

Effect of Tensile Stress on the Soft Magnetic Properties of Nanocrystalline Magnetci Core

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Abstract

In the study, amorphous alloy thin strips were prepared by Fe_{73.5}Cu₁Nb₃Si_{13.5}B₉ single-roll fast quenching, continuous fast tensile stress annealing was conducted under nitrogen-protected atmosphere, and then it was fabricated by coiling to form Nanocrystalline toroidal cores. The DC and AC magnetization characteristics of the nanocrystalline core specimens were examined using a TD8220-A DC tester and a TD8120 AC tester to investigate the effect of tensile stress on the soft magnetic properties of the nanocrystalline magnetci core. The results show that tensile stress annealing leads to the degradation of soft magnetic properties of nanocrystalline magnetci core, and the loss decreases with the increase of annealing tensile stress, and decreases by more than 42% at high frequency (200000Hz) compared with free annealed nanocrystalline magnetci core, showing good high frequency magnetization properties. The study is a guideline for optimizing the high-frequency magnetic properties of nanocrystalline magnetci core.

Keywords

Stress Annealing; Nanocrystalline Magnetci Core; DC Characteristics; AC Characteristics.

1. Introduction

In the late 1980s, a new class of Fe-based alloys showing excellent soft magnetic properties was first reported by Yoshizawa [1,2] et al. of Hitachi Metals, Japan, with the composition of Fe_{73.5}Cu₁Nb₃Si_{13.5}B₉, under the trade name "FINEMET". Based on amorphous alloys, nanocrystalline soft magnetic alloys (FINEMET) have been developed by crystallization. The outstanding advantage of these alloys is that they combine the high magnetic susceptibility of iron-based amorphous alloys with the high permeability and low loss of cobalt-based amorphous alloys, and are inexpensive iron-based materials, for which a lot of research has been done in theory and application. Finemet alloys [3,4] have excellent soft magnetic properties such as high permeability, low coercivity, high electrical conductivity, and low loss, and have a broad application prospect in many soft magnetic electronic devices such as magnetic cores [5], mutual inductors, transformers, switching power supplies, and motors [6]. With the continuous development of electronic technology and the advancement of active devices, the size and weight of electronic products have been greatly

reduced, which has driven the development of amorphous soft magnetic devices in the direction of light, thin and small [7]. However, the current process of making amorphous soft magnetic devices needs to further improve its effectiveness, and the effectiveness improvement depends on the exploration of heat treatment process. For new energy vehicles, one of the most important bottlenecks that need to be broken in the development is the problem of charging piles. To further promote fast charging and make charging more convenient [8], is an important development task at present. The requires the search for cores that can resist high currents, the lower the loss the better, and such materials are more suitable for making cores with high current resistance. Stress annealing can effectively reduce the remanent B_r of the material and obtain a flat hysteresis return with much lower losses. In the paper, a new and self-developed continuous annealing device is used to stress anneal Fe based amorphous thin strips [9-11] with different stresses to make stress annealed cores. The DC soft magnetic properties and AC soft magnetic properties of the stress-annealed cores were tested, and the effects of different stresses on their magnetic properties were investigated.

2. Experiments

2.1 Preparation of Nanocrystalline Magnetic Cores

The sample used in the experiment is Febased alloy thin strip ($Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$), which is prepared by single roll fast quenching method with a width of 3.2 mm and a thickness of 15 μm . The experiment is carried out with a self-developed iron-based amorphous thin strip heat treatment device, which allows thin strips with width less than 4 mm and thickness $25 \pm 5 \mu m$ to pass through. The annealing is carried out by means of a single alloy strip moving continuously through the furnace chamber, the movement process can apply axial stress to the amorphous strip, the stress size is continuously adjustable, the amorphous alloy thin strip is driven by The thin strip of amorphous alloy is wound on the active wheel after passing horizontally through the annealing furnace by the driven wheel and driven by the stepping motor on the active wheel to rotate the active wheel so as to drive the thin strip of amorphous alloy through the annealing furnace and complete the annealing.

The experiment was conducted in a nitrogen atmosphere at an annealing temperature of $540^\circ C$ with an applied stress of 0-80.16 MPa and a strip travel speed of 7 cm/min. The circumference of the active wheel is 63 cm, the active wheel rotates 6. The nanocrystalline thin strip obtained by circle annealing can make a stress annealed core, the annealed nanocrystalline thin strip is wound on an iron ring mold, the nanocrystalline thin strip ports are welded with an amorphous nanocrystalline metal welder, and then the ring core sample is slowly removed from the iron ring mold, the ring core The sample masses were all controlled at 1.15 g, inner diameter of 18 mm and outer diameter of 20 mm. In the experiment, the epoxy resin curing agent AB glue is modulated according to the ratio of 10:3, and the completed annealed cores are put into the blended epoxy resin curing agent and soaked under vacuum, soaked for a certain period of time, the curing agent enters the cores to make them completely immersed in paint, and then no more gas is discharged from the curing agent to end the immersion paint, and then the cores are taken out of the immersion paint and placed in a constant temperature blast drying oven for $100^\circ C$ Drying for 1 hour, the dried cores will be placed in the lab at the vent to air dry.

2.2 Performance Test

The DC soft magnetic properties of the sample were tested under $H_m=6000 A/m$ environment by using the Tianheng measurement and control TD8220-A soft magnetic DC test system. magnetic permeability. The AC soft magnetic properties of the samples were tested with the Tianheng TD8120 soft magnetic AC test system. Under the environment of $B_m=0.2 T$, the frequencies were taken as $f=1 kHz, 2 kHz, 5 kHz, 10 kHz, 20 kHz, 40 kHz, 60 kHz, 80 kHz, 100 kHz, 120 kHz, 140 kHz, 160 kHz, 180 kHz$ and $200 kHz$, and the P_{cm} -curve, P_{cv} -curve.

3. Results and Discussion

3.1 Effect of Tensile Stress on the DC Soft Magnetic Properties of Nanocrystalline Magneti Core

Figure 1. shows the DC hysteresis loop measured for the stress-annealed sample at 540°C. The force applied during temperature annealing is 0-80.16 MPa, and the protective gas introduced during annealing is nitrogen. The curves in Figure 1. show the DC hysteresis lines of the ring core samples annealed at 540°C with different stresses applied respectively, Table 1. DC test results of Fe based alloy core samples, The stresses applied during annealing have a large effect on the cores, with the applied stresses increases, the slope of the hysteresis line decreases in order and the permeability decreases in order; each anisotropic field increases in order. The stress applied during the annealing process has a large effect on the saturation magnetic induction strength of the core, which decreases sequentially with the increase of the tensile stress.

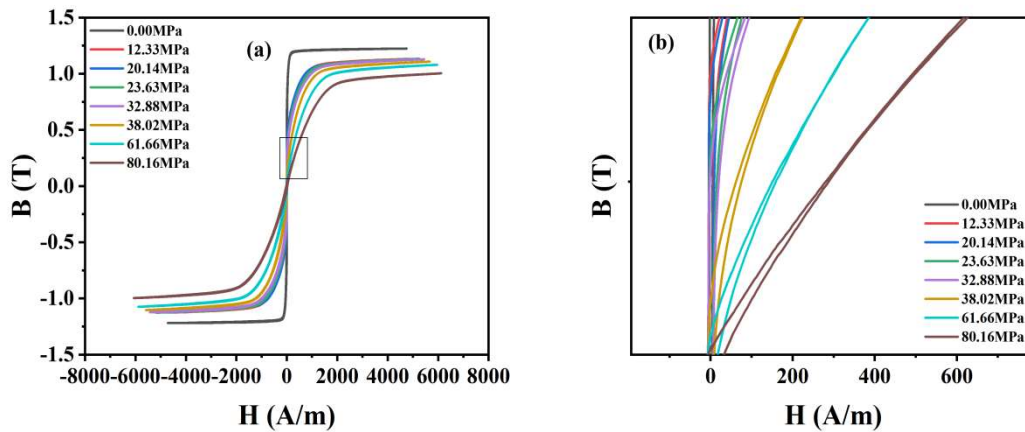


Figure 1. (a) DC hysteresis line diagram of the Fe based alloy core sample. (b) Enlarged view of the box in Figure (a)

Table 1. DC test results of Fe based alloy core samples

σ (MPa)	B_s (T)	B_r (T)	H_c (A/m)	μ_i (mH/m)	μ_{max} (mH/m)
0.00MPa	1.20	0.52	3.96	27.13	85.32
12.33 MPa	1.18	0.47	4.45	3.04	54.23
19.52 MPa	1.16	0.42	4.89	3.13	36.36
20.14 MPa	1.15	0.37	5.27	3.14	39.52
22.61 MPa	1.13	0.33	5.59	2.62	33.02
23.63 MPa	1.12	0.28	5.86	2.99	24.93
26.72 MPa	1.12	0.24	6.07	2.30	18.15
32.88MPa	1.12	0.21	6.13	2.65	15.36
35.96 MPa	1.12	0.17	6.23	2.35	11.05
38.02 MPa	1.11	0.14	6.28	2.03	5.90
46.24 MPa	1.10	0.10	6.30	1.78	4.84
54.46MPa	1.08	0.07	6.28	1.50	3.86
61.66 MPa	1.07	0.03	6.22	1.39	2.48
80.16 MPa	1.06	0.00	6.12	0.85	0.82

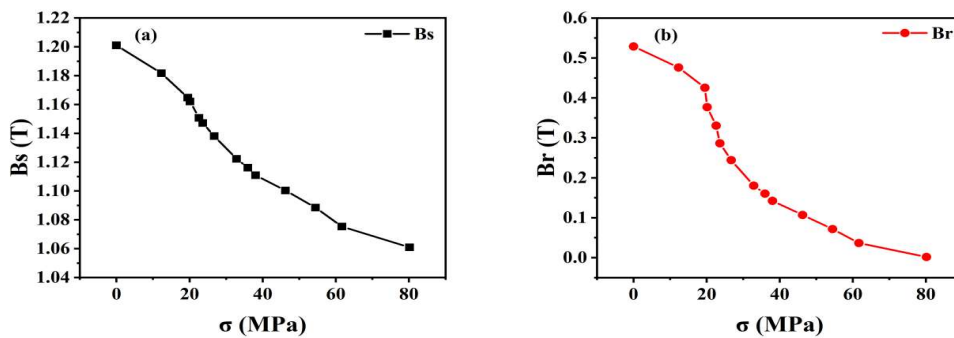


Figure 2. (a) Plot of saturation magnetic induction strength B_s versus stress for Febased alloy core sample;(b) Residual magnetization strength B_r versus stress for Febased alloy core sample(b)

Figure 2 (a) shows the DC saturation magnetic induction strength B_s versus stress for the Fe based alloy core sample, the stress applied during the annealing process has an effect on the saturation magnetic induction strength of the core, which shows a decreasing trend with the increase in tensile stress. The saturation magnetic induction strength B_s of the 80.16 MPa sample (540°C stress annealed) is 1.06087T, 11.6% lower compared to the 540°C free annealed sample (0 MPa sample). Figure 2. (b) shows the DC residual magnetization strength B_r versus stress for the Fe based alloy core samples, with increasing tensile stress, the residual magnetization strength shows a decreasing trend. 80.16 MPa sample (540°C stress annealed) has a residual magnetization strength B_r of 0.00175T, shows a 63.6% decrease compared to 540°C free annealed sample.

Figure 3 (a) shows the DC starting permeability μ_i versus stress for the Febased alloy core sample with μ_i of 27.1379 mH/m for the 540°C free annealed sample. Chapman fit to the data points in the graph, it can be seen that the DC onset permeability μ_i of the Fe based alloy core sample decreases exponentially with the increase in applied stress as shown in the relationship equation (1):

$$\mu_i = a \cdot (1 - e^{-b\sigma})^c \quad (1)$$

where: σ is the applied stress; a is 0.01561; b is 1.85342E-6; c is - 0.50996.

Figure 3 (b) shows the maximum permeability μ_{max} versus stress for the Fe based alloy core sample in the range of 0-38.02 MPa, μ_{max} decreases rapidly, with μ_{max} of 5.90742 mH/m for the 38.02 MPa sample, a decrease of 93.1 % compared to the 540°C free annealed sample. In the range of 38.02-80.16 MPa, μ_{max} decreases slowly, and μ_{max} for the 80.16 MPa sample is 0.82952 mH/m, which is 99.1% lower than that of the 540°C free annealed sample. 99.02% decrease compared to the freely annealed sample.

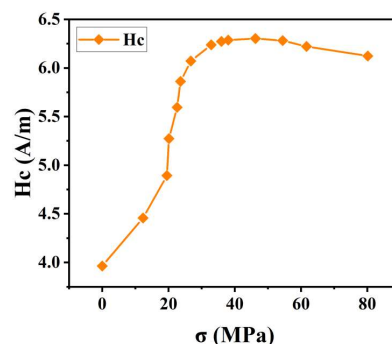


Figure 3. Coercivity H_c versus stress for the Fe based alloy core sample

Figure 3 shows the DC coercivity H_c versus stress for the Fe based alloy core sample. The DC coercivity shows an increasing trend with the increase of tensile stress in the range of 0-46.24 MPa. The DC coercivity of the 46.24 MPa sample is 6.30271 A/m, which is 58.9% higher compared to the 540°C free annealed sample. In the range of 46.24-80.16 MPa, shows a decreasing trend of DC coercivity with increasing tensile stress. The DC coercivity of 80.16 MPa sample is 6.12251 A/m, which is 2.8% lower compared to 46.24 sample.

3.2 Effect of Tensile Stress on the AC Soft Magnetic Properties of Nanocrystalline Magnetci Core

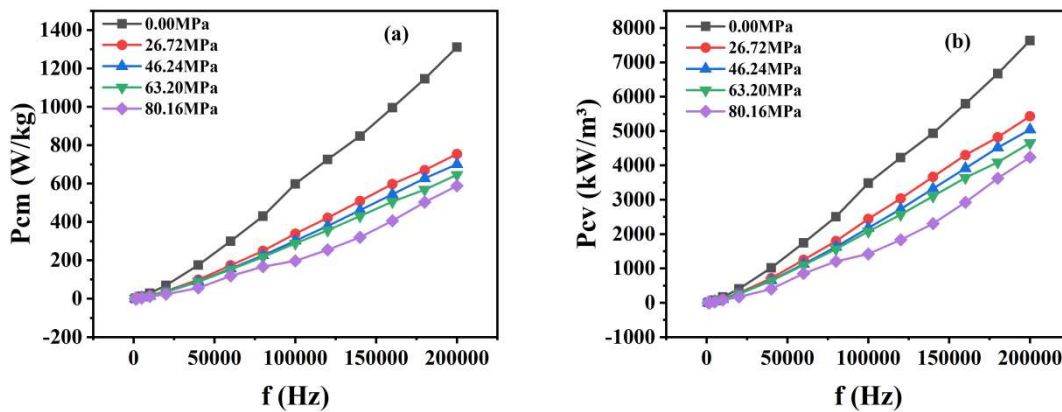


Figure 4. Frequency characteristics curve of P_{cm} loss per unit mass after annealing of Fe based alloy core samples (a). Frequency characteristic curve of unit volume loss P_{cv} of Fe based alloy core sample after annealing (b)

Figure 4(a) shows the frequency characteristic curves of the loss per unit mass P_{cm} of the Fe based alloy core sample after annealing. From the figure, it can be seen that the loss P_{cm} of the stress annealed core is lower than that of the free annealed core, indicating that the stress applied during the temperature annealing process has a significant effect on reducing the loss of the core. With the increase of the applied stress, the loss P_{cm} of the sample after annealing decreases; at $f=1\text{kHz}-200\text{kHz}$, the loss of the Fe based alloy core sample increases with the increase of frequency. The high frequency characteristics of the samples are obvious, and the P_{cm} of the stress annealed sample decreases significantly at 200000Hz, and the loss P_{cm} of the 26.72 MPa sample is 42.5% lower than that of the free annealed one.

Figure 4(b) shows the frequency characteristic curves of loss P_{cv} per unit volume of Fe based alloy core sample after annealing, from which it can be seen that the loss P_{cv} of stress annealed cores is lower than that of free annealed ones, indicating that the stress applied during temperature annealing has a significant effect on reducing the loss of cores. With the increase of the applied stress, the loss P_{cv} of the core sample after annealing decreases; at $f=1\text{kHz}-200\text{kHz}$, the loss of the Fe based alloy core sample increases with the increase of frequency. The high frequency characteristics of the sample are obvious, and the P_{cm} of the stress annealed sample decreases significantly at 200000Hz. Figure 9 shows the loss versus annealing stress curve for the Fe based alloy core sample at 200000Hz, as shown in the figure, tensile stress annealing leads to the decrease of soft magnetic properties of nanocrystalline magnetci core, and the loss decreases with the increase of annealing tensile stress. The loss P_{cv} of the 80.16 MPa sample is 44.4% lower than that of the freely annealed one, and the loss P_{cm} of the 80.16 MPa sample is 55.2% lower than that of the freely annealed one, exhibiting good magnetization characteristics at high frequencies.

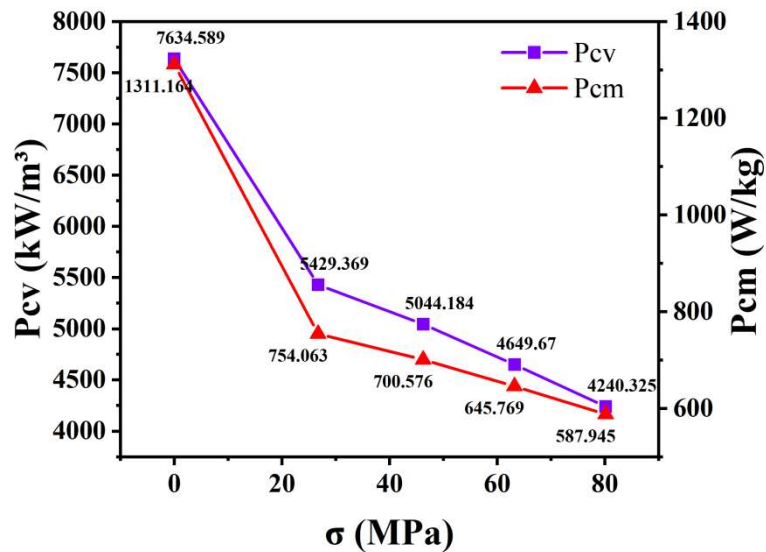


Figure 5. Loss vs. annealed stress curve for Fe based alloy core samples at 200000Hz

4. Conclusion

Based on continuous rapid tensile stress annealing, the effects of annealing tensile stress on the soft magnetic properties of Fe based alloy nanocrystalline magnetci core were investigated as follows.

(1) The tensile stress annealing leads to a significant decrease in the permeability, saturation magnetic induction strength and residual magnetic induction strength of nanocrystalline magnetci core, while the coercivity shows different stress response characteristics, which increases rapidly with annealing tensile stress at $\sigma < 46.24$ MPa and decreases slowly at $\sigma > 46.24$ MPa.

(2) The core loss decreases significantly with the increase of annealing tensile stress, especially under high frequency excitation, showing a good advantage of high frequency loss.

Therefore, tensile stress annealing can modulate and optimize the soft magnetic properties of nanocrystalline magnetci core to meet the requirements of different industrial applications.

Acknowledgments

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