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Structure and properties of the composite materials consisting of the nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy powders and polyethylene

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Abstract: This paper presents the material and technological solution which makes it possible obtaining the nanocrystalline, ferromagnetic powder material of $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy after its thermal nanocrystallization with its succeeding high-energy milling. Another aspect was developing the technology to obtain the nanocrystalline composites made by binding the obtained powder material with the high density pressureless polyethylene (PEHD) with the controlled ferromagnetic and mechanical properties.

Keywords: Nanocrystalline composite, FINEMET alloy, High density low-pressure polyethylene, High-energy grinding, One-sided uniaxial pressing

1. INTRODUCTION

The nanocrystalline magnetic soft Fe-based materials are competitive to the conventional magnetic materials because of their advantageous mixture of the relatively low manufacturing costs, as well as of their good physical and mechanical properties. They are manufactured most often by the mechanical synthesis and rapid quenching of the metallic liquid connected with the controlled crystallisation [1,2]. The main disadvantage of these manufacturing methods are their limitations pertaining to the geometrical form of the manufactured nanomaterials (powder or thin strip), which limit their range of applications to a great extent. Therefore, to extend their potential applications it is necessary to connect the nanocrystalline magnetic materials with other materials – creating thus the composite materials. The thermosetting or chemically cured polymers are used most often to manufacture composites, whose volume portion in the composite does not exceed 20 % and the low-melting metals, e.g., zinc in the amount of about 15 % mass [3,4].

This paper presents the material and technological solution leading to obtaining the composite materials consisting of the nanocrystalline powders of the $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy and polyethylene, and examination results of their structure, as well as mechanical and magnetic properties.

2. RESEARCH PROCEDURE

Amorphous strips of the $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ as quenched metallic glass 0.030 mm thick and 9.0 mm wide were used for investigations. The strips from the investigated alloy were cast with the planar-low-casting (PFC) onto the surface of the rotating cooling drum in the argon protective atmosphere. The strips were heat treated by holding at the temperature of 823 K for 1 h (thermal nanocrystallization) in the Thermolyne 6020C chamber electric furnace. Phases: crystalline αFe(Si) and the amorphous intergranular one - developed as a result of the primary crystallization, are the products of heat treatment of the $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ metallic glass strips. The nanocrystallization temperature selected in this way ensures the most advantageous magnetic properties for this alloy [3,4].

Powders of the $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy after its thermal nanocrystallization were made by the high-energy grinding of the initially crumbled strips in the shaker type 8000 SPEX CertiPrep Mixer/Mill for 0.25 hour, 1 hour, 3 hours, and for 5 hours in the air (mechanical nanocrystallization).

The powders obtained in this way were used to make the composite. The high density low-pressure polyethylene (PEHD) powder was used as binder – with mass fractions of 2.5 %, 5.0 % and 7.5 %. The components were mixed in the shaker type 8000 SPEX CertiPrep Mixer/Mill. Mixing time was determined experimentally and was 0.25 h.

The module for composites forming has been designed. The module consists of the die enclosed in the heater coupled with the Zwick testing machine type Z100 set up for compression tests. It was possible, with the stand set up like that to compact the fabricated components (one-sided uniaxial pressing). The parameters of the pressing process were: pressure 350 MPa, temperature 443 K, pressing time 0.25 h.

The obtained composites were examined on the Lake Shore Cryotronics Inc VSM vibratory magnetometer.

OPTON DSM 940 scanning electron microscope was used for examination of powders with the 250x magnification. To determine the average size of the powder particles and of the measurement error using the computer image analysis system coupled with the LEICA MEF4A light microscope and with the OPTON DSM 940 scanning electron microscope.

Compression strength of composites was determined on INSTRON 1195 universal testing machine.

3. RESEARCH RESULTS

Test results of mechanical properties of the obtained composites are presented in Table 1. The best mechanical properties among the investigated materials are characteristic of composites with the polyethylene mass portion of 5 %.

Microscopic images of composite fractures obtained after decohesion in the compression test are presented in Figure 1. Observation of shapes and dimensions of powder particles, depending on strip grinding time after its thermal nanocrystallization revealed that along with the grinding time extension powder grain size and its standard deviation decrease (Table 2, Figure 1).

Test results of the magnetic properties of the source strips and composites are presented in Table 3. Composites with the nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy powder obtained by milling the strips for 0.25 h have the most advantageous magnetic properties. They demonstrate the smallest values of the coercive force and the highest values of the relative permeability and saturation induction.

Table 1.
Mechanical properties of the investigated composites

Composite type		Size		
PEHD fraction in composite [% mas.]	Strip grinding time [h]	Compression strength R_c [MPa]	Unit shortening A_c [%]	Young's modulus E_c [MPa]
2.5	0.25	25.65	8.27	309.91
	1	53.41	8.98	594.31
	3	43.57	6.60	659.63
	5	28.81	9.51	302.91
5.0	0.25	50.25	10.34	485.75
	1	57.27	8.68	659.81
	3	46.73	12.32	379.29
	5	54.47	15.99	340.63
7.5	0.25	39.35	10.95	359.13
	1	55.52	14.85	373.84
	3	56.57	10.36	545.87
	5	47.08	16.44	286.33

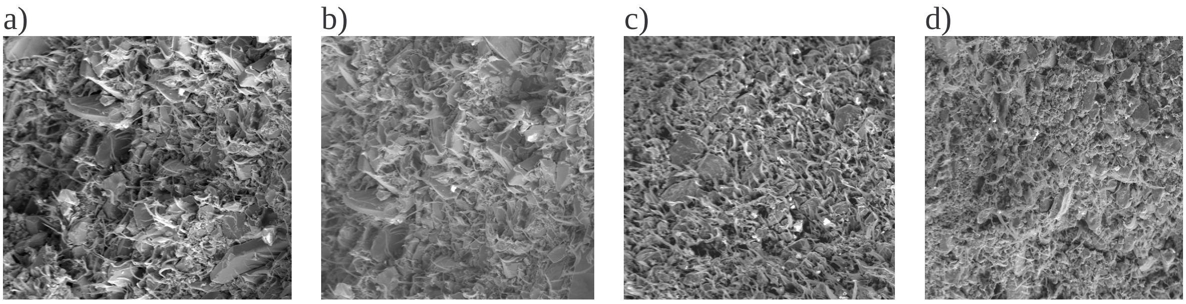

Figure1. Microscopic images of composite fractures obtained after decohesion in the compression test - polyethylene mass portion of 5.0 % with powder of $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy – milling time: a) 0.25 h, b) 1 h, c) 3 h, d) 5 h

Table 2.
Grain size of powders used as a component in the investigated composites

Grain size	Strip grinding time [h]			
	0.25	1	3	5
average [μm]	34.708	20.256	15.342	8.130
maximum [μm]	69.2	42.4	30.4	17.8
minimum [μm]	10.3	8.9	5.1	2.2
standard deviation, s	12.491	8.879	7.578	4.474
wariance, s^2	156.015	78.840	57.424	20.013

Table 3.
Magnetic properties of strips in the as quenched state, after thermal nanocrystallization, and of the obtained composites

Composite type		Size				
PEHD fraction in composite [% mas.]	Strip grinding time [h]	H_c [A/m]	B_r [T]	B_s [T]	μ_{max}	P_{max} [W/kg]
2.5	0.25	537.69	0.0061	1.304	81	1.748
	1	706.20	0.0073	1.294	80	1.310
	3	862.58	0.0094	1.272	65	1.706
	5	935.19	0.0101	1.314	64	1.811
5.0	0.25	421.88	0.0034	1.248	80	1.804
	1	604.94	0.0058	1.139	76	1.391
	3	697.09	0.0088	1.289	62	2.036
	5	932.16	0.0104	1.274	60	1.990
7.5	0.25	362.33	0.0033	1.240	60	1.014
	1	626.71	0.0059	1.300	34	0.597
	3	673.56	0.0105	1.127	30	1.001
	5	783.47	0.0126	1.070	26	0.528
Strip in the as quenched state		46.11	1.068	1.601	5174	0.482
Strip after thermal nanocrystallization		26.36	1.204	1.414	58883	0.187

4. CONCLUSION

Shape and size of particles of the powders used has the biggest influence on the magnetic properties of composites.

Basing on the investigations carried out it was found out that the most advantageous conjunction of the magnetic and mechanical properties is displayed by composites with the 5% polyethylene mass portion with the nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy powder obtained by milling the strips for 0.25 h.

The research carried out has made it possible to develop the general technological process that makes it possible to fabricate composites consisting of the nanocrystalline powders of the soft magnetic material and thermoplastic polymer with the required magnetic and mechanical properties.

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