M.Yu. Glavatskikh, R.S. Il’yasov

ELECTROMAGNETIC-ACOUSTIC TRANSFORMATION IN AMORPHOUS MATERIALS

Physical-Technical Institute, Ural Division of RAS
132, Kirov St., 426001 Izhevsk, Russia
Tel.: (3412) 430081; Fax: (3412) 250614
E-mail: emp@fti.udm.ru

The temperature dependences of the of the basic parameters of the electromagnetic-acoustic transformation (EMAT) in the ferromagnetic amorphous alloy Fe_{81}-$B_{13,5}$-$Si_{3,5}$-C_2 *have been studied experimentally. Anomalies of the considered parameters in the range of relaxation of the quenching stresses, in the structural relaxation range and in the vicinity of the Curie point have been found. It has been shown that the changes of the magnetoelastic properties are due to the stress relaxation belonging to irreversible processes, whereas the changes of elastic properties are mainly caused by the structural relaxation. The anomalies of the EMAT parameters of amorphous and crystalline ferromagnets have been shown to be similar in the vicinity of the Curie point. However, the effect of amplification of the EMAT efficiency near the Curie point in amorphous alloys is much weaker.*

The study of the processes of mutual transformation of electromagnetic and acoustic waves allows one to get new reliable information about the elastic and magnetoelastic properties of materials. Such information is useful in clarifying the character of the structural and magnetic changes in materials caused by the temperature, magnetic field and applied elastic stress variations. In the last two decades, the phenomenon of the electromagnetic-acoustic transformation (EMAT) in crystalline ferromagnets has been deeply investigated, which allowed one to create extended experimental and theoretical basis that can be successfully applied to the study of amorphous alloys.

As a rule, the materials with disordered structure should not have the macroscopic unidirectional anisotropy. However, there are alloys with the uniaxial anisotropy caused by special conditions of preparation, heat treatment etc. The macroscopic magnetic anisotropy may be induced by an external magnetic field applied during both heat treatment and preparation of the sample. In the former case, the action of the external magnetic field leads to the appearance of the preferred direction in the previously isotropic ferromagnet and hence to the emergence of residual magnetization. The axis of anisotropy may lie in the plane of the film or be perpendicular to it depending on the conditions of sputtering [1]. The mechanisms of the macroscopic anisotropy appearance were explained in detail in papers [2,3]. The occurrence of the macroscopic magnetic anisotropy was attributed to the existence of the short-range order and the anisotropy of the bond orientation distribution [2] or to the appearance of a definite pseudodipole shoft-range order [3]. In addition to the induced anisotropy, in amorphous alloys there appears local magnetic anisotropy. The change in the sample shape caused by the uniaxial anisotropy (here we mean the deformation at a constant volume) results in linear magnetostriction of the amorphous ferromagnet [4].

In this work, the temperature dependences of the basic EMAT parameters in the amorphous ferromagnetic alloy Fe_{81}-$B_{13,5}$-$Si_{3,5}$-C_2 have been studied experimentally. The above mentioned parameters provide information on the dynamic magnetostriction, the elastic modulus and the internal friction. The choice of the object of investigation was due to the fact that the alloy studied belongs to the magnetostrictively active materials. In addition, the metal-metalloid alloys with doped 20 atomic percent of metalloid have the Curie point below the point of crystallization. This circumstance allows us to study the peculiarities of the EMAT in the vicinity of the Curie point when the material is in amorphous state.

To investigate the magnetoelastic and elastic properties of the amorphous alloy, the resonant EMAT technique allowing a precise estimation of the elastic responses of a ferromagnet was chosen. The essence of the resonant technique is an excitation of the standing acoustic waves by the electromagnetic field of an inductive transducer along one or other size of the sample. The specimens were narrow 5x60 mm films cutted from a 50 mkm thick foil. The foil was produced by quenching from the liquid state. For the chosen temperature range and specimen thickness, the resonances of the symmetrical s_o mode are close to the longitudinal wave velocity ($k_t d<<1$, $k_t=w/c_t$, where w is the cyclic frequency, c_t is the transverse ultrasound velocity, d is the thickness).

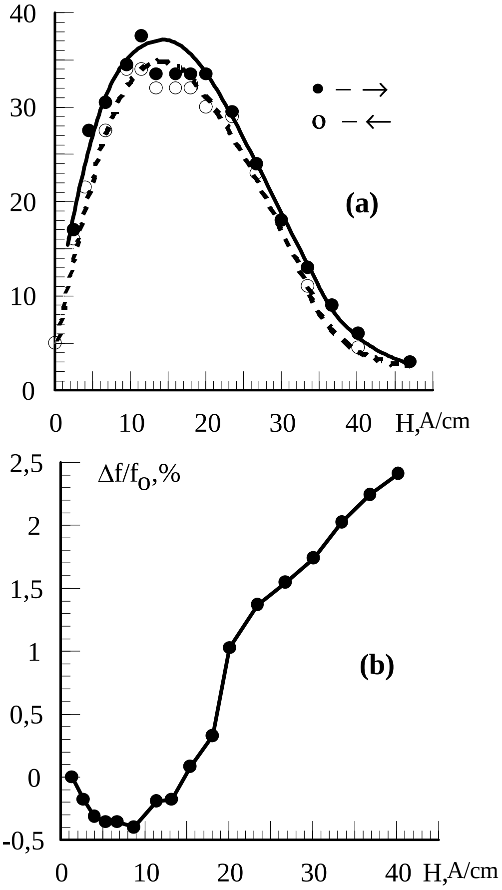

Fig.1. Field dependences of double EMAT efficiency (a) and ratio $\Delta f/f_0$(b) at room temperature.

Figure 1a shows the field dependence of the EMAT efficiency. The extremum of the dependence lies in region of weak fields because the considered alloy belongs to the magnetic-soft materials. For reference, the maximum of *e (H)* in crystalline materials is observed at a field magnitude of about 200-300 A/cm. The behavior of *e (H)* in crystalline ferromagnets is described by the expression:

$$e \sim \frac{1}{r c_l}\left(q M_o c\right)^2 h Q \ , \qquad (1)$$

where r is the density, $ñ_l$ is the velocity of the longitudinal ultrasound, q is the magnetoelastic constant, M_o is the magnetization, c is the reversible magnetic susceptibility, h is the amplitude of the alternating magnetic field, Q is the acoustic quality factor.

As the field magnitude increases, the dependence *e (H)* goes to zero, since the magnetic susceptibility tends to zero. This is a distinguishing feature of the anisotropic linear magnetostriction. For comparison, when the bulk magnetostriction of the paraprocess prevails, the field dependence of the EMAT efficiency transforms into a line which is field-independent and parallel to the x-axis [5]. This is due to the fact that the susceptibility is a constant away from the Curie point. Hence, the behavior of the alloy in the vicinity of the room temperature is characterized by the anisotropic linear magnetostriction.

It is known that the *DE* effect is observed in both crystalline and amorphous materials. Besides, its magnitude is positive in most cases, that is, the elastic modulus increases when an external magnetic field is applied. However, the negative *DE* effect in the initial stage of the magnetization process is observed in some crystalline and amorphous materials. With further magnetization the *DE* effect becomes positive. Figure 1b shows the field dependence of the ratio Df/f_o. This ratio determines the behavior of Young's modulus, since $f_o(H)\sim\sqrt{E(H)}$. The magnitude of the *DE* effect amounts to 9%, which corresponds to Df_o ~ 3%. The phenomenon of the negative *DE* effect in amorphous alloys prepared by quenching is due to the existence of a complicated domain structure. Such a structure gives rise to magnetostrictive deformation even at the zero field and hence a decrease in the elastic modulus[6].

The temperature experiments were carried out as follows: the specimens were heated from the room temperature to 360 ^{î}Ñ and then cooled. The EMAT parameters were measured at 10–20^{î}Ñ intervals. The measurements were carried out at a field H=5,4 À/ñm that corresponds to the minimum of *e (H)* at room temperature.

The temperature dependences of the considered parameters in amorphous magnetic alloys show a number of anomalies (see Fig. 2a,b,c). The curves differ substantially from similar dependences of the crystalline ferromagnets. To explain the results obtained let us consider the basic processes that occur in the amorphous alloys under heating.

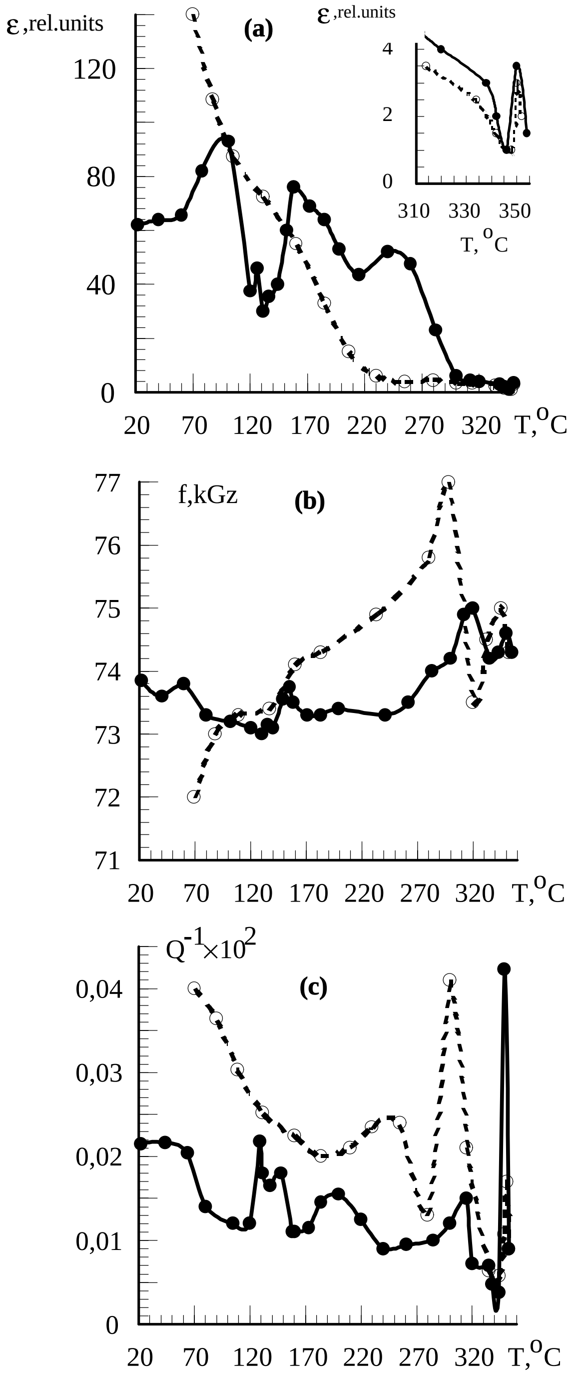

Fig.2. Temperature dependences of double EMAT efficiency (a), resonant frequency (b) and internal friction (c) in H=5,4 A/cm:• - heating; o - cooling.

First, the quenching stresses relaxation takes place during the heating of quenching-produced amorphous alloys. This process is observed at lower temperatures and falls in the category of irreversible processes. On further heating, there occur processes of structural relaxation resulting in the metastable equilibrium. As discussed in [4], in multi-component amorphous alloys such a multistage process goes on with successive formation of various types of the nearest-neighbor atomic surrounding. During the structural relaxation the internal stresses reduce, which leads to a decrease in the magnetoelastic anisotropy and to improvement of the magnetoelastic properties. The structural relaxation may both reversible and irreversible. The amorphous alloy undergoes the "ferromagnet-paramagnet" transition near the Curie point T_C =350$^{\hat{\imath}}$C. Further heating leads to the crystallization of the alloy.

Let us consider the influence of the above-mentioned processes on the EMAT parameters.

The internal stresses and their relaxation play an important part in the formation of the magnetoelastic properties. The basic kind of magnetic anisotropy in the considered magnetostrictive alloys is the magnetoelastic anisotropy. According to [7], the constant of the magnetoelastic anisotropy may be written as:

$$K_{eff}\sim k_{me}\sim l_s s_i,, \qquad (2)$$

where l_s is the magnetostriction of saturation, s_i are mechanical stresses. Substitution of the expression for the susceptibility (see [7]) $c\sim M_S^2/k_{eff}$ into Eq. (1) shows, that the dependence of the EMAT signal is inversely related to the square of the mechanical stresses. According to [4], the magnetic component of the elastic modulus is inversely proportional to the stresses: $DE/E\sim 3E_S| l_S |½s_i$, where E_S is the elastic modulus at the saturated magnetic field. Moreover, the magnetoelastic attenuation is inversely related to the internal stresses: $Q^{-1}\sim s\, l_S E/s_i^2$ too.

The processes of structural relaxation must be accompanied by significant changes of the magnetic-independent components of the elastic parameters. The growth of the material density caused by the structural relaxation must result in an increase of the elastic modulus for all amorphous alloys [4].

In the vicinity of the Curie point the EMAT parameters exhibit the following peculiarities: the EMAT efficiency and the internal friction have a sharp maximum, and the elastic modulus has a jump. All these changes are due to the isotropic magnetostriction of the paraprocess. Hence, these are magnetoelastic changes. Thus, taking account of the processes occurring in amorphous alloys under heating and of the character of their influence on the physical properties, the temperature dependences of the EMAT parameters may be explained as follows.

The maximum of the efficiency of the double EMAT is located above the room temperature (see Fig.2a). This is due to the beginning of the relaxation process that leads, according to (2), to an increase of k_{eff} and hence to an increase in the susceptibility c. Next, as $e(Ò)$ decreases, peaks of different width are observed. It may be supposed that the peak near 140^{î}Ñ is due to the relaxation of quenching stresses. A peak of the internal friction (see Fig.2c) and a small minimum of the resonant frequency (see Fig.2b) are also observed in this range. The former is caused by the decrease of $s_{i,}$ and the latter is a result of the growth of the defect of the elastic modulus of magnetoelastic nature. Since this process is irreversible, no particular anomalies of the EMAT parameters were observed on cooling. A higher-temperature maximum of $e(Ò)$ supposedly is due to the structural relaxation. It is believed that the changes in the nearest-neighbor surrounding are accompanied by an irreversible relaxation of microstresses. This is confirmed by the absence of the maximum of the EMAT efficiency in the considered range on cooling. However, the maximum of the internal friction is conserved. The changes of Q^{-1} involve both elastic and magnetoelastic components of the internal friction. Probably, the contribution from the second component dominates, because the heating was fast and the anomalies of Q^{-1} (see Fig.2c) in the range of 200-300^{î}C were retained on cooling.

The elastic modulus is growing within the considered range. The first cause of this fact is the decrease of the defect of the elastic modulus (*DE* effect) caused by magnetic saturation. The second one is the increase of the elastic component of E due to the structural relaxation.

The anomalies of the EMAT parameters are observed in the vicinity of the Curie point $Ò_{Ñ}$=350^{î}C and are similar in character to the anomalies observed in crystalline materials: the internal friction increases by an order of magnitude (see Fig.2c); e has a small maximum (see Fig.2a); there is an jump of the elastic modulus (see Fig.2b). The realization of the magnetostrictive mechanism of the EMAT above the Curie point is not possible because of the transition of the amorphous magnetic alloy into the paramagnetic state.

The quenching stresses and other kinds of mechanical stresses relax on subsequent cooling. As a result, an increase of e and Q^{-1}, and a decrease of f_r caused by the growth of the defect of the elastic modulus are observed at room temperature as compared to the original values.

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