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TEMPERATURE DEPENDENCE OF THE COERCIVE FORCE OF AMORPHOUS Fe-B ALLOYS

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In the present paper the temperature dependence of the coercive force and that of the magnetization of amorphous Fe-B alloys containing 16.3 at. % B was studied. The results are interpreted in connection with the structural state of the alloys in the initial state and with the structural change appearing in the process of sample heating. They point out the existence of the inhomogeneous stresses in the initial state of the sample and they reflect also the mechanism of the transition from the amorphous into the crystalline state, which is realized gradually by the formation of the crystalline α-Fe and by the formation and decomposition of the metastable crystalline phase Fe_3B.

ТЕМПЕРАТУРНАЯ ЗАВИСИМОСТЬ КОЭРЦИТИВНОЙ СИЛЫ В АМОРФНЫХ Fe-B СПЛАВАХ

В предлагаеммой работе была исследована температурная зависимость коэрцитивной силы, то есть и магнетизации аморфных Fe-B сплавов содержащих 16,3 атом. % В. Полученные результаты обясняются в связы со структурным состоянием сплавов в началном состоянии и со структурными изменениями имеющими место в процесе нагревания образца.

Результаты поуказивают на существование неоднородных напряжений в исходном состоянии образцов и отражают механизм аморфно-кристалической трансформации, который происходит последователно, сначала образованием кристаллического α-Fe и образованием и распадом метастабильной кристаллической фазы Fe_3B.

I. INTRODUCTION

Magnetic properties of amorphous ferromagnetic alloys reflect to a great extent their structural state. The authors of a number of papers [1—5] pointed out the connection between the structure — especially its changes — and the macroscopically measured magnetic quantities. This is particularly important also when the

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properties of amorphous Fe-B alloys are considered, at least because the transition of this alloy from the amorphous state into the crystallic state is a relatively complex one. Authors of [6] have investigated the mechanism of the crystallization of these alloys using both the results of the measurements of the temperature dependence of the magnetization and the results of the structural studies by the Mössbauer spectroscopy; they have shown that peculiarities of the crystallization process are reflected in a characteristic way on the obtained magnetization vs. temperature curves. In this work we present the results of the study of the temperature dependence of various magnetic quantities — above all of the coercive force — of the amorphous Fe-B alloys and the comparison of these results with the structural changes as described in the above mentioned paper.

II. SAMPLES AND EXPERIMENTAL METHODS

Measurements were made on amorphous samples prepared from the Fe-B alloy containing 16.3 at. % B. The samples were prepared in the Central Research Institute for Physics of the Hungarian Academy of Sciences in Budapest by the melt spinning technique providing a sufficient high cooling rate. The samples had the form of long ribbons 16 ± 0.5 μm thick and 1 mm wide. The amorphous state was checked by X-ray diffraction. The macroscopic magnetic properties of the samples were measured by the astatic magnetometer. The domain structure of the samples was investigated by the Bitter-Akulov powder technique.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Figs. 1 and 2 show the experimentally found dependence of the coercive force H_c upon the temperature T when the rate of the temperature increase was ≈ 1.7 °C/min. This rate was found to be suitable with regard to the occurring structural changes. Fig. 1 covers the temperature range from 0 °C to 400 °C, Fig. 2 covers the range from 0 °C to 800 °C. A relatively complicated dependence $H_c(T)$ reflects in a characteristic way the structural changes in the sample, caused by the temperature increase. Fig. 3 shows the temperature dependence of the remanent magnetization J_R and magnetization in the constant external magnetic field 80 A/m resp. 2400 A/m on the decreasing branch of the hysteresis loop (J_{80} resp. J_{2400}). These dependences are in a qualitative agreement with those published in [6], but they disclose also some new factors. They indicate that the transition from the amorphous into the crystalline state with the increase of the temperature in the alloy $Fe_{83.7}B_{16.3}$ is realized in two stages. At the temperature of 360 °C each of the measured magnetizations decreases to zero value. The Curie temperature of the amorphous phase determined from these dependences is ≈ 347 °C. This value is in good agreement with results of [7]. Crystallization of the alloy, which is realized in the first stage by the formation of the crystalline α-Fe [6], is observed on the coercive force at the temperature of about 390 °C (see Fig. 1). However, it must be taken into account that to observe the change of the coercive force due to the formation of crystalline α-Fe, a certain amount of this phase must be present in the alloy and this amount depends on the sensitivity of the measuring apparatus. Fig. 4 shows the dependence of the coercive force upon the annealing time of the sample at the temperature of 300 °C (the coercive force was measured after cool-down to 20 °C). After annealing for more than 60 min. an apparent increase of the coercive force can be observed. This increase should be connected with the

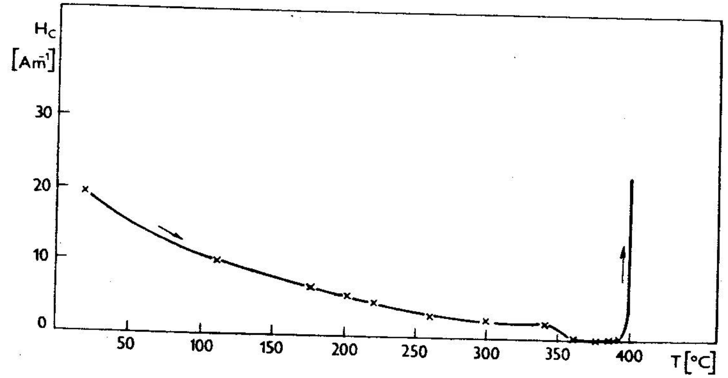

Fig. 1. Temperature dependence of the coercive force. Heating rate of the sample was ≈ 1.7 °C/min.

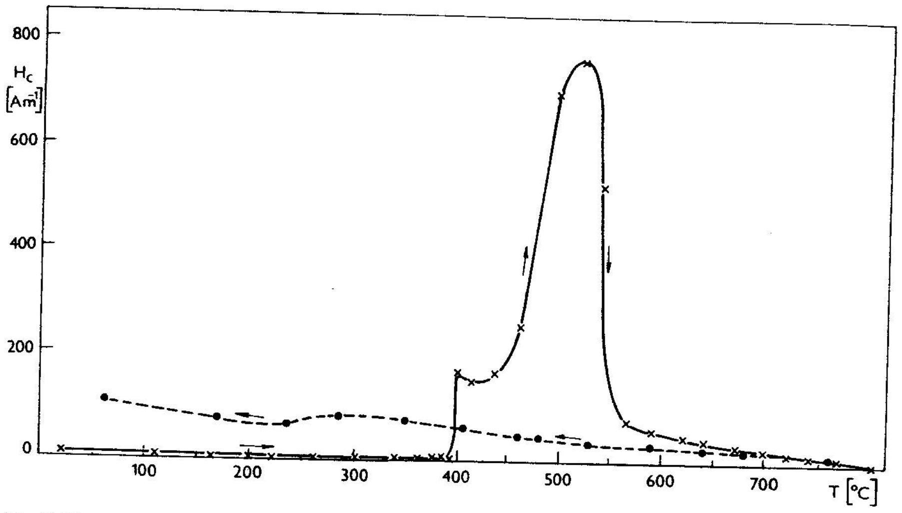

Fig. 2. Temperature dependence of the coercive force. Heating rate of the sample was ≈ 1.7 °C/min.

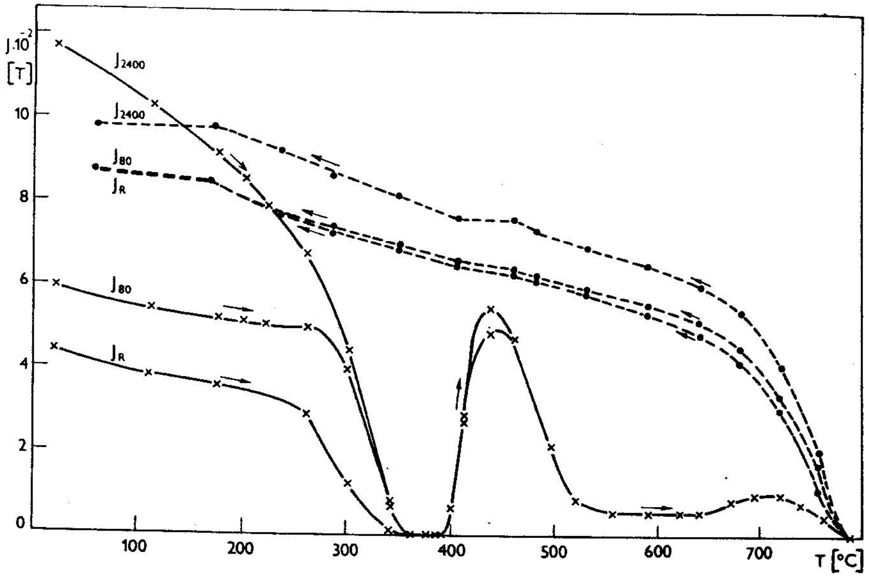

Fig. 3. Temperature dependence of the remanent magnetic polarization, magnetic polarization in the constant external magnetic field of 80 A/m (J_{80}), resp. 2400 A/m (J_{2400}), on the decreasing branch of the hysteresis loop. Heating rate of the sample was ≈ 1.7 °C/min.

structural changes influencing the irreversible magnetization processes due to domain wall displacement. The rapid increase of the coercive force is connected with the beginning of crystallization of the α-Fe during heat treatment (this crystallization is enhanced by the structural inhomogeneities in the initial state of the samples, whose existence may be reasonably assumed). This conclusion, obtained from the investigation of the coercive force, is supported also by the results of paper [8], in which the kinetics of the crystallization of Fe-B amorphous alloys was investigated by electric resistance measurements.

A further increase of magnetization values in Fig. 3 can be connected with the continuing crystallization of α-Fe and of the metastable crystalline compound Fe_3B. A decrease of the values of magnetization — after a certain maximum has been reached — should be connected with the temperature dependence of the spontaneous magnetization of this phase. (Its Curie temperature may be estimated from this diagram at about 528 °C, because the Curie temperature of α-Fe and of another compound which would be taken into account — Fe_2B — is substantially higher. Still further observed changes of the magnetization may be connected with the decomposition of the Fe_3B compound [6] into two ferromagnetic phases α-Fe and Fe_2B [9]. During this process the volume of the ferromagnetic phase with the higher Curie temperature gradually increases and due to this a maximum at the temperature of ≈710 °C appears on the measured dependences in Fig. 3. The cooldown dependences obtained for the cooling rate of about 5 °C/min indicate the presence of the metastable phase Fe_3B in the alloy (see the temperature region around 450 °C).

The described structural changes are reflected in a characteristic way on the temperature dependence of the coercive force. This dependence is significantly influenced by the following three factors: 1) presence of the inhomogeneous internal stresses in the sample, which are introduced into the material during its preparation [10] and which are responsible for the local uniaxial anisotropy caused by the interaction of these inhomogeneous stresses with the magnetostriction; 2) absence of the grain boundaries in an amorphous material, which have an important influence on the irreversible magnetization processes effected by the domain wall displacements; 3) mechanisms of the structural changes during the transition of the sample from the amorphous into the crystalline state; that is the formation, the growth and eventually the decomposition of the crystalline compounds.

On the dependence $H_c(T)$ (Fig. 1) an apparent initial decrease of the coercive force with temperature may be seen; this decrease should be connected with the relaxation of the internal inhomogeneous stresses in the sample. The existence of the stresses of this kind is indicated also by the character of the domain structure observed in the initial state of the sample (Fig. 5). The picture of the domain structure clearly shows the presence of certain stress centres. It should be noted that the investigation of the magnetic properties of crystalline materials provides

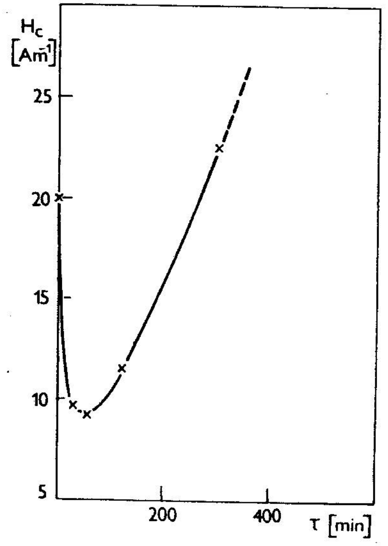

Fig. 4. Dependence of the coercive force on the annealing time at a temperature of 300 °C (the coercive force was measured after the sample had been cooled down to 20 °C).

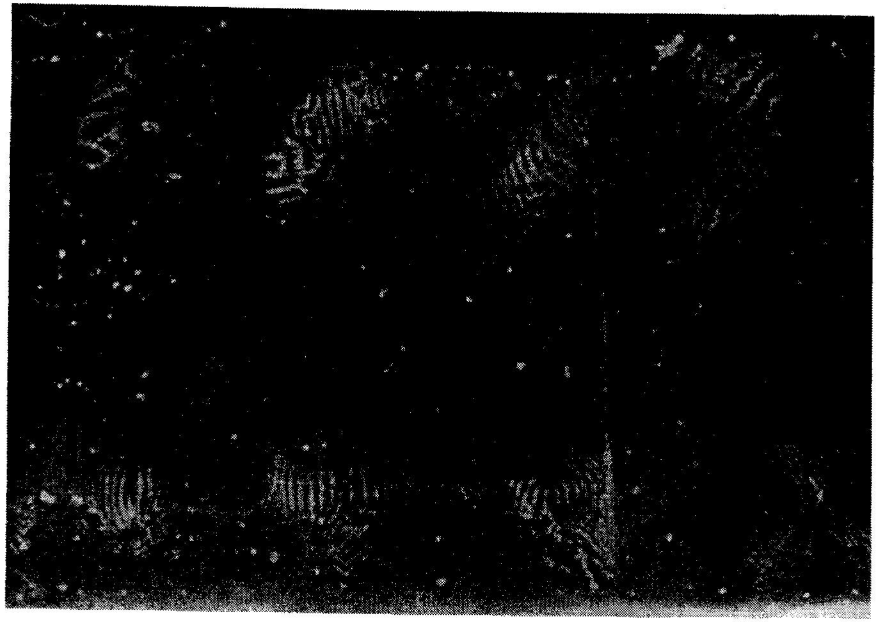

Fig. 5. Domain structure in the initial state of the sample.

qualitatively the same dependence of the coercive force on the internal stresses as that observed on the investigated amorphous samples (e.g. [11]).

The continuing considerable increase of the coercive force should be connected with the formation of the crystalline phase α-Fe (due to the formation of the grain boundaries) accompanied at higher temperatures with the formation of the metastable compound Fe_3B. In crystalline ferromagnets there is a known connection — in some cases — between the coercive force and the size of inclusions present in the material [12, 13]. It seems that an analogous coupling will be present also in the amorphous ferromagnets, which is indicated also by the dependence of $H_c(T)$ in the temperature range 460—560 °C. Even when the phase Fe_3B is ferromagnetic and its magnetization disappears at the temperature of about 528 °C, particles of this compound still form an obstruction for the domain wall movement. It should be taken into account that the coercive force will depend not only on the size of the particles, but also on their coupling with the surroundings [14, 15].

Decomposition of the compound Fe_3B with increasing temperature (into two phases α-Fe and Fe_2B) contributes further to the apparent decrease of the coercive force. The coercive force attains zero values when the ferromagnetic state of the crystalline phase α-Fe and Fe_2B disappears.

The coercive force increases with the decrease of the temperature; its course is influenced by the extent which the structural state determined by the equilibrium diagram Fe-B has attained while the maximum temperature is maintained and is also connected with the temperature dependence of the spontaneous magnetization of the present phase, respectively with the temperature dependence of their magnetocrystalline anisotropy and with other structural characteristics.

The observed mechanism of crystallization of the amorphous alloy Fe-B [6], confronted with the results of measurement of the macroscopic magnetic quantities, suggests that the alloy structure in the initial state is inhomogeneous. When at an increasing temperature α-Fe crystallizes as the first from the amorphous state, there will probably be regions with higher contents of boron in the alloy in its initial state. These regions are the potential nuclei for the later crystallization of the Fe_3B phase (or, in some cases, Fe_2B). The existence of such structural inhomogeneities is known also from the study of other amorphous systems, for example Pd-Si-Co, Pd-Si-Fe [1—3]: in the alloy $Fe_{40}N_{40}P_{14}B_6$, for example, the formation of regions rich in phosphorus, resp. boron is expected [4, 5].

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