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Influence of the Cooling Rate on the Curie Temperature Value for Amorphous Fe-Based Alloys

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The Curie temperature is one of the most important parameters for ferromagnetic materials. With increasing temperature, thermal vibrations in the crystal structure and changes in the settings of magnetic dipoles occur. The material goes from ferro- to paramagnetic state. This phenomenon is well described for materials with a crystal structure. In the case of amorphous alloys, the Curie temperature is not a discrete value but a temperature range over which a magnetic transition occurs. The paper presents the results of the research on the magnetic polarization of saturation as a function of temperature for rapid-quenched alloys. Samples of different diameters, i.e., 0.5, 0.75, 1 mm, were prepared. The thermomagnetic curves were measured using a Faraday magnetic balance in the temperature range from room temperature to 1100 K in a homogeneous magnetic field with a constant intensity of 0.7 T. Based on the analysis of the relationship $(\mu_0 M_S)^{1/\beta}$, it was found that with the decrease in the cooling rate of the alloy, the solidification time of the alloy increased, and the atoms rearranged into further distances as Curie temperature value increased. For the return curves, the Curie temperature corresponding to the Fe_2B crystalline phase was recorded. In this case, some changes were also noted depending on the cooling rate.

topics: Curie temperature, rapid quenched alloys, injection-casting method

1. Introduction

Rapidly cooled alloys often exhibit different magnetic and mechanical properties compared to alloys with the same chemical compositions produced at much lower cooling rates [1, 2]. This difference is related to the re-distribution of alloy component elements within the volume of the material. In the case of amorphous alloys, we can talk about chemical and topological disorder [3–6]. These differences are of great importance to the resulting properties of this type of material. In magnetic rapidly cooled alloys with an amorphous structure, there is a chemical and topological ordering of short-range atoms in relation to the selected central atom. This means that the magnetic structure is not inherently connected with a crystalline structure. Both chemical and topological changes in the volume of the material affect the fluctuations of magnetic parameters, such as the exchange integral, magnetic anisotropy and the local magnetic moment [7, 8]. The stability of the ferromagnetic state is determined by a temperature value known as the Curie temperature [9–11]. It should be noted here that the Curie temperature can be used to classify the properties of materials into ferromagnetic (below this temperature) and paramagnetic (above this temperature). Due to their periodic structure, magnetic crystalline materials have a discrete Curie temperature value. Amorphous materials, on the other hand, are characterised by a rather narrow Curie temperature range, which should always be considered when analysing this type of material [12]. Changing the diameter of an alloy sample while maintaining the amorphous structure can affect the Curie temperature range. Currently, the electrical engineering and electronics industries are looking for materials with exceptional properties, offering stable operation at elevated Curie temperatures. Therefore, amorphous ferromagnets are often considered for use in specialised equipment.

The aim of this study was to investigate the magnetic polarisation of saturation, as a function of temperature, for the $Fe_{60}Co_{10}Y_{10}B_{20}$ alloy. The samples were produced in the form of rods of various diameters, using a method involving the injection of the liquid alloy into a water-cooled copper mould. The resulting Curie temperatures were determined by analysis of thermomagnetic curves.

2. Materials and methods

Polycrystalline test samples were produced using an arc furnace. High-purity elements were used to make the alloy ingots: Fe — 99.99%, Co — 99.99%, Y — 99.95%, and B — 99.9%. The selected and alloying components were weighed and placed on a copper water-cooled plate. The combination of the elements took place under a protective argon atmosphere, preceded by the melting of pure titanium, which was used to absorb the remaining oxygen in the chamber. The fused alloying components were re-melted several times to obtain a homogeneous alloy. The 10 g ingots prepared this way were cleaned mechanically and with an ultrasonic cleaner. These ingots were then divided into smaller pieces, which became batch portions for producing the rapidly cooled alloy samples. Using an induction furnace, samples were made in the form of rods, each with a diameter of either 0.5, 0.75 or 1 mm. The rods were made with a method involving forcing the liquid alloy into a copper water-cooled mould (injection-casting).

The structure of the rod samples was investigated using a Bruker D8 Advance X-ray diffractometer. The samples were irradiated with X-rays within the 2° angle range from 30 to 100°. The exposure time for the 0.2θ measuring step was 7 s. A cobalt lamp was installed in the measuring apparatus.

The magnetic properties of the samples were investigated using a Faraday magnetic balance. The samples were tested in a constant magnetic field of 0.7 T. Approximately 25 mg of each test sample was placed in the weight basket. Magnetic saturation polarisation, as a function of temperature, was measured within the range from room temperature to 1100 K.

All studies were conducted on samples that had been fragmented using a low-energy process.

3. Results

Figure 1 shows the X-ray diffraction images measured for the tested alloys.

The X-ray diffractograms obtained for the tested samples of the $Fe_{60}Co_{10}Y_{10}B_{20}$ alloy exhibit only wide, fuzzy maxima — typical for amorphous materials. The design of the alloy, combined with the production method, facilitated the production of fully amorphous rods with diameters of up to 1 mm. In the case of Fe-based amorphous materials, a diameter of 1 mm is a significant thickness. The Curie temperature is a very important parameter for characterising ferromagnetic alloys. Figure 2 shows the curves of magnetic saturation polarisation as a function of temperature.

Based on the shape of the curves, it can be concluded that each of the examined samples is characterised by one transition from the ferromagnetic state to the paramagnetic state in the amorphous state. Figure 3 shows curves describing the relationship of $(\mu_0 M_s)^{1/\beta}$.

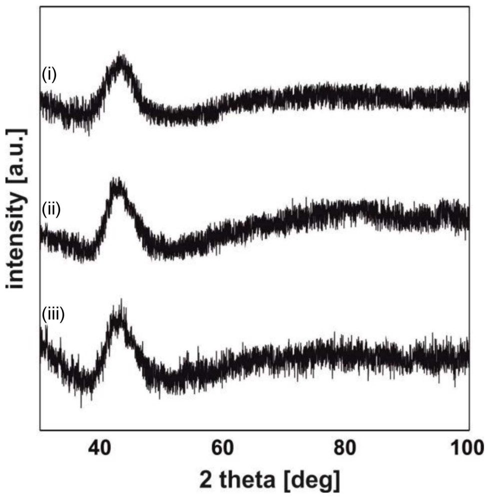

Fig. 1. X-ray diffractograms obtained for the $Fe_{60}Co_{10}Y_{10}B_{20}$ alloy samples with diameters (i) 0.5 mm, (ii) 0.75 mm, (iii) 1 mm.

TABLE I

Magnetic properties of the $Fe_{60}Co_{10}Y_{5+x}Zr_{5-x}B_{20}$ alloys and the identified crystalline phases. Here, $T_{C,am}$ and $T_{C,am2}$ are Curie temperature for the amorphous phases (heating and cooling, respectively) and $T_{C,crys}$ is Curie temperature for the crystalline phase (cooling)

Sample diameter [mm]	$T_{C,am}$ [K]	$T_{C,am2}$ [K]	$T_{C,crys}$ [K]
0.5	569	606	998
0.75	574	610	1015
1	580	611	1018

A slight increase in the Curie temperature value for the amorphous state can be observed with an increase in the diameter of the tested rod (Fig. 3a, c, e). This is a result of a slight change in the configuration of the alloying components within the volume of the tested rods — depending on their thickness. In the process of solidification from liquid to solid state, with increasing rod diameter, the solidification time increases, and this has a direct impact on the re-distribution of alloy components. This statement means that, even for the same chemical composition, the amorphous structure may exhibit different properties depending on the time duration of formation.

For return curves, it is possible to determine two transitions from the paramagnetic to the ferromagnetic state, and thus two T_C values are observed (Fig. 3b, d, f). This is related to the crystallisation products resulting from the heating of samples. Based on the determined Curie temperature values, it was found that the crystalline phase that was formed during the heating of the sample is Fe_2B. The results of the analysis of the thermomagnetic curves are summarised in Table I.

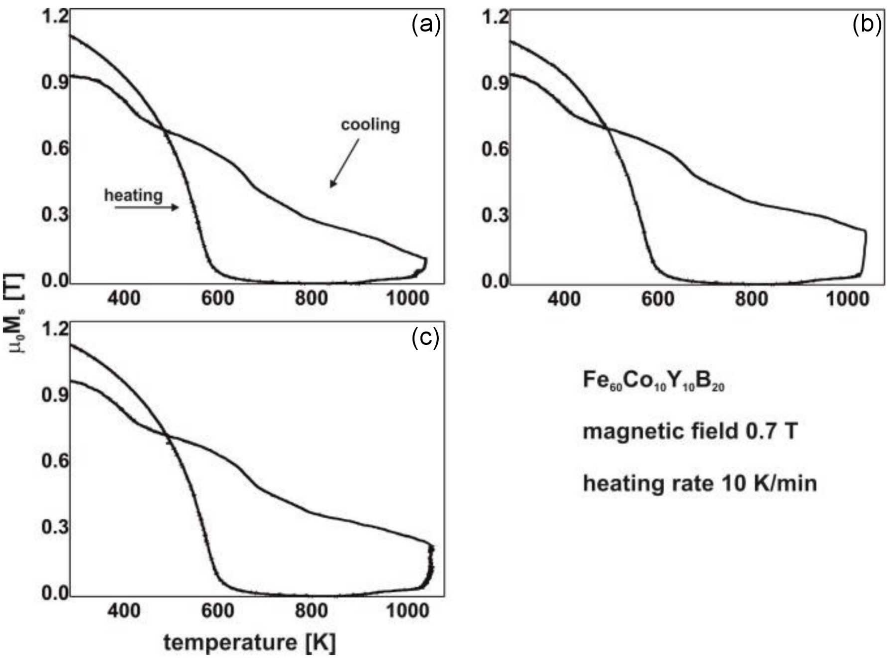

Fig. 2. Thermomagnetic curves obtained for the $Fe_{60}Co_{10}Y_{10}B_{20}$ alloy samples with diameters: (a) 0.5 mm, (b) 0.75 mm, (c) 1 mm.

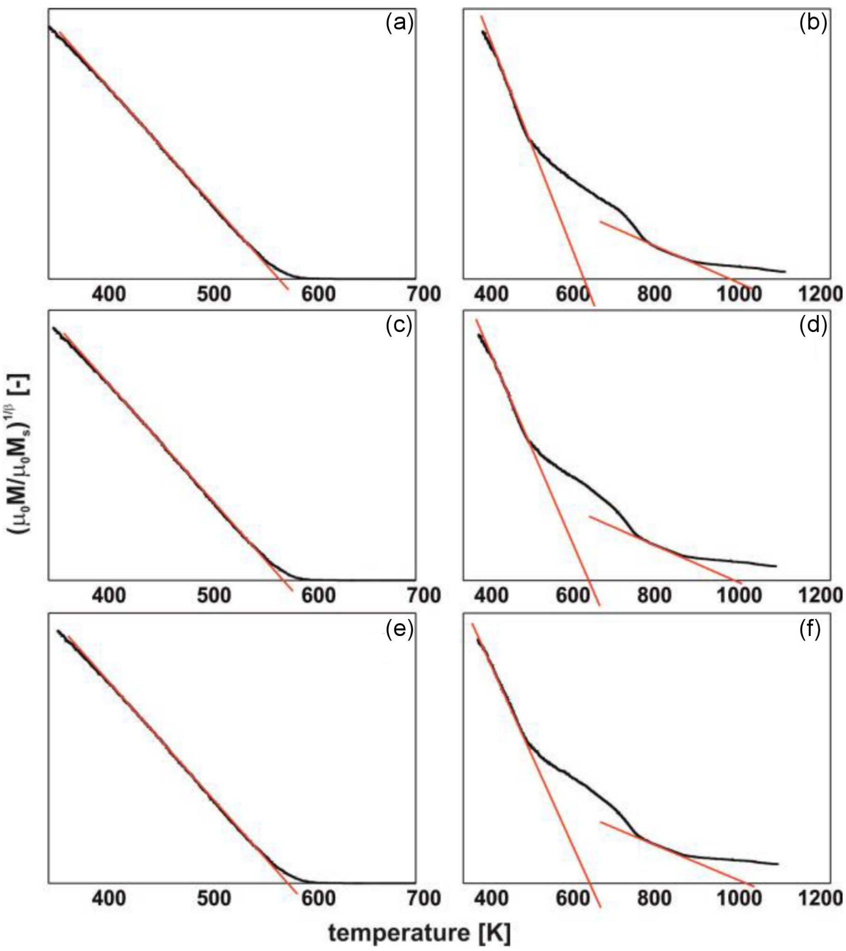

Fig. 3. Relationship of $(\mu_0 M_S)^{1/\beta}$ determined for the $Fe_{60}Co_{10}Y_{10}B_{20}$ alloy samples with diameters: (a, d) 0.5 mm, (b, e) 0.75 mm, (c, f) 1 mm (b, d, f — for cooling curves).

Attention should be paid to discrepancies in the obtained values. For the Fe_2B phase, the value of T_C = 1015 K [13] is assumed. The differences occurring in the measurements may be related to the structure of the alloys in the post-solidification state. An alloy with a diameter of 0.5 mm should have the highest degree of topological disorder, which is associated with a shorter time of solidification of the alloy compared to samples with a larger diameter. In turn, a higher degree of ordering of alloys with a larger diameter causes an increase in the Curie temperature value. This assumption is also confirmed by a higher T_C value for the amorphous phase, i.e., both for the alloy in the post-solidification state and on the return curves. Further evidence of a higher degree of order for samples with larger diameters arises from the value of magnetic saturation polarisation above 1000 K — this value increases much faster for samples with larger diameters. These slight changes can have a significant impact on the crystallisation process and thus on the T_C value for the Fe_2B phase. A lower value for a sample with a diameter of 0.5 mm may be related to the excess number of boron atoms in the resulting crystalline phase.

4. Conclusions

The aim of this study was to investigate the relationship between the magnetic polarisation of saturation, as a function of temperature, and the diameter of the amorphous alloy, and thus, indirectly, the cooling rate. A smaller-diameter alloy sample took less time to solidify. For this reason, it is characterised by a higher degree of disorder. A longer solidification time allows atoms to take positions resembling locally a crystal lattice. It should be emphasised that this is only a similar configuration (and only in certain areas of the samples), which is still a fully amorphous structure. The obtained results prove that it is possible to design an alloy with a desired Curie temperature value, and it is possible to control this value by controlling the cooling rate of the liquid alloy.

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