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# Thermal and magnetic properties of selected Fe-based metallic glasses

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## ABSTRACT

**Purpose:** The work presents a thermal stability characterization and soft magnetic properties analysis of selected Fe-based metallic glasses.

**Design/methodology/approach:** The studies were performed on ribbons prepared by the planar flow casting technique, which is a method of continuous casting of the liquid alloy on a surface of turning copper based wheel. The methods of X-ray diffraction were used for the qualitative phase analysis. The thermal properties associated with crystallization temperature of the glassy alloys were measured using the differential thermal analysis. The magnetic properties were determined by the Maxwell-Wien bridge, fluxometer and VSM methods.

**Findings:** The studied $Fe_{72}B_{20}Si_4B_4$ and $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ metallic glasses in as-cast state were fully amorphous. The Curie temperature (Tc) for $Fe_{72}B_{20}Si_4B_4$ alloy has a value of 582 K and $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ has higher Tc, which has a value of 605 K. The obtained magnetic properties allow to classify the studied amorphous alloys in as-cast state as soft magnetic materials. The coercive field of tested alloys has a value about 8 A/m. The maximum magnetic permeability of $Fe_{72}B_{20}Si_4B_4$ alloy ($\mu_{max}$ = 21500) is much higher than $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ metallic glasses ($\mu_{max}$ = 3200). Similarly, saturation magnetization of $Fe_{72}B_{20}Si_4B_4$ alloy ($B_s$ = 1.04 T) is higher than $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ ($B_s$ = 0.99 T) amorphous alloy.

**Practical implications:** The studied glassy alloys are suitable materials for many electrical application in different elements of magnetic circuits and for manufacturing of sensors and precise current transformers.

**Originality/value:** The obtained results confirm the utility of applied investigation methods in the thermal and magnetic properties analysis of examined amorphous alloys.

**Keywords: Amorphous materials; Metallic glasses; Soft magnetic properties**

MATERIALS

## 1. Introduction

Metallic glasses are a novel class of engineering materials, which have unique mechanical, thermal, magnetic and corrosion properties [1-4]. Those properties are attractive compared with conventional crystalline alloys and are very useful in a wide range of engineering applications. Amorphous state formation depends on the alloy composition and the manufacturing process conditions. The rapid solidification of metallic liquids is the most often used for metallic glass preparation [5-9].

Iron-based glassy alloys seem to be one of the most interesting materials due to their soft magnetic properties including high saturation magnetization. They are suitable materials for many electrical devices such as electronic measuring and surveillance systems, magnetic wires, sensors, band-pass filters, magnetic shielding, energy-saving electric power transformers [10-13].

## 2. Material and research methodology

The aim of the present work is the thermal stability characterization and soft magnetic properties analysis of Fe-based amorphous alloys using XRD, DTA and VSM methods.

The investigated materials were cast as ribbon shaped metallic glasses with thickness 0.03 mm and width 10 mm. The ribbons were manufactured by the planar flow casting technique, which is a method of continuous casting of the liquid alloy on the surface of a turning copper based wheel. The casting conditions include linear speed of copper wheel: 20 m/s and ejection over-pressure of molten alloy: 200 mBar.

The chemical composition and dimensions of ribbon of examined alloys are presented in Table 1. The chemical composition of that Fe-based metallic glasses allows to cast this kind of materials in bulk forms (rods, rings) by suction or centrifugal casting methods.

Table 1.
Chemical composition and dimensions of ribbon of investigated metallic glasses

| Ordinal number | Chemical constitution [at.%] | | | | | Dimensions of ribbons [mm] | |
|---|---|---|---|---|---|---|---|
| | Fe | Co | B | Si | Nb | Thickness | Width |
| 1 | 72 | - | 20 | 4 | 4 | 0.03 | 10 |
| 2 | 36 | 36 | 19 | 5 | 4 | 0.03 | 10 |

Phase analysis was carried out using the Seifert-FPM XRD 7 diffractometer equipped with cobalt anode. It was supplied by current intensity of 25 mA and voltage of 35 kV. The data of diffraction lines were recorded by "step-scanning" method in $2\theta$ range from 30° to 90° and 0.1° step.

The thermal properties associated with crystallization temperature of the amorphous alloys were measured using the differential thermal analysis (DTA, Mettler TA-1) at a constant heating rate of 6 K/s under an argon protective atmosphere.

The Curie temperature of investigated alloys was determined by measuring a volume of magnetization in function of heat treatment temperature. The Curie temperature was calculated from the condition dM(T)/dT=minimum [14].

The initial magnetic permeability was measured by using the Maxwell-Wien bridge. Applied magnetic field was a value of 0.5 A/m and frequency about 1 kHz.

The maximum magnetic permeability in function of magnetic field was examined by the fluxometer, which allows to measure changes of magnetic flux in tested material.

The magnetic hysteresis loops of studied metallic glasses were measured by the resonance vibrating sample magnetometer (R-VSM). Sample oscillates parallely to the direction of external magnetic field and configuration of pick-up coils in the form of small Smith coils were applied [15].

Obtained hysteresis loops allowed to determine coercive field and saturation magnetization of tested samples.

## 3. Results and discussion

The X-ray diffraction investigations have revealed that the studied as-cast metallic glasses were fully amorphous. The diffraction pattern of the samples has shown the broad diffraction halo characteristic for the amorphous structure (Fig.1).

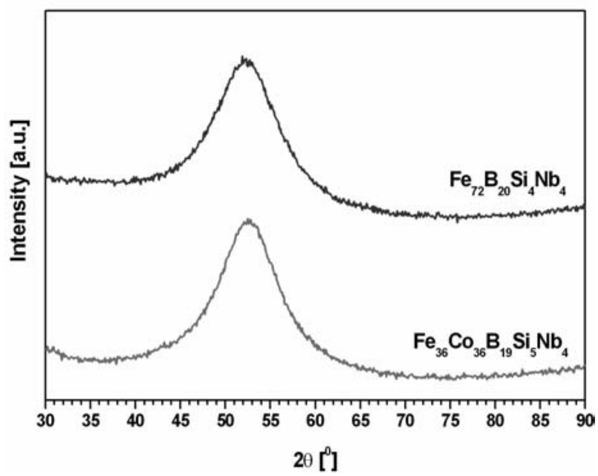


Fig. 1. X-ray diffraction pattern of $Fe_{72}B_{20}Si_4B_4$ and $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ ribbons in as-cast state

Figure 2 shows normalized curves M(T)/M(300 K) in situ with linear heating rate 5 K/min for examined glassy alloys. The increase of heat treatment temperature causes the decrease of magnetization of tested materials, which is connected with magnetic transformation point. The Curie temperature ($T_c$) for $Fe_{72}B_{20}Si_4B_4$ alloy has a value of 582 K and $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ has higher $T_c$, which has a value of 605 K.

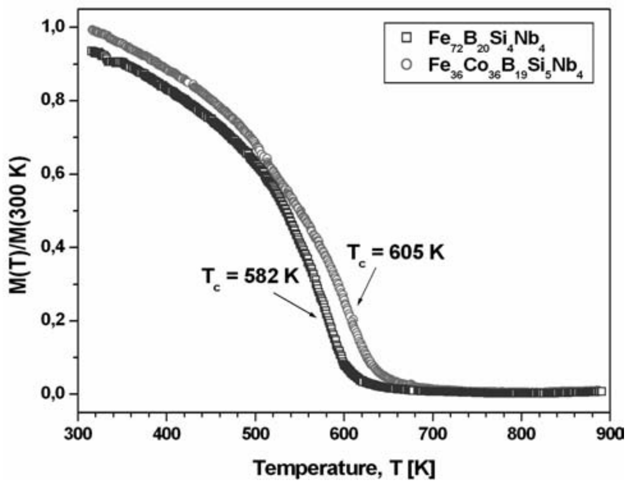


Fig. 2. Normalized curves of magnetization of $Fe_{72}B_{20}Si_4B_4$ and $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ glassy alloys

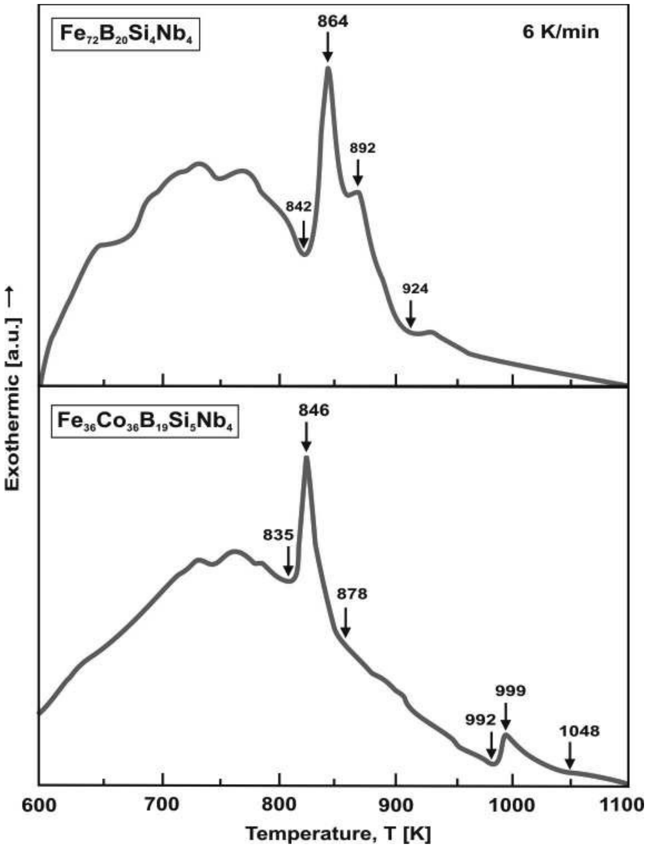


Fig. 3. DTA curves of $Fe_{72}B_{20}Si_4B_4$ and $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ glassy alloy ribbons

DTA curves measured on a fully amorphous ribbon samples in as-cast state for examined alloy compositions are shown in Figure 3.

Differential thermal analysis of examined glassy alloys in as-cast state allowed to determine crystallization temperature from DTA curves. The crystallization temperature of $Fe_{72}B_{20}Si_4B_4$ alloy has a value of 864 K. A two stage crystallization process was observed for $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ alloy. The first stage crystallization temperature has a value of 846 K and a second stage crystallization temperature is 999 K.

The crystallization temperature obtained from DTA curves and Curie temperature determined from normalized curves of magnetization are connected with thermal properties of studied metallic glasses in as-cast state.

Figure 4 presents magnetic permeability in function of magnetic field of $Fe_{72}B_{20}Si_4B_4$ and $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ glassy alloys. The maximum magnetic permeability of $Fe_{72}B_{20}Si_4B_4$ alloy ($\mu_{max}$ = 21500) is much higher than $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ metallic glasses ($\mu_{max}$ = 3200). What is more, the initial magnetic permeability ($\mu_r$) of $Fe_{72}B_{20}Si_4B_4$ is 1300 and $\mu_r$ = 760 for $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ alloy.

From magnetic hysteresis loops obtained from VSM measurements of investigated materials, coercive field and saturation magnetization was determined (Fig.5).

The coercive field of tested metallic glasses has a value about 8 A/m, exactly $H_c$ = 8.0 A/m for $Fe_{72}B_{20}Si_4B_4$ and $H_c$ = 8.8 A/m for $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ alloy. The saturation magnetization of $Fe_{72}B_{20}Si_4B_4$ glassy ribbon ($B_s$ = 1.04 T) is higher than $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ ($B_s$ = 0.99 T) amorphous alloy. The magnetostriction measured for examined materials is $\lambda = 4.8 \times 10^{-6}$ of $Fe_{72}B_{20}Si_4B_4$ amorphous alloy and $\lambda = 4.9 \times 10^{-6}$ for second amorphous ribbon.

The magnetic after effects ($\Delta\mu/\mu$) was determined by measuring changes of magnetic permeability of examined alloys as a function of time after demagnetization $\mu=\mu(t)$.

The obtained magnetic properties allow to classify the studied amorphous alloys in as-cast state as soft magnetic materials.

Table 2 also gives information about thermal and magnetic properties of studied amorphous alloys in form of a ribbon.

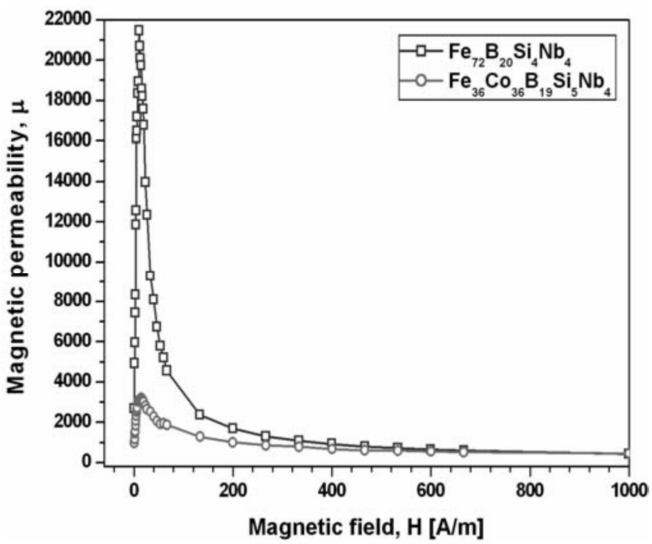


Fig. 4. Maximum magnetic permeability in function of magnetic field for studied metallic glasses

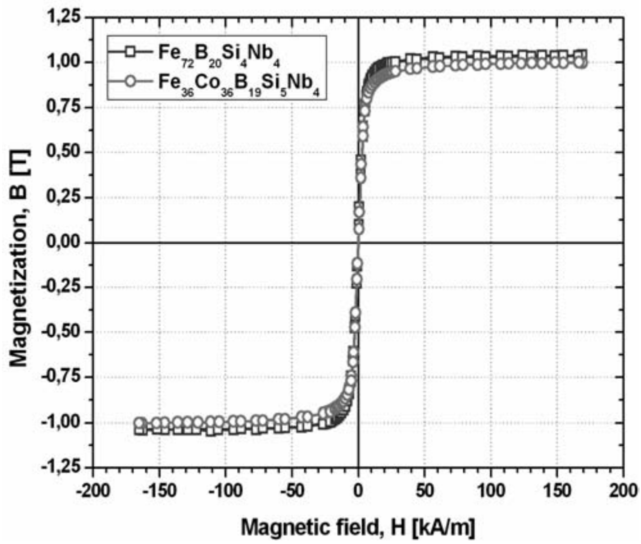


Fig. 5. Hysteresis loops of $Fe_{72}B_{20}Si_4B_4$ and $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ glassy alloy ribbons

Table 2.
Thermal and magnetic properties $Fe_{72}B_{20}Si_4B_4$ and $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ glassy alloys

| Alloy | Thermal properties | | Magnetic properties | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $T_c$ [K] | $T_x$ [K] | $B_s$ [T] | $H_c$ [A/m] | $\mu_r$ | $\mu_{max}$ | λ ($10^{-6}$) | Δμ/μ [%] |
| $Fe_{72}B_{20}Si_4B_4$ | 582 | 864 | 1.04 | 8.0 | 1300 | 21500 | 4.8 | 7.1 |
| $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ | 605 | 846 | 0.99 | 8.8 | 760 | 3200 | 4.9 | 14.7 |

## 4. Conclusions

The investigations performed on the ribbons of $Fe_{72}B_{20}Si_4B_4$ and $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ metallic glasses allowed to formulate the following statements:

- the X-ray diffraction investigations revealed that studied as-cast metallic glasses were fully amorphous,
- the crystallization and Curie temperature is connected with thermal properties of studied metallic glasses,
- the coercive field of tested metallic glasses has a value of 8 A/m for $Fe_{72}B_{20}Si_4B_4$ and 8.8 A/m for $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ alloy,
- the saturation magnetization of $Fe_{72}B_{20}Si_4B_4$ glassy ribbon ($B_s$ = 1.04 T) is higher than $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ ($B_s$ = 0.99 T) amorphous alloy,
- the maximum magnetic permeability of $Fe_{72}B_{20}Si_4B_4$ alloy ($\mu_{max}$ = 22500) is much higher than $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ metallic glasses ($\mu_{max}$ = 3200),
- the investigated magnetic properties allow to classify the studied amorphous alloys in as-cast state as soft magnetic materials.

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