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OBTAINING FERROMAGNETIC BULK NANOCRYSTALLINE ALLOYS WITH HIGH MECHANICAL STRENGTH

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Abstract: *The paper presents researches on the achievement of bulk ferromagnetic nanocrystalline alloys from Fe-Cr-Ga-P-Si-C family with high strength and hardness. The alloys were elaborated by copper mold casting, and were structurally characterized by X-ray diffraction. The magnetic properties were investigated using a VSM 880 vibrating sample magnetometer and mechanical properties were determined by microhardness measurements and compression tests. It was found that higher chromium contents increases the mechanical strength (hardness and compression strength) of the elaborated alloys.*
Key words: *ferromagnetic alloys, bulk nanocrystalline alloys, compressive strength, hardness*

1. INTRODUCTION

Year 1988 is considered by most experts as the year of the first discovery of ferromagnetic nanocrystalline alloys. Yoshizawa and his colleagues showed on Fe-Cu-Nb-Si-B and later on Fe-Cu-M-B-Si family (where M = Nb, V, Mo, Zr) nanocrystallized alloys, exceptional magnetic characteristics: saturation induction of 1.2 T, low coercivity, magnetic permeability at high frequencies above 10^3 (Codrean et al., 2007). These alloys named "Finemet" are the first family of ferromagnetic nanomaterials with significant economic impact.

They are followed by nanoalloys called "Nanoperm" (Fe-M-B families, with M = Zr, Nb, Hf) recommended for special applications, mostly in manufacture of power transformers (Codrean et al., 2007).

Meanwhile, the strength of nanocrystalline alloys is higher than crystalline and even amorphous alloys. It is well known that grain size is affecting the limit of elasticity, resistance properties and the deformability of materials. Thus, for $Al_{85}Ni_5Y_{10}$ alloy nanocrystallized by controlled devitrification have been noticed spectacular increases in hardness compared to the amorphous state (with 20-40%) and compared with best conventionally cast crystalline aluminium alloy and heat-treated later (200 - 300%) (Inoue et al., 2000).

Therefore, the purpose of this work is to determine the mechanical characteristics of ferromagnetic nanocrystalline alloys and how are influenced by their chemical composition.

2. ELABORATION OF THE NANOCRYSTALLINE ALLOYS AS RODS

One of the obtaining methods of ferromagnetic alloys with nanocrystalline structure is based on ultrarapid melt cooling.

The first step to get nanocrystalline alloys was to obtain a master alloy in form of bars, with an optimal chemical composition.

In our previous researches, the used chemical compositions in order to obtain the nanocrystalline alloys were: $Fe_{75-x}Cr_xGa_4P_{13}Si_5C_3$, where x = 2, 3, 4, 5 [Serban et al., 2009]. The elaboration of the master alloy was done by melting induction in argon atmosphere of the raw materials: iron based alloys Fe-P, Fe-C, Fe-Si and high purity powders of Cr and Ga. Microscopic structure of the master alloy revealed the presence of a fine eutectic and some dendritic crystals which belong to a solid solution based on iron (Fig. 1).According to previous experiments, the elaboration of bulk nanocrystalline alloys as rods of 2 mm diameter was achieved by copper mold casting (Fig. 2). The technology of elaboration involves the following steps:

- cutting the master alloy to obtain sections of 5 grams;
- inserting the master alloy into the quartz crucible which has at the bottom an evacuate nozzle of the melt with 1 mm in diameter. In this crucible the master alloy is remelted by induction in argon atmosphere;
- melt ejection into the cavity of the mold.

The main used parameters of the process were:

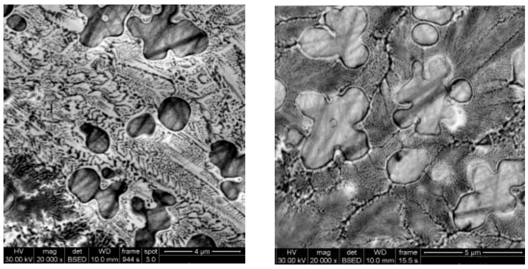
- process temperature is 100 °C higher than fusion temperature of the alloy
- overpressure applied on melt: 0,25 atm

Following these steps rods with 2 mm in diameter and 20-25 mm length were obtained (Fig. 3), marked according to Table 1.

The rods thus obtained were structurally analyzed by X-ray diffraction, performed on a DRON 3 diffractometer, using Mo radiation and wave length λ = 0,71 Å. The diffraction pattern obtained (Fig. 4) indicates a nano crystalline structure, reduced intensity peaks belong to a supersaturated solid solution based on iron.

Chemical compositions, % at.	Mark
Fe_{73} Cr_2 Ga_4 P_{13} Si_5 C_3	NB2
Fe_{72} Cr_3 Ga_4 P_{13} Si_5 C_3	NB3
Fe_{71} Cr_4 Ga_4 P_{13} Si_5 C_3	NB4
Fe_{70} Cr_5 Ga_4 P_{13} Si_5 C_3	NB5

Tab. 1. The mark of the obtained rods



a) 2 % at. Cr b) 5 % at. Cr

Fig. 1. SEM images of master alloy

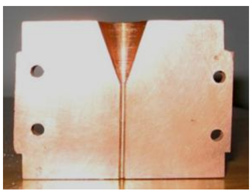


Fig. 2. Copper mold for rods processing

Fig. 3. As-cast specimen

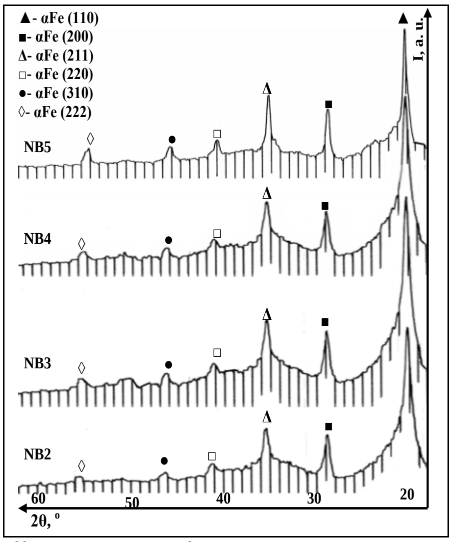


Fig. 4. Diffraction pattern of the alloys

It can be noticed also that an increased content of chromium leads, in the same cooling conditions, to a light increase of crystals, evidenced by enlargement of intensity of top interferences.

4. MAGNETIC AND MECHANICAL PROPERTIES OF THE OBTAINED ALLOYS

Nanocrystalline alloys proved to have excellent soft magnetic properties, better than crystalline and even amorphous alloys because of the crystalline grains dimension.

The coercivity of crystalline alloys depends strongly of their size because the magnetic domain walls interact with the grain boundaries. As the grain size decreases, Hc growths and reaches to a maximum value for grain sizes of approximately 100 nm. Further grain size reduction leads to a rapid decreasing of coercivity which varies by D^6 law (Scwarz et al., 2004).

Magnetic characterization of the elaborated alloys was performed with a VSM 880 vibrating sample magnetometer. Figure 5 shows the hysteresis loop for the obtained alloys.

It can be noticed that these alloys present good soft magnetic properties (coercive field beetwen 1.24 and 1.91 kA/m) and the higher Cr content alloy has both high saturation magnetization and high coercive field.

Mechanical properties of the elaborated alloys were determined by micro-hardness measurements and compression tests. Compression tests were performed on an Instron machine. The speed of load implementation was $5x10^{-4}$ s^{-1}. Microhardness tests were performed on a digitally Volpert Micro Vickers Hardness Tester using a load of 500 grams.

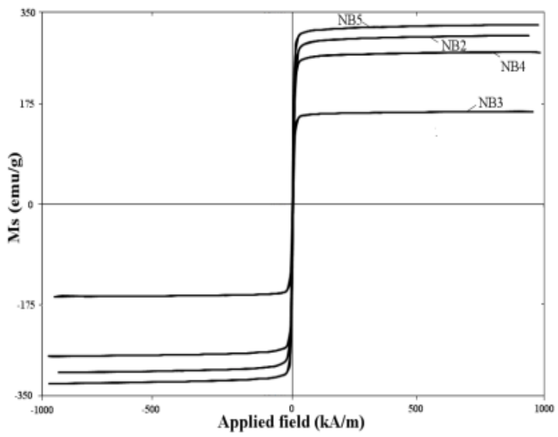


Fig. 5. Hysteresis loops measured

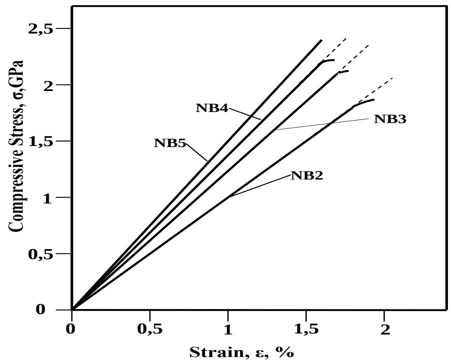


Fig. 6. The stress-strain curves obtained from compression tests

Compression curves obtained (Fig. 6) shows a brittle behaviour of alloys. However, for alloys with less chromium is remarkable a little plastic deformation before breaking. Values obtained from compression and microhardness tests are shown in Table 2.

Alloy	Compresive strength, σ_f [Gpa]	Fracture strain $_{\varepsilon f,}$ [%]	Yield strength σ_f Gpa]	Yield strain $_{\varepsilon f,}$ [%]	Vickers Hardness $HV_{0,5}$
NB2	1,80	1,90	1,72	1,81	690
NB3	1,97	1,82	1,93	1,75	770
NB4	2,14	1,77	2,1	1,70	820
NB5	2,38	1,68	2,38	1,68	890

Tab. 2. The values of mechanical properties

5. CONCLUSIONS

The nanocrystalline structures can be obtained by ultrarapid melt cooling. The researches performed showed the possibility of obtaining ferromagnetic bulk nanocrystalline alloys of Fe-Cr-Ga-P-Si-C as rod form by copper mold casting. The elaborated alloys have high mechanical strength, presenting a fragile behaviour during compression test. It was found that with increasing the content of chromium increases the mechanical strength (hardness and compression strength). The further work will be focussed on the obtaining of bulk nanocrystalline ferromagnetic alloy in shape of socket used for magnetic shielding.

6. ACKNOWLEDGEMENTS

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