ATLANTIS PRESS
Advances in Engineering, volume 100
International Conference on Manufacturing Engineering and Intelligent Materials (ICMEIM 2017)

Effects of Annealing on Magnetic Properties of Amorphous and Nano crystal line $(Fe_{0.5}Co_{0.5})_{73.5}Cu_1Nb_3Si_{13.5}B_9$ Wires

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Keywords: Amorphous and Nanocrystalline Wire, Thermal Treatment, Permeability Spectrum.

Abstract. Amorphous $(Fe_{0.5}Co_{0.5})_{73.5}Cu_1Nb_3Si_{13.5}B_9$ wires were submitted to the thermal treatment of Joule-heating at current (j_a = 26 - 45.5 A/mm^2) and time（t = 20 - 600 s）. The effects of annealing on the magnetic properties has been investigated in order to improve the soft magnetic properties by the measurements of longitudinal hysteresis loop and the circular permeability, $\mu = \mu' - j\mu''$, determined from the measurements of impedance, $Z = R + jX$, as functions of frequency (f = 10 - 10^5 Hz). We found that the most outstanding soft magnetic properties were observed in samples annealed at j_a = 32 - 36 A/mm^2 for 20 s due to the nanocrystallization. On the other hand, all samples exhibit the relaxation-type feature of permeability spectrum. In addition, from the changes of circular permeability with the annealing time, we can conclude that the optimum annealing condition to acquire best magnetic soft properties is a longer or a shorter time for the amorphous or the nanocrystalline alloy, respectively.

Introduction

Fe-based amorphous and nanocrystalline alloys have been one of the most attractive topics in studying of soft magnetic materials. Compared with the traditional Si-steel or soft ferrite, these alloys exhibit good stability due to higher Curie temperature and lower energy loss as well as superior soft magnetic properties such as high permeability, low coercivity[1-3]. Especially, the substitution of Co for Fe in the Finemet alloys can elevate largely the Curie temperature above 150^{o}C, so it has been the candidate in the application of high temperature and high frequency[4,5]. Magnetic spectrum refers to the frequency-dependence of AC permeability from domain wall displacements at low field region. Generally, there are two kinds of domain wall resonance (DWR): the type of resonance and the one of relaxation corresponding to the case of small or large damping factor, respectively. Therefore, the complex permeability spectrum can properly demonstrate the feature of AC magnetic properties of the materials. In this work, we'll report the effects of Joule-heating on the DC and AC magnetic properties of $(Fe_{0.5}Co_{0.5})_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy.

Experiments

Amorphous (Fe0.5Co0.5)73.5Cu1Nb3Si13.5B9 wire with diameter 2r0 = 0.14 mm was produced by in-rotating-water quenching technique. Some pieces of samples (15 cm in length) were cut for heat treatment. The samples were annealed by different DC current (ja = 26 - 45.5 A/mm2) for 20 s in air. In addition, two series of samples were treated by ja = 29.2 and 35.7 A/mm2, respectively, at the range of t = 20 - 600 s in order to study the annealing-time effects. Longitudinal hysteresis M(H) loop was measured by a system of flux-meter with a searching coil and a solenoid ((2 cm and 60 cm in length, respectively) under the control of a computer. As for the measurements of circular permeability, an Agilent LCR meter was used to measure the impedance Z = R + jX =R + jωL. The AC frequency used for the measurements was in range of f = 1 kHz - 2 MHz. The complex circular permeability, μ = μ′- jμ″, was derived from[6], μ′= 8πX/ωl and μ″= 8π(R - RDC)/ωl, where RDC, the DC resistance, l = 10 cm, the length of the measured segment of the sample.

Results and Discussion

The evolutions of low-field cocervity, H_C, determined from the measured longitudinal hysteresis $M(H)$ loop, and DC circular permeability, μ_{DC}/μ_0, deduced by $\mu_{DC} = \mu'(f \rightarrow 0)$, with the annealing current, j_a, are plotted in Fig. 1. With increasing j_a, H_C decreases from 5 A/m of as-cast sample to a minimum value of 0.5 A/m at j_a = 32 - 36 A/mm^2 and then increases rapidly with elevated j_a. In contrast, μ_{DC}/μ_0 exhibits the opposite trend. This change can be understood by considering the process of nano-crystallization at j_a = 32 - 36 A/mm^2. The large crystal-grains produced at about j_a > 40 A/mm^2 result in the enhancement of H_C.

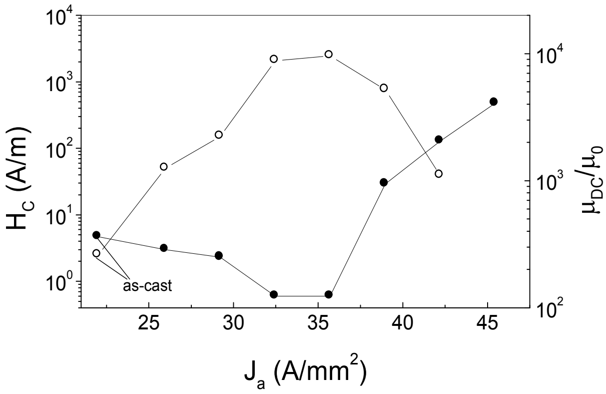

Figure 1 Annealing current j_a dependences of the cocervity H_C and circular permeability μ_{DC}/μ_0.

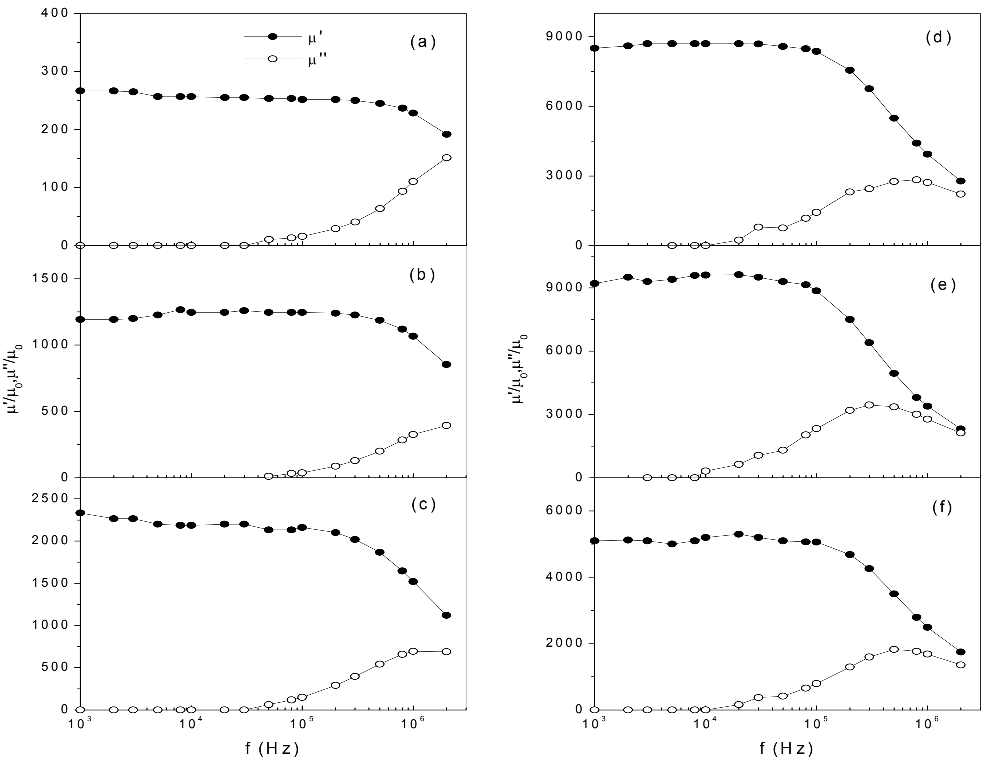

Figure 2 The evolution of magnetic spectra with the annealing current

j_a = 0 (a), 26 (b), 29.2 (c), 32.5 (d), 35.7 (e) and 39 A/mm^2 (f).

The evolution of magnetic spectra with the current j_a = 0 – 39 A/mm^2, is shown in Fig. 2. The spectra of all samples show the relaxational feature: from a plateau at low f to a monotonous decrease at higher f of μ, and a increase at low f and then a decrease at high f of μ''. Theoretically, the relaxation frequency f_τ is defined as the value where the maximum of μ'' occurs[7]. With increasing j_a, the relaxation frequency f_τ decrease monotonously, meanwhile the real part μ' increase from 270 of as-cast sample to 9200 of the best nanocrystalline sample (j_a = 35.7 A/mm^2) and then reduce to 5000 of the sample(j_a = 39 A/mm^2). The evolutions of magnetic spectra with the annealing time (t =20 - 600 s) for current j_a = 29.2 and 35.7 A/mm^2 are shown in Fig. 3. The relaxational feature is remained for all samples.

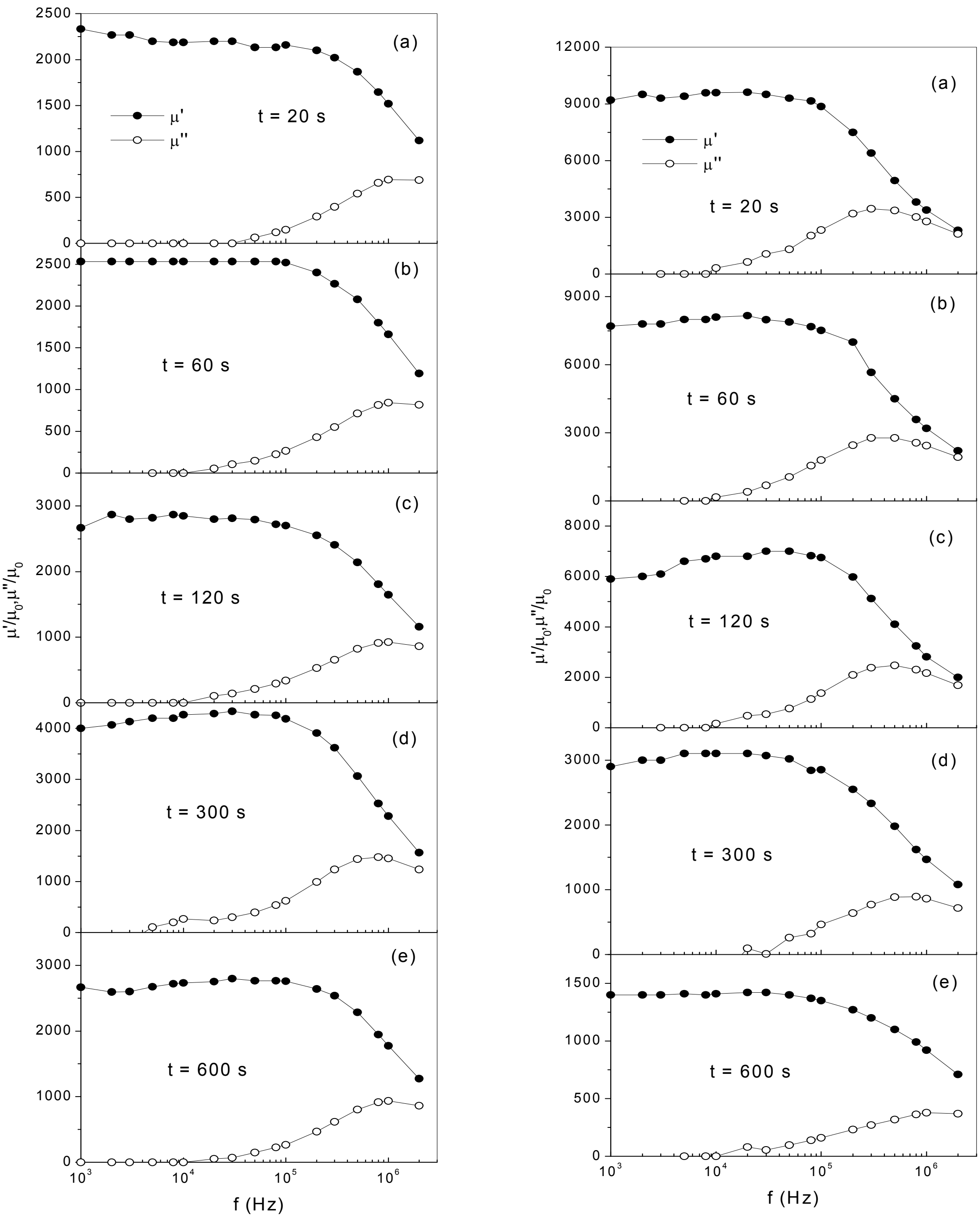

Figure 3 The evolution of magnetic spectra with the annealing time t

for current j_a = 29.2 A/mm^2(left) and j_a = 35.7 A/mm^2 (right)

For j_a = 29.2 A/mm^2, with increasing t, the real part of AC permeability increase gradually from 2200 to 4100, then reduce to 2700. It indicates that a proper longer time for a small annealing current is helpful to improve the soft magnetic properties. From Fig. 1 we see that the wires annealed at j_a = 29.2 A/mm^2 remain in amorphous state, so a longer time may result in the further relief of internal stress or in the nanocrystallization in the sample. For j_a = 35.7 A/mm^2, with increasing *t*, the real part of complex permeability exhibits a monotonous decrease from 9200 to 1300, while the relaxation frequency increases gradually. This result indicates that a shorter time is advantageous to get a good soft magnetic alloy. The samples anneald at j_a = 35.7 A/mm^2 consist of nanocrystalline and residual amorphous phases. According to the exchange coupled theory, the coecivity is proportional to D^6, *D* the grain-sized[1]. Therefore, the deterioration of soft magnetic property with longer time can be ascribed to the grow up of the nano-particles.

Conclusions

In conclusions, the most outstanding magnetic soft properties have been observed in the samples annealed at ja = 32 - 36 A/mm2 for 20 s due to the nanocrystallization. All samples exhibit the relaxation-type feature of permeability spectrum. The optimum annealing condition to acquire best magnetic soft properties is a longer or a shorter time for the amorphous or the nanocrystalline alloy, respectively.

Acknowledgement

This work has been supported by the Project of Scientific Research Plan of Education Bureau of Hebei Province of Reference No. ZD2015201.

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