

## Influence of Chemical Composition on the Curie Temperature Change in Amorphous Alloys

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Amorphous alloys are characterized by a disordered structure. The arrangement of atoms is chaotic and it is difficult to determine the parameters describing their properties. In soft magnetic ferromagnets, one of the main parameters describing their applicability is the Curie temperature. However, in amorphous materials, due to their metastable nature, the Curie temperature occurs in a rather narrow range. Using the measurements of the magnetic saturation polarization as a function of temperature and the critical exponent  $\beta = 0.36$ , the value of the Curie temperature can be determined. The paper presents the results of  $\mu_0 M(T)^{1/\beta}$  tests carried out for two amorphous alloys with similar chemical composition. The influence of chemical composition on the course of the  $\mu_0 M(T)$  curve and changes in the share of characteristic areas describing rearrangements of atoms in the structure of alloys were observed.

topics: bulk amorphous alloys, Curie temperature, coercive field, soft magnetic properties

### 1. Introduction

Depending on their chemical composition, amorphous alloys have much better mechanical and magnetic properties than their crystalline counterparts. In many industries, great emphasis is placed on introducing better and better materials with specific properties into products. Both materials exhibiting the so-called soft magnetic properties [1, 2] and hard magnetic properties [3–5] are desirable. Due to the constantly growing progress in the field of electronics and electrical engineering, materials with good magnetic properties that can be used as transformer cores or chokes are of particular interest [5–7]. Therefore, research is constantly being conducted on amorphous and nanocrystalline alloys, the properties of which can be controlled, among others, by small changes in the chemical composition [8–10]. It should be added here that there are two groups of amorphous materials: classical and bulk amorphous materials [11]. The classic ones include mainly thin tapes with a thickness of about 100  $\mu\text{m}$ . Such tapes are produced at cooling rates up to 106 K/s. Using the melt spinning technique, which involves squirting liquid metal onto a rotating copper wheel, it is possible to produce tapes with an amorphous structure. Unfortunately,

this method does not enable the production of thicker samples of given shapes, which significantly limits the application possibilities of the materials. From the 1970s to the end of the 1990s, work was carried out on the possibility of obtaining samples in the form of plates or rods with thicknesses above 0.5 mm [12]. In 1989, A. Inoue from Tohoku University in Japan presented for the first time criteria enabling the systematic production of amorphous materials with thicknesses greater than the maximum for tapes [13, 14]. Since then, a new group of amorphous materials has been distinguished, called bulk amorphous materials. Inoue established in his assumptions that to achieve good glass transition ability, it is necessary to carefully design the chemical composition of the alloy. The most important thing is that the alloy consists of at least three components, the atomic radii of at least the main components differ by more than 12%, and the negative heat of mixing between the components is as high as possible. All these criteria are intended to limit the migration of atoms in the solidifying alloy, which, of course, prevents the formation of a crystalline structure. In amorphous materials, and especially in bulk amorphous materials, there can be changes in the structure within the amorphous state, which is reflected in sensitive property measurements.

The paper presents test results performed for bulk amorphous alloys of composition  $\text{Fe}_{34}\text{Co}_{34}\text{Nb}_4\text{W}_2\text{Me}_3\text{B}_{23}$ , where  $\text{Me} = \text{Y}$  or  $\text{Gd}$ . The structure of the alloys and their magnetic properties were examined.

## 2. Experimental procedure

Polycrystalline alloys were produced in an arc furnace. The process was carried out in a protective atmosphere of argon on a copper plate cooled by water. The ingredients used were 99.99% pure (for boron — 99.9%). Ingots weighing 5 g were melted using a non-fusible tungsten electrode at an intensity of 180–300 A. The remelting process was preceded by melting a titanium getter to capture the remaining oxygen in the working chamber. The process was repeated 5 times to homogenize the structure and chemical composition of the alloy. Rapidly quenched alloys were made by cooling using the injection casting method. Samples were obtained in the form of rods with a diameter of 1 mm and a length of 20 mm. The production process was carried out in a protective atmosphere of argon. The polycrystalline batch was placed in a quartz crucible with a hole of 1 mm in diameter. Melting was carried out using eddy currents, and the liquid alloy was forced into a copper mold cooled by water under argon pressure.

The structure of the alloys was examined using X-ray diffraction. The tests were carried out using a Bruker ADVANCE 8 X-ray diffractogram equipped with a  $\text{Cu } K_\alpha$  lamp. The measurement was carried out in the range of  $30\text{--}100^\circ$  of the  $2\theta$  angle with a time of 5 s per measurement step of  $0.02^\circ$ .

Thermomagnetic curves were measured using a Faraday magnetic balance. The measurement was carried out in the range from room temperature to 850 K at a constant external magnetic field intensity of 0.7 T.

Static magnetic hysteresis loops were measured using a VSM 7307 vibration magnetometer in the range of an external magnetic field up to 2 T.

## 3. Results

Figure 1 shows X-ray diffraction patterns measured for the produced alloys. The recorded diffractograms show only broad maxima coming from X-rays reflected on atoms chaotically distributed in the volume of the alloys. This proves the amorphous structure of the tested alloys. Samples of the produced alloys were subjected to thermomagnetic tests.

The saturation magnetic polarization curves are shown in Fig. 2. The curves show single mild inflections related to the transition of the magnetic phase from the ferro- to paramagnetic state.

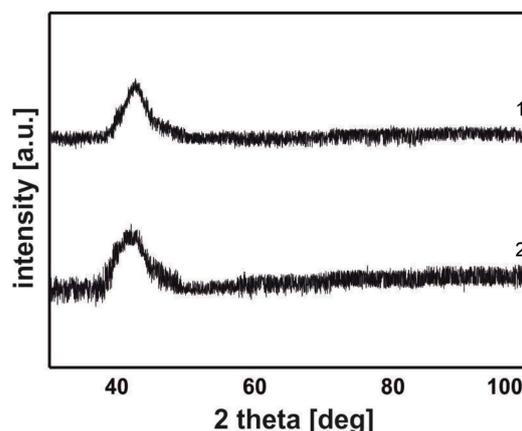


Fig. 1. X-ray diffraction patterns for the rod-form samples of the investigated alloys: 1 —  $\text{Fe}_{34}\text{Co}_{34}\text{Nb}_4\text{W}_2\text{Y}_3\text{B}_{23}$ , 2 —  $\text{Fe}_{34}\text{Co}_{34}\text{Nb}_4\text{W}_2\text{Gd}_3\text{B}_{23}$ .

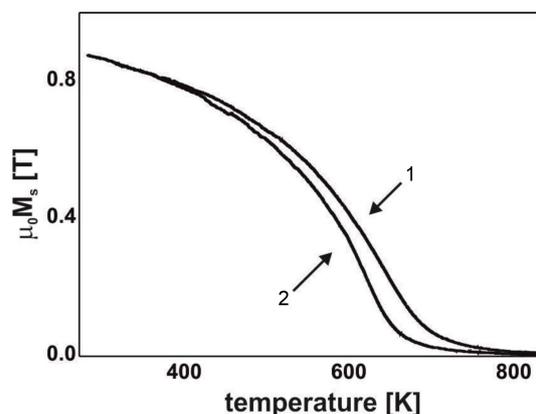


Fig. 2. Thermomagnetic curves obtained for the tested alloy samples: 1 —  $\text{Fe}_{34}\text{Co}_{34}\text{Nb}_4\text{W}_2\text{Y}_3\text{B}_{23}$ , 2 —  $\text{Fe}_{34}\text{Co}_{34}\text{Nb}_4\text{W}_2\text{Gd}_3\text{B}_{23}$ .

It should be remembered that for amorphous alloys, the  $T_C$  value is rather the temperature range in which the magnetic transition occurs (it is not a discrete value). This is due to the presence of micro-areas in the alloy volume with slightly different atomic arrangements. The measured curves were analyzed using the critical coefficient  $\beta = 0.36$  used for ferromagnetics meeting Heisenberg's assumptions [15] (Fig. 3).

Curie temperature  $T_C$  values were determined based on the  $(\mu_0 M)^{1/\beta}$  curves. It was found that the alloy with the addition of Gd is characterized by a lower  $T_C$  value (629 K) compared to the alloy with the addition of Y (643 K).

Figure 4 shows static magnetic hysteresis loops. The measured loops are similar to each other. However, for the alloy with the addition of Gd, a more than twice lower value of the coercive field  $H_C$  was determined with almost the same saturation magnetization value  $M_S$ .

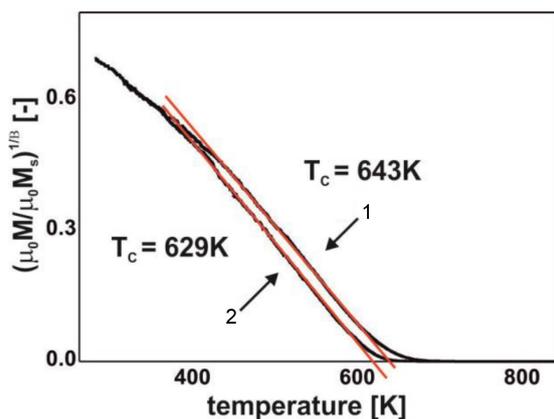


Fig. 3. Relationship of  $(\mu_0 M)^{1/\beta}$  with temperature,  $T$ , for the tested alloys: 1 —  $\text{Fe}_{34}\text{Co}_{34}\text{Nb}_4\text{W}_2\text{Y}_3\text{B}_{23}$ , 2 —  $\text{Fe}_{34}\text{Co}_{34}\text{Nb}_4\text{W}_2\text{Gd}_3\text{B}_{23}$ .

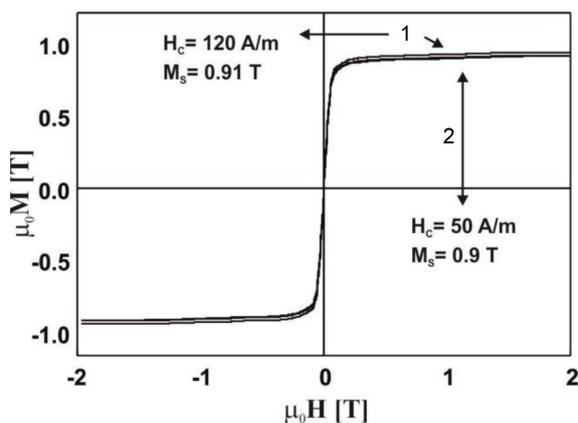


Fig. 4. Static magnetic hysteresis loops for the tested alloys: 1 —  $\text{Fe}_{34}\text{Co}_{34}\text{Nb}_4\text{W}_2\text{Y}_3\text{B}_{23}$ , 2 —  $\text{Fe}_{34}\text{Co}_{34}\text{Nb}_4\text{W}_2\text{Gd}_3\text{B}_{23}$ .

Gd has ferromagnetic properties, unlike Y. However, the addition of Gd reduces the  $T_C$  value. This is related to the influence of Y on the structure of the alloy. The presence of this element increases the number of free volumes, which causes the stabilization of the subcooled liquid and, consequently, a possible increase in the  $T_C$  and  $M_S$  values. This influence is related, among other things, to the significant size of Y atoms (atomic radius 182 pm). Such a relationship is observed in the case of the tested alloys.

#### 4. Conclusions

The work showed that the addition of Gd at the expense of Y improves the magnetic properties of Fe–Co–B alloys. Gadolinium and yttrium have similar atomic radius lengths. However, these elements have different properties. Due to its electronic structure, Gd has ferromagnetic properties, while Y is

paramagnetic. However, the addition of Gd does not improve  $M_S$  and  $T_C$ . However, the addition of this component facilitates the magnetization process, as indicated by the value of the coercive field. As is known, the addition of Gd affects the formation of hard magnetic phases. However, as the above test results indicate, a small addition of Gd may improve the soft magnetic properties as long as the rapidly cooled alloy remains in the sphere of the amorphous structure.

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