Influence of thermo-magnetic treatment on magnetoelastic properties of Fe$_{81}$Si$_{4}$B$_{14}$ amorphous alloy

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Abstract. Paper presents the results of magnetoelastic investigation carried out on the ribbon ring-shaped samples made of Fe$_{81}$Si$_{4}$B$_{14}$ amorphous alloy. Samples were subjected to different thermal treatment in magnetic field to reduce value of residual stresses generated during the rapid quenching process as well as induce anisotropy. Under the influence of compressive stresses, the shape of hysteresis loop changes significantly for all investigated samples. The highest stress sensitivity was observed for sample annealed in the magnetic field perpendicular to the ribbon direction. In this case flux density $B$ increased from 75 mT to 205 mT under compressive stress up to 10 MPa.

1. Introduction

Iron-based amorphous alloys (such as Fe$_{81}$Si$_{4}$B$_{14}$) are used in power-conversion applications, as well as for cores of inductive component [1]. In addition such alloys can be used as the sensing cores of the magnetoelastic force and stress sensors [2].

Under the external compressive stress $\sigma$, the value of flux density $B$ in amorphous alloy can change significantly [3]. This significant changes are connected with the lack of magnetocrystalline energy in total free energy of amorphous alloy. As a result stress-induced magnetoelastic energy has significant influence on total free energy of amorphous alloy sample [4].

It should be indicated, that both value of magnetic anisotropy in the amorphous alloy as well as the direction of easy-axis may be controlled during the thermo-magnetic treatment. As a result, the way and values of magnetoelastic changes under the influence of stresses from external forced may be controlled. This phenomenon creates the possibility of optimization of magnetoelastic sensing elements according to the needs connected with sensor development process.

On the other hand, from the point of view of production of electronic components, value of stresses applied to the material may be especially large in case of miniature inductive cores. In such a case, even small forces may cause significant stresses. For this reason magnetoelastic characteristics should be carefully analyzed in the case on new amorphous alloys developed for practical applications. Magnetoelastic effect may have impact on the efficiency and other functional properties of the inductive component and cause malfunction or even damage of electronic device – such as switching mode power supply [5].
2. Method of investigation

Testing of the magnetoelastic characteristics of iron-based amorphous alloy samples require methodology enabling achievement of the uniform stresses $\sigma$ in the ring shaped core. Moreover investigated core have to be wounded by magnetizing and sensing winding, to measure magnetic hysteresis loop. Method enabling magnetoelastic tests of the ring-shaped amorphous alloy core was developed previously [3]. Schematic view of the device for practical realization of magnetoelastic investigation is presented in figure 1.

![Fig. 1. Device for application of the uniform compressive stress to the ring-shaped sensing element](image)

Compressive force $F$ is applied to device by hydraulic press via the base backings 1. Between nonmagnetic backing 2 and the ring core 3, the special elastic spacer is placed to guarantee uniform distribution of the stresses $\sigma$ in the tested core. Magnetizing and measuring windings are placed in special grooved races 2a in backings 2. Moreover the ball joint was used to avoid bending of the sample, which may lead to non-uniform stress distribution in the sample.

During the investigation three samples made of Fe$_{81}$Si$_{4}$B$_{14}$ rapidly quenched amorphous alloy ribbon were tested. All samples were annealed in 300 °C for one hour. Sample no. 1 was annealed without external magnetic field, whereas sample no. 2 was annealed in magnetic field $H_a = 4$ kA/m parallel to the ribbon direction and sample no. 3 was annealed in field $H_a = 150$ kA/m perpendicular to the ribbon direction. Magnetic field $H_a$ applied during the annealing induced anisotropy in samples.

3. Results

The influence of compressive stress $\sigma$ on the shape of the hysteresis loop $B(H)_\sigma$ is presented in figure 2, whereas magnetoelastic characteristics $B(\sigma)_H$ of all tested samples are presented in figure 3.

![Fig. 2. $B(H)_\sigma$ characteristics of Fe$_{81}$Si$_{4}$B$_{14}$ amorphous alloy with perpendicular anisotropy (core no. 2)](image)
Fe$_{81}$Si$_4$B$_{15}$

$T_a = 300 \, ^\circ C / 1\, h$

$H_m = 45 \, A/m$

27 A/m
18 A/m
13.5 A/m
9 A/m

a)

Fe$_{81}$Si$_4$B$_{15}$

$T_a = 300 \, ^\circ C / 1\, h$

annealed in parallel field

$H_m = 45 \, A/m$

27 A/m
18 A/m
13.5 A/m
9 A/m

b)

Fe$_{81}$Si$_4$B$_{15}$

$T_a = 300 \, ^\circ C / 1\, h$

annealed in perpendicular field

$H_m = 45 \, A/m$

27 A/m
18 A/m
13.5 A/m
9 A/m

c)

Fig. 3. Magnetoelastic $B(\sigma)_H$ characteristics of Fe$_{81}$Si$_4$B$_{14}$ amorphous alloy:

a) sample without anisotropy induced during annealing (core no. 1),
b) sample with anisotropy parallel to the ribbon (core no. 2),
c) sample with anisotropy perpendicularly to the ribbon (core no. 3)
Under the influence of compressive stresses $\sigma$, the shape of hysteresis loop changes significantly. For all investigated samples value of coercive force $H_c$ decreases under stresses $\sigma$, what is connected with strong stress-induced anisotropy generated during rapid quenching of amorphous alloys.

For all investigated samples subjected to compressive stresses $\sigma$, the increase of value of flux density $B$ in the sample (achieved for given value of magnetizing field $H_m$) was observed. It should be indicated, that the highest stress sensitivity was observed for sample no. 3 annealed in the magnetic field perpendicular to the ribbon direction. In this case flux density $B$ increased from 75 mT to 205 mT under compressive stress up to 10 MPa. In means, that value of flux density increases 172 %, whereas for sample annealed in parallel field this increase was nearly 140%.

Moreover for all tested samples nearly parallel $B(\sigma_H)$ characteristics were observed. This confirms, that the highest relative changes of flux density $B$ are observed for lower values of magnetizing field $H_m$. This phenomenon is caused by the fact, that for lower values of magnetizing field, participation of magnetostatic energy in total free energy is lower. As a result magnetoelastic energy has stronger influence on the total free energy, what causes higher relative changes of flux density $B$ in investigated cores.

4. Conclusion

Presented results indicate, that Fe$_{81}$Si$_{4}$B$_{14}$ rapidly quenched amorphous alloy exhibit high stress sensitivity in both states: subjected to thermo-magnetic treatment as well as subjected to annealing without magnetic field. On the other hand, for all samples, curves of magnetoelastic $B(\sigma_H)$ characteristics were nearly parallel and value of flux density $B$ increases under the compressive stresses $\sigma$. This results suggest that value of magnetic anisotropy energy induced during thermomagnetic heat treatment is lower than stress-induced anisotropy generated during the rapid quenching of Fe$_{81}$Si$_{4}$B$_{14}$ amorphous alloy. This effect requires further analyses as well as optimization of parameters of thermo-magnetic heat treatment.

Significant stress sensitivity of Fe$_{81}$Si$_{4}$B$_{14}$ rapidly quenched amorphous alloy gives possibility of its application in construction of magnetoelastic stress and force sensors. Moreover this effect has to be considered during development of inductive components based on this alloy composition.

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