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Magnetic Properties of the Rapidly Solidified Bulk Alloy: $Fe_{61}Co_{10}B_{20}Y_{8-x}W_yPt_x$ (where: $x = 1, 2$; $y = 0, 1$)

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In the literature, research into rapidly cooled Pt-based alloys usually features samples that are produced in the form of thin ribbons. This work presents the effect of the addition of a small quantity of W and Pt on the magnetic properties of massive two-phase alloys, the samples being produced in the form of plates with a thickness of 0.5 mm. Both amorphous and crystalline phases were observed in the alloys, the phase proportions depending on the composition of the alloy. Generally, it is assumed that alloys with added Pt are characterised by a relatively high saturation magnetization and magnetocrystalline anisotropy, which is mainly influenced by the presence of the crystalline phases: FePt and Fe_3Pt. For the investigated alloys, it was noted that the gradual substitution of W and Pt in place of Y within the alloy $Fe_{61}Co_{10}B_{20}Y_{8-x}W_yPt_x$ increased the value of saturation magnetization ($\mu_0 M_s$) and reduced the coercive field (H_c). On the basis of XRD pattern analysis it was found that, within the sample with the highest concentration of Pt, there are crystallites of the smallest size and the proportion of the α-Fe crystalline phase is much greater than for the other studied samples.

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1. Introduction

One of the latest groups of materials offering unique properties is that of the so-called massive amorphous alloys and their related nanomaterials. Both massive amorphous and nanocrystalline alloys have been used widely in the power and electronic industries [1]. Alloys based on the transition metals (metal - metalloid) are in particular demand, where the main constituents are: Fe, Co and B [2]. However, in order to obtain a solid amorphous alloy based on FeCoB, additional components are required in a quantity of up to a few percent. This procedure aims to increase the the glass forming ability. One such ingredient is Y [3]. In general, alloys of FeCoBY featuring 1–8%at. added Y exhibit soft magnetic properties [3, 4]. In recent years, intensive research has been conducted into Pt-based alloys [2, 5, 6, 7]. In most scientific studies, the Pt additive comprises more than 5% of the investigated material, which leads to significant magnetic hardening of the described alloys; also, most of these studies were conducted on rapidly-cooled tape or ribbon samples [2, 5, 6, 7]. A two-phase magnetic structure in Pt-tapes can be obtained as a result of thermal treatment [5, 7]. In the case of massive rapidly-cooled alloys, appropriate selection of production parameters offers the possibility to produce, in a single step, a nanocrystalline alloy with two magnetic phases (magnetically soft and magnetically hard). In Pt-based alloys, primarily Fe_3Pt and FePt intermetallic compounds are formed. The presence of the Fe_3Pt intermetallic phase is related to gigantic magnetostriction and the emergence of FePt with high magnetocrystalline anisotropy ($K = 7$ MJ/m^3) [7]. The appearance of an amorphous matrix featuring this combination of intermetallic phases promotes the change of the magnetic properties of the alloys and it is then possible to talk about hybrid magnetic materials, in which two magnetic phases coexist: magnetically soft and hard.

This paper presents the results of investigations into the: structural, magnetic and thermomagnetic properties of massive rapidly-cooled $Fe_{61}Co_{10}B_{20}Y_{8-x}W_yPt$ alloys; the samples being made using a casting method.

2. Experimental procedure

Alloys with the compositions: $Fe_{61}Co_{10}B_{20}Y_{8-x}W_yPt_x$ (where: $x = 1, 2$; $y = 0, 1$) were melted sequentially in an arc furnace; high-purity components were used in each production process: Fe-99.95%, Co-99.95%, Y-99.95%, B-99.95%, W-99.95%, and Pt-99.95%.

Samples of each alloy were prepared in the form of plates 0.5 mm thick and 5 mm wide; in order to achieve this, the liquid melt injection method was applied, using a water-cooled copper mould. The whole process was undertaken under a protective Ar atmosphere.

The plates of the alloy samples ($Fe_{61}Co_{10}B_{20}Y_{8-x}W_yPt_x$ (where: x = 1, 2; y = 0, 1)) were crushed to powder-form in a mortar, and then subjected to structural research using X-ray diffraction (Cu Kα radiation) within the 2θ angle range of 20° to 100° with a step 0.02°. The temperature dependent magnetization of the samples was measured within the range of 300K to 850K using a Faraday magnetic balance. The magnetic properties of the materials were determined using a vibration magnetometer (VSM), using a maximum magnetic field of up to 2 T.

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3. Results

Figure 1 contains XRD patterns for the studied samples in the form of plates of 0.5 mm thickness.

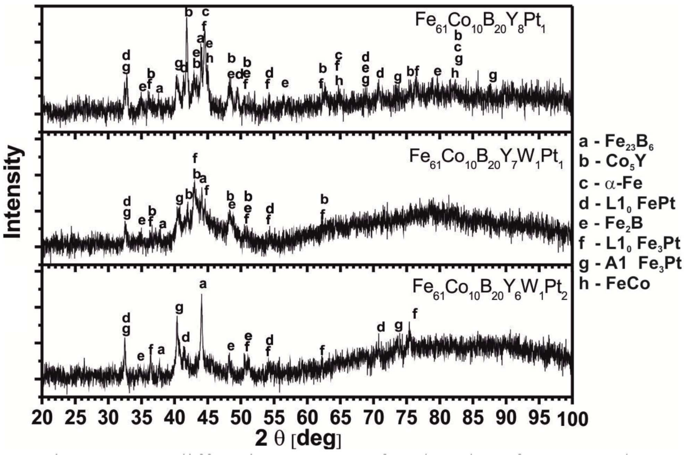

Fig. 1. X-ray diffraction patterns for the plate-form samples of the investigated alloys.

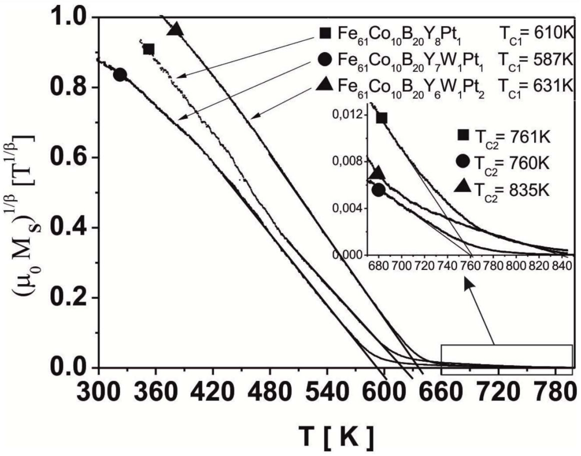

Fig. 2. Thermomagnetic curves for the investigated samples.

The X-ray diffraction patterns shown in Fig. 1 are similar to each other. There are numerous wide diffraction peaks of low intensity. Such X-ray diffraction patterns are typical of biphasic materials consisting of amorphous and crystalline parts. On the basis of analysis using the program 'Match XRD 3.4.2', seven crystalline phases were identified within the volume of the alloy: α-Fe, $Fe_{23}B_6$, Fe_2B, $L1_0$ FePt, Fe_3Pt, Co_5Y, and FeCo. The phase Fe_3Pt should be separated here into a disordered phase: A1 Fe_3Pt (a magnetically soft phase) and an ordered phase: $L1_0$ Fe_3Pt (a magnetically hard phase). The Curie temperature is an important parameter for describing the temperature stability of the magnetic properties of the studied alloys. Figure 2 shows the thermomagnetic curves obtained for the studied alloys.

TABLE I

Data from analysis of the static hysteresis loops (VSM) for $Fe_{61}Co_{10}B_{20}Y_{8-x}W_yPt_x$, where: $\mu_0 M_S$ - saturation magnetization, H_c — coercivity. T_{C1} — first Curie temperature, T_{C2} — second Curie temperature.

	$\mu_0 M_S$ [T]	H_c [A/m]	T_{C1} [K]	T_{C2} [K]
$Fe_{61}Co_{10}B_{20}\mathbf{Y_8Pt_1}$	1.22(2)	2640	612(3)	763(3)
$Fe_{61}Co_{10}B_{20}\mathbf{Y_7W_1Pt_1}$	1.12(2)	2400	592(3)	760(3)
$Fe_{61}Co_{10}B_{20}\mathbf{Y_6W_1Pt_2}$	1.2(2)	934	636(3)	835(3)

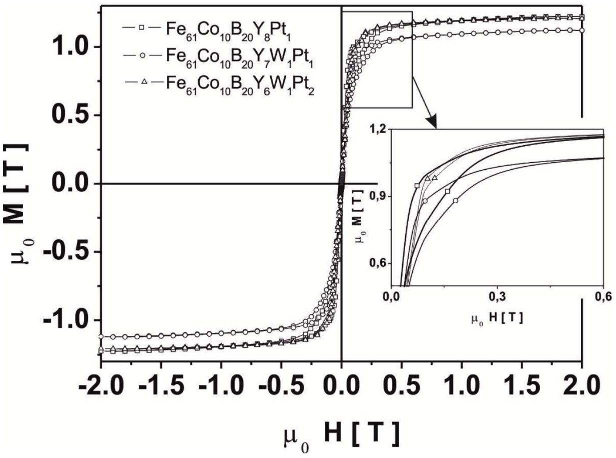

Fig. 3. Static hysteresis loops for the investigated samples.

Within the temperature range extending to 850K, all of the investigated alloys have two Curie T_C temperatures. In the studied alloys, there are "two orders" of structures of which the amorphous matrix volume is approximately 90%. The first well-defined Curie temperature T_{C1} corresponds to the amorphous matrix and the ordered phase A1 Fe_3Pt (which is magnetically soft); the second, T_{C2}, is associated with the crystalline phase with its hard magnetic properties. The T_{C1} temperature occurs within a fairly wide range of temperatures, and this is directly related to the nature of amorphous alloys. The T_{C2} temperature is approximately 760K and this parameter determines the magnetic stability of the ferromagnetic phase $L1_0$ FePt, [2] for the alloys $Fe_{61}Co_{10}B_{20}Y_8Pt_1$ and $Fe_{61}Co_{10}B_{20}Y_7W_1Pt_1$. In the case of the $Fe_{61}Co_{10}B_{20}Y_6W_1Pt_2$ alloy, the temperature T_{C2} was much higher (830K); this can be explained by the formation of a semi-hard magnetic phase, Co_5Y. The Curie temperatures, determined from the thermomagnetic curves, are shown in Table I. The investigated alloys should be delimited not only because of the presence of the amorphous and crystalline structure but also to take into account the magnetic structure: both magnetically soft and hard. In Fig. 3, the static magnetic hysteresis loops are shown for the samples.

The static hysteresis loops obtained for the alloys $Fe_{61}Co_{10}B_{20}Y_8Pt_1$ and $Fe_{61}Co_{10}B_{20}Y_7W_1Pt_1$ reveal their biphasic magnetic nature. Near the so-called 'knee', the separation of the hysteresis loop can be seen clearly - evidently connected with the presence of the two magnetic phases. This type of hysteresis loop is called 'wasp-waisted' [8]. In the case of the hysteresis loop for the alloy $Fe_{61}Co_{10}B_{20}Y_6W_1Pt_2$, this broadening is very small. In Table I, the data obtained from analysis of the static hysteresis loops are collected.

3. Discussion

Using a liquid melt injection technique, biphasic alloys containing more than 90% amorphous matrix and a few percent share of crystalline structure can be produced. It should be noted that the intensity and width of the diffraction peaks is characteristic for nanocrystalline materials. The precursor sample was $Fe_{61}Co_{10}Y_8W_1B_{20}$, which is a magnetically soft ferromagnetic alloy ($\mu_0 M_s \approx 1.5$ T, $H_c \approx 60$ A/m) [4]. It was hypothesised that the introduction to the tested alloys of 1% at. Pt would increase the number of nucleation sites - which is associated with the fragmentation of the structure. According to previous work [9], the introduction of 1%at. Pt (optimal value [9]) to ferromagnetic soft alloys should facilitate the nucleation of primarily the α-Fe phase. In the case of the investigated alloys, obtained in a single production step, the process of nucleation of the crystalline phases takes place in a completely different way compared with that taking place in conventional convex alloys. Therefore, the product of the crystallization process can be quite different. Due to the limited melt solidification time, which is the total time for the relaxation processes, the crystallization product may be different - resulting in crystalline phases with crystallites not exceeding 100 nm. It should be mentioned here that the base alloy $Fe_{61}Co_{10}Y_8W_1B_{20}$was designed according to the Inoue criteria [10] which determines its good glass-forming ability (GFA). In such designed alloys, the viscosity is more than tripled at the time of solidification; this phenomenon limits the migration of atoms to within shorter distances. This, in turn, prevents the formation of a single crystalline state. Therefore, some weakly developed crystalline states could be identified in the studied alloys. Considering the 'ability to mix' of Fe and Co with other individual atoms: Fe-Pt $\Delta H_{AB}^{mix} = -13$ kJ/mol, Fe-B $\Delta H_{AB}^{mix} = -26$ kJ/mol, Co-Y $\Delta H_{AB}^{mix} = -22$ kJ/mol [11], it should be hypothesised that such systems are most energetically favourable. These assumptions were confirmed by the analysis of the XRD diffractograms (Fig. 1). Surprisingly, within the volume of the samples, no crystalline phases were found that were based on Pt-Y, for which $\Delta H_{AB}^{mix} = -83$ kJ/mol [11]. This can be explained by the fact that, within the volume of the alloys, cluster systems with Fe as the main component were formed preferentially. The complexity of the structure of the studied alloys is also manifested in their magnetic properties. Based on static analysis of the hysteresis loops for the alloys $Fe_{61}Co_{10}B_{20}Y_8Pt_1$ and $Fe_{61}Co_{10}B_{20}Y_7W_1Pt_1$, the presence of two magnetic phases was confirmed by XRD studies (Fig. 1). In the alloy with 2% of Pt, the share of FePt and Co_5Y is practically invisible (Table I). Also Fe_3Pt is divided into an ordered and disordered phase. However, in the case of the studied alloys, the amorphous matrix (for which the volume fraction is estimated to be over 90%) has a decisive role in the soft magnetic properties. The dominance of this phase is visible clearly on the thermomagnetic curves (Fig. 2). For amorphous FeCoB-based alloys with soft magnetic properties, the Curie temperature is within the limits 550K–650K [2]. The second Curie temperature, T_{C2}, determined for the $Fe_{61}Co_{10}B_{20}Y_8Pt_1$ and $Fe_{61}Co_{10}B_{20}Y_7W_1Pt_1$alloys, corresponds to the hard magnetic phase FePt. For the third alloy, the crystalline phase Co_5Y almost completely disappeared and residual quantities of the crystalline phases $L1_0$ FePt and $L1_0Fe_3Pt$ appeared - also featuring hard magnetic properties.

In conclusion, the results included in this paper are consistent and corroborate one another.

4. Conclusions

1. A two-phase amorphous crystalline alloy in a volume of two magnetic phases may be prepared in a single step.
2. A rapid-cooling process blocks the creation of the disordered phase A1 Fe_3Pt for the alloys: $Fe_{61}Co_{10}B_{20}Y_8Pt_1$ and $Fe_{61}Co_{10}B_{20}Y_7W_1Pt_1$.
3. The Curie temperature of the amorphous matrix coincides with the temperature of the disordered Fe_3Pt phase.
4. The introduction of 2% at. Pt reduces the share of magnetically hard $L1_0$ FePt in favour of a soft magnetic phase.

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