1.38 |
| 3          | 15.2 | 75.08| 0.42 | 6.5  | 1.57 | 1.38 |
| 4          | 15.2 | 74.99| 0.51 | 6.5  | 1.57 | 1.38 |
| 5          | 15.2 | 74.14| 0.86 | 6.5  | 1.57 | 1.38 |
Sintering was carried out for the alloy Nd\(_{15.2}\)Fe\(_{75.5}\)C\(_{\chi}\)B\(_{6.5}\)Cu\(_{1.5}\)Ti\(_{1.3}\) (\(x: 0.17 \ldots 0.86\) % at.) after compaction under a mechanical press at the initial pressure \(P = 12\) MPa (total pressure was 0.9 GPa + \(P\) MPa) [31]. Sintering occurred at a temperature \(T = 1013\) K (740 °C) [32] for 1.5 h, the choice of this sintering temperature was due to the fact that at a temperature of \(928\) K a triple fusible eutectic is formed \(\text{Fe}_{14}\text{Nd}_{2}\text{B} + \text{Nd}_{1.1}\text{Fe}_{4}\text{B}_{4} + \text{Nd}_{3}\), which promotes liquid-phase sintering.

The reliability of the scientific results is confirmed by the use of modern research instruments (optical microscope OLIMPYS IX-70, Dron-3 diffractometer, scanning electron microscope JEOL JSM-6360LA, vibration magnetometer, closed-loop magnetometer); the error in the reproduction of the results is 3...10 %.

Thus, at this stage, a comprehensive study of the influence of external pressure and doping of fast cooling products on the structure and properties of finished compacts.

**Research result**

From General considerations, it is clear that an increase in the sintering time leads to an increase in the average diameter of the grains, as well as an increase in their number, and a decrease in the sintering temperature – to a decrease in the grain growth rate and, accordingly, to a decrease in their final size. Reducing the sintering temperature, of course, also helps to reduce the rate of nucleation, and in the amorphous component, respectively, to reduce the number of grains of the phase. When changing three parameters (temperature, pressure and sintering time), it is possible to obtain a structure with the required number of grain embryos per unit volume and their most likely sizes.

Thus, on the basis of model representations it can be concluded that to increase the coercive force it is necessary to reduce the size of the non-magnetic phase NdCu\(_2\). To do this, in order to seal the sample, the external pressure was increased to \(12\) MPa, and the sintering temperature was reduced from \(1323\) K [33] to \(1013\) K, in the region of existence of fusible triple eutectic and the sintering time was extended to 1.5 hours. [34]. In order to obtain a higher concentration of particles of the crushed phase NdCu\(_2\). The structures of the compacts obtained in this way are given in Fig. 4. This figure shows that the structure of this compact is much denser and more perfect than the structure of the compact of the same composition, which was baked at 9.5 MPa [33].

![Fig. 4. The structure and microstructure of the compacts composition Nd\(_{15.2}\)Fe\(_{75.5}\)C\(_{\chi}\)B\(_{6.5}\)Cu\(_{1.5}\)Ti\(_{1.3}\) at different magnifications: a – 0.33 % stock. C; b – 0.51 per cent at. C; c – 0.59 % ad. C; d – 0.86% ad. C.](image-url)
Microstructure, chemical composition and distribution of elements on the surface of the compact composition \( \text{Nd}_{15.2}\text{Fe}_{74.99}\text{B}_{6.6}\text{C}_{0.51}\text{Cu}_{1.57}\text{Ti}_{1.38} \) which was sintered at a temperature of \( T = 1013 \, \text{K} \) for 1.5 hours, shown in Fig.5. From Fig. 5 and table 3 it can be seen that there is a phase in the sample \( \text{NdCu}_2 \) (white areas), as well as etching pits indicate a high concentration of crystal defects in the sample.

The paper presents a statistical analysis with the construction of the particle size distribution \( \text{NdCu}_2 \) in baked compacts. From Fig. 6 it is seen that the particle size of the phase \( \text{NdCu}_2 \), which are present in the baked sample obtained under the above conditions, decreased to 0.1 \( \mu \text{m} \) compared to an average size of 0.35 \( \mu \text{m} \) for previous sintering conditions [33]. If the size distribution of grains is subject to the Gauss law, we should expect that in the sample there are particles phase \( \text{NdCu}_2 \) (spherical) much smaller size (< 0.05 \( \mu \text{m} \), Fig. 6). The presence of such particles should lead to a significant increase in the coercive force. As shown in [34], the probability of the existence of phase particles \( \text{NdCu}_2 \), with dimensions less than 0.05 \( \mu \text{m} \) is extremely high, it is safe to say that the pinning effect makes a major contribution to the mechanism of increasing the coercive force. In table 4 shows the comparison of the rate of nucleation and growth of particles \( \text{NdCu}_2 \).

It is seen that the average diameter for the inclusions is almost the same (within the error), the embryo formation rate falls by almost 5 times, and the particle growth rate falls by almost 3 times with a decrease in the sintering temperature. This explains the difference in the maximum number of phase particles \( \text{NdCu}_2 \) in the volume of the compact and the existence of two peaks that are offset relative to each other: for the initial pressure of 9.5 MPa – 400 nm and 1000 nm, and for the initial pressure of 12 MPa – 200 nm and 600 nm.

### Table 3 – Local chemical analysis of the compact \( \text{Nd}_{15.2}\text{Fe}_{74.99}\text{B}_{6.6}\text{C}_{0.51}\text{Cu}_{1.57}\text{Ti}_{1.38} \)

| № point | Content of elements, at% | Phase                  |
|---------|--------------------------|------------------------|
|         | Ti | Fe | Cu | Nd | C  |                  |
| 1       | 1.5| 79.25 | 3.5 | 11.55 | 4.2 | \( \text{Nd}_3\text{Fe}_2\text{B} \) |
| 2       | 3.5| 1.6  | 55.7 | 32.8 | 6.4 | \( \text{NdCu}_2 \) |
| 3       | 2.8| 5.2  | 57.3 | 31.4 | 3.3 | \( \text{NdCu}_2 \) |
| 4       | 5.7| 3.4  | 54   | 30.7 | 6.2 | \( \text{NdCu}_2 \) |

Earlier in [35, 36] the magnetic properties of individual scales were studied \( \text{Nd}_{15.2}\text{Fe}_{75.5-x}\text{C}_{x}\text{B}_{6.6}\text{Cu}_{1.57}\text{Ti}_{1.38} \) (x0.17...0.86% ad), hardened from a liquid state, as well as magnetic plastics, which are made of flakes after annealing from alloys of the same composition. It should be noted that the magnetic plastics made from flakes, which are obtained after quenching and annealing at a temperature of 773...873 K, have a significant coercive force, about 1450 kA/m, and, at the same time, a slight residual induction of 0.5...0.6 T [36].

For rice. 7 hysteresis loops are presented for compacts that are sintered at an initial pressure of 12 MPa and a temperature of 1023 K. It is Seen that they differ significantly from hysteresis loops for compacts that are sintered at a temperature of 1323 K, namely: the loop approaches a rectangular one. At the same time, there is an area with "constriction".
To determine the actual value of the magnetic energy of the magnets prepared from the sintered compacts made from alloys bonded Nd\(_{15,2}\)Fe\(_{75,5-x}\)C\(_x\)B\(_{6,6}\)Cu\(_{1,57}\)Ti\(_{1,38}\) (x: 0.33...0.86% of JSC). For this purpose, the baked compacts were crushed in a ball mill and magnetic plastics were made from powders using traditional technology. Microstructure of bonded, which are thus obtained, served on rice 8.

The determination of the magnetic properties of the obtained bonded was carried out on demagnetization curves (Fig. 9). As can be seen from this figure, the coercive force of magnitoplasts, which are made of compacts that are sintered at a sintering temperature (T = 1013 K) and initial pressure (P = 12 MPa), has increased sharply compared to the previous sintering regime [33], and reached values of 900...1350 kA/m with a residual magnetic field of 0.6...0.8 TL.

For rice 10 the dependence of the coercive force value \(H_C\) on the carbon concentration in the initial alloy is presented. Based on the previous results, a number of experiments to determine the effect of carbon concentration in the alloy were performed Nd\(_{15,2}\)Fe\(_{75,5-x}\)C\(_x\)B\(_{6,6}\)Cu\(_{1,57}\)Ti\(_{1,38}\) on the magnetic properties of compacts obtained under external pressure. In addition to the results obtained in this paper in Fig. 10 summary data of previous works are given [35,37-39]. From them it can be seen that the maximum coercive force falls on the composition of 0.2...0.5% at. carbon's.
Discussion of results

The analysis of experimental data allows us to state that the rapid cooling of the alloy Nd\textsubscript{15.2}Fe\textsubscript{75.5}C\textsubscript{6.6}Cu\textsubscript{1.57}Ti\textsubscript{1.38} in hardening products (scales) amorphous and crystalline phases are formed. It is established that the main crystalline phases are Nd\textsubscript{2}Fe\textsubscript{14}B, Nd\textsubscript{2}Cu\textsubscript{2}, clean Nd phase, which is identified as intermetallic NdCu\textsubscript{2}.

It is known that Nd\textsubscript{2}Fe\textsubscript{14}B formed in the system Nd-Fe-B at protectionshow reaction. In the case of rapid cooling from the liquid phase Nd\textsubscript{2}Fe\textsubscript{14}B crystallizes directly from the liquid, bypassing the equilibrium transformation. In addition to phase Nd\textsubscript{2}Fe\textsubscript{14}B in this alloy, a phase of the type NdCu\textsubscript{2}, which exists in the Nd-Cu system with an atomic composition of Cu = 33 AO. % Nd [40], but the copper content in the alloy under study does not exceed 1.6 % AO. and so phase NdCu\textsubscript{2} according to the equilibrium state diagram, can not be formed in this alloy. It is known that in the Fe-Cu system under certain conditions (the presence of carbon more than 0.3 at.%), a complete stratification in the fluid may occur [41]. Therefore, the probability of formation of micro domains, which are enriched in copper in the liquid alloy, a large because carbon stabilizes the region of nesmehivaemost of copper with the main alloy element, iron. So, at high-speed cooling of the alloy from the liquid state intermetallic compounds NdCu, it can be obtained as a metastable phase based on micro-groups enriched with copper and other elements. According to Miroshnichenko I. S. [42], phases Nd\textsubscript{2}Fe\textsubscript{14}B, NdCu\textsubscript{2} can be called phases with limited metastability.

Previously [33] derived the scales of the composition Nd\textsubscript{15.2}Fe\textsubscript{75.5}C\textsubscript{6.6}Cu\textsubscript{1.57}Ti\textsubscript{1.38} placed in the mold and pressed using a mechanical press, then scapla in a vacuum oven at a temperature of 1323 K. the sintering Temperature was chosen according to the technological process of production of anisotropic permanent magnets. As mentioned earlier, the material of the clamp and mounting bolts was selected so that an additional “thermal” pressure of up to 1 HPa could be obtained. Under high pressure conditions, stresses occur that accelerate diffusion processes in the sample [43,44]. Thus, on the one hand, the volume growth of phases is carried out Nd\textsubscript{2}Fe\textsubscript{14}B i NdCu\textsubscript{2} and at the same time, their stability will be stable, since high pressure displaces the phase equilibrium points in the high temperature region, in accordance with the law of Clapeyron-Clausius.

Since the phase Nd\textsubscript{2}Fe\textsubscript{14}B under these conditions, it does not have time to form into individual grains, and the ndcu2 phase sizes are such that they do not interfere with the movement of domain boundaries, in this case the value of the coercive force of the sample remains almost constant. In order to avoid the rapid growth of NdCu2 phase, the initial pressure was increased and the sintering temperature was reduced to the triple fusible eutectic temperature (1013 K), and the sintering time was increased to 1.5 hours. These conditions practically did not affect the rate of the phases nucleation NdCu\textsubscript{2} and Nd\textsubscript{2}Fe\textsubscript{14}B and at the same time reduced the rate of growth of these phases. As can be seen from figure 4.6, the phase size NdCu\textsubscript{2} decreased from 160 kA/m to 1300 kA/m. Along with this, the amorphous component of the films crystallizes stable and metastable phases under high pressure. The amorphous component is an unordered structure with the absence of a long-range order and therefore, under these conditions, the density of imperfections tends to the maximum, and the processes of transfer of alloying elements, namely, carbon, copper and titanium, to the zone of imperfections (Suzuki-kotrell Cloud, dislocation nuclei, etc.) are accelerated. Reaching critical dimensions, clusters of imperfections enriched with alloying elements also become an obstacle to the displacement of domain boundaries.

Thus, carbon affects the properties of alloys in two ways Nd\textsubscript{15.2}Fe\textsubscript{75.5}C\textsubscript{6.6}Cu\textsubscript{1.57}Ti\textsubscript{1.38} (x: 0.33...0.86% of the stock): on the one hand, in the presence of carbon (0.33...0.86 at.%) in a liquid alloy, micro-areas are formed, which are enriched with copper, on the basis of which crystals are formed from a liquid state during quenching NdCu\textsubscript{2}. On the other hand, during crystallization of the amorphous component in alloys Nd\textsubscript{15.2}Fe\textsubscript{75.5}C\textsubscript{6.6}Cu\textsubscript{1.57}Ti\textsubscript{1.38} under high pressure conditions, imperfections are formed in which the alloying elements – carbon, copper, titanium, neodymium-are diffused. Micro areas, reaching critical sizes, become an obstacle to the displacement of domain boundaries. And in the first, and in the second cases actively manifests itself pinning-effect.

Complex alloying with carbon, titanium and copper of the alloy “Neomax” was used to increase the magnetic anisotropy of the phase Nd\textsubscript{2}Fe\textsubscript{14}B, the dispersion of the primary crystals (modifications of titanium) and the formation of a paramagnetic phase NdCu\textsubscript{2} that allows you to use the pinning effect.

Summary

1. We obtain the cheap cost material exceeding the known magnetic systems.
2. Fast cooling of alloys Nd\textsubscript{15.2}Fe\textsubscript{75.5}C\textsubscript{6.6}Cu\textsubscript{1.57}Ti\textsubscript{1.38} leads to the formation of metastable phases Nd\textsubscript{2}Fe\textsubscript{14}B and NdCu\textsubscript{2}, bypassing the equilibrium of the reaction.
3. With a decrease in the sintering temperature from 1323 K to 1013 K under high external pressure, the growth process of metastable phases slows down, which makes it possible to obtain nanoplate phase formations in a compact NdCu\textsubscript{2}, which prevent the movement of domain boundaries. This increases the value of the coercive force by an order of magnitude (Hc = 1350 kA/m), and the residual induction of almost 2 times (Br = 0.8 T).
4. It is shown that for non-magnetic inclusions of the NdCu2 phase up to 50 nm in size it is possible to obtain the value of the coercive force 6...8 MA/m. For the size values
of non-magnetic inclusions 1...The value of the coercive force of 100–200 kA/m was obtained at 10 μm, which coincides with the experimental data.

5. Under high external pressure, the maximum coercive force falls on the composition of alloys with carbon in the amount of 0.33...0.51 at. %, due to the maximum diffusion force of C, Cu, Those in the field of imperfections of the structure and interference with the movement of domain boundaries.

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Гуляєва Т. В., Брехаря Г. П. Про дослідження впливу зовнішнього тиску та вуглецю на структуроутворення та властивості компактів, що спечено на основі швидко охолоджених сплавів Nd–Fe–(C, B)-Cu–Ti (Частина 2)

Мета роботи. Комплексне дослідження термодинамічних та фізико-хімічних умов утворення фаз в готових постійних магнітах, що виготовлено на основі систем Nd–Fe–B.

Методи дослідження: металографічний, рефлексоспектральний, магнітометричний.

Отримані результати. Досліджувались вплив зовнішнього тиску та незначної кількості вуглецю (0,17...0,86 %ат.) на структуру та властивості постійних магнітів, які виготовлені на основі системи Nd–Fe–B, що леговані міддю та титаном. Для виготовлення постійних магнітів з високою магнітною енергією використано продукти швидкого охолодження з рідкого стану. Для цього лусики, що отримані методом ЗРС, пресували у прес-форми та спікали в вакуумі. Прес-форми та ботми, що їх скріплюють, виготовлені зі сплавів, у яких різні коефіцієнти лінійного розширення. Цей метод досі змог використовувати високого тиску (є 1 ГПа) під час спікання. Спікання виконували у вакуумі під тиском Р = 12 МПа та при температурі 1013 К.

Показано, що вуглець діючо впливає на властивості сплавів Nd55, Fe25,5, C6,6, Cu1,5, Ti1,3 (x: 0,33...0,86 %ат.): з одного боку, в присутності вуглецю (0,33...0,86 %ат.) в рідкому стані, утворюються мікрообласті, які збагачені міддю, на балі яких при загартуванні з рідкого стану зароджуються кристали Nd6Cu1. З іншого боку, при кристалізації аморфної складової в сплавах Nd55, Fe25,5, C6,6, Cu1,5, Ti1,3 в умовах високого тиску утворюються області недосконалостей, в яких є двох виділюються легувальні елементи – вуглець, мідь, титан, неодим. Мікрообласті, досягаючи критичних розмірів, стають перешкодою зміцнення границь доменів. І в першому, і в другому випадках активно проявляється піннінг-ефект.
Научная новизна. Встановлено, що зниження температури спікання швидко охолодженних лусочков сплавів Nd15,2Fe75,5-(C, B, Cu, Ti)1,10 в умовах високого тиску порядку 0,9 ГПа від технологічної 1323 К до температури 1013 К практично не впливає на швидкість зародження метастабільних фаз NdCu₃ та Nd₆Fe₂B і в той же час знижує швидкість їх росту. Однак, це призводить до збільшення коерцитивної сили готових магнітів від 160 кА/м до 1300 кА/м.

Практична цінність. Одержані в роботі результати мають важливе значення для подальшого розвитку фізичного матеріалознавства магнітожорстких матеріалів та сучасної техніки.

Ключові слова: спікання, "твердий тиск", відпал, основна магнітожорстка фаза, фаза з обмеженою метастабільністю, коерцитивна сила.

Гуляева Т. В., Брезара Г. П. Об исследовании влияния внешнего давления и углерода на структурообразование и свойства компактов, испеченных на основе быстро охлажденной сплавов Nd-Fe-(C, B)-Cu-Ti (Часть 2)

Цель работы. Комплексное исследование термодинамических и физико-химических условий образования фаз в готовых постоянных магнитах, изготовленных на основе системы Fe-Nd-B.

Методы исследования: металлографический, рентгеноспектральный, магнитометрический.

Полученные результаты. Исследуется влияние внешнего давления и незначительного количества углерода (0,17...0,86 %) на структуру и свойства постоянных магнитов, изготовленных на основе системы Nd-Fe-B, легированных медью и титаном. Для изготовления постоянных магнитов с высокой магнитной энергией использовано продукты быстрого охлаждения из жидкого состояния. Для этого чешуек, полученные методом ЗЖС, прессовали в пресс-форме и спекали в вакууме. Пресс-форма и болты, которыми скрепляют, изготовленные из сплавов с различными коэффициентами линейного расширения. Этот метод позволяет достичь высокого давления (≈ 1 ГПа) при спекании. Спекание выполняли в вакууме под давлением P = 12 МПа + 0,9 ГПа и при температуре 1013 К.

Показано, что углерод оказывает двоякое влияние на свойства сплавов Nd15,2Fe75,5-(C, B, Cu, Ti)1,10 (х: 0,33...0,86 %): С одной стороны, в присутствии углерода (0,33...0,86 %) в жидкого сплаве, образуются микрообласти, которые обогащены медией, на базе которых при закалке из жидкого состояния зарождаются кристаллы NdCu₃. С другой стороны, при кристаллизации аморфной составляющей в сплавах Nd15,2Fe75,5-(C, B, Cu, Ti)1,10, в условиях высокого давления образуются области несовершенства, в которые диффундируют легирующие элементы – углерод, медь, титан, неодим. Микрообласти, достигая критических размеров, становятся препятствием для смещения границ доменов. И в первом, и во втором случаях активно проявляется пиннинг-эффект.

Научная новизна. Установлено, что снижение температуры спекания быстро охлажденных чешуек сплавов Nd15,2Fe75,5-(C, B, Cu, Ti)1,10 в условиях высокого давления порядка 0,9 ГПа от технологической 1323 К до температуры 1013 К практически не влияет на скорость зарождения метастабильных фаз NdCu₃ и Nd₆Fe₂B и в то же время снизает скорость их роста. Однако, это приводит к увеличению коерцитивной силы готовых магнитов 160 кА/м до 1300 кА/м.

Практическая ценность. Полученные в работе результаты имеют важное значение для дальнейшего развития физического материаловедения магнитожестких материалов и современной техники.

Ключевые слова: спекание, "твердое давление", отжиг, основная магнитожесткая фаза, фаза с ограниченной метастабильностью, коерцитивная сила.