

# Effect of Continuous DC Longitudinal Magnetic Field Heat Treatment on Soft Magnetic Properties of $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$ Amorphous Cores

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**Abstract.** The effect of continuous DC longitudinal magnetic field heat treatment on soft magnetic properties of  $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$  amorphous cores was studied. The results showed that comparing with the amorphous cores without magnetic field heat treatment, the permeability increases and the coercivity decreases after the longitudinal magnetic field heat treatment. At the same time, the rectangular ratio  $B_r/B_m$  of the amorphous cores increases from 0.58 to 0.94, and the rectangular hysteresis loop is obtained, the loss value of  $P_s$  the amorphous cores is significantly reduced at low frequency, while it is almost the same at the high frequency. At  $f=50\text{Hz}$  and  $B_m=1.3\text{T}$ , the loss value of  $P_s$  is  $0.278\text{W/kg}$  in the heat treatment without magnetic field, and the loss value of  $P_s$  was  $0.153\text{W/kg}$  in the longitudinal magnetic field heat treatment, which was 44.9% lower than that of heat treatment without magnetic field. The effect of structural relaxation on magnetic properties of the magnetic cores in longitudinal magnetic heat treatment is not significant, and the magnetic properties exhibit good stability.

## 1. Introduction

$\text{FeSiB}$  amorphous alloy is widely used in the preparation of distribution transformer cores owing to excellent soft magnetic properties [1-3]. It can greatly reduce the no-load loss and no-load current of the transformers [4-5]. With the advancement of energy saving and consumption reduction in power grid work, amorphous alloy distribution transformers will be widely promoted and applied.

Amorphous alloy transformer cores are firstly annealed under the protection of nitrogen, and then in longitudinal magnetic field with the flowing nitrogen atmosphere, which is called "two-step heat treatment" [6-7]. The so-called longitudinal magnetic field heat treatment refers to the large magnetic field which is applied in the same direction as the actual magnetic flux of the magnetic cores during the heat treatment. It can be used to increase the rectangular ratio of the magnetic cores. However, the two-step heat treatment not only consumes large energy and time, but also damages the magnetic cores due to transfer of large mass core.

In this paper, the two-step heat treatment method is improved with the combination of two heat treatment steps. At the same time, the magnetic field is changed into DC longitudinal magnetic field, which is applied to the whole process of magnetic core heat treatment. This paper mainly studies the soft magnetic properties of the amorphous cores under the DC longitudinal magnetic field heat treatment, and it also evaluates the application value of the magnetic core.

## 2. Experimental

$\text{Fe}_{78}\text{Si}_9\text{B}_{13}$  amorphous alloy strip with bright and clean surface was prepared by single roll rapid quenching method, the width is  $50\pm 0.2\text{ mm}$  and the thickness is  $27\pm 0.2\mu\text{m}$ . The amorphous alloy strip



is made into a ring amorphous core with an outer diameter of 100mm and an inner diameter of 60mm by using a belt winding machine.  $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$  amorphous cores were subsequently heat treated at  $380^\circ\text{C}$  for 90min in nitrogen gas atmosphere. Heat treatment is in two ways: one is the heat-treatment without magnetic field in nitrogen gas atmosphere (short for "heat treatment without magnetic field"); the other is the longitudinal magnetic field heat treatment that the magnetic field is 800 A/m in nitrogen gas atmosphere (short for "longitudinal magnetic field heat treatment").

The phase structure of  $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$  amorphous alloy strip was analyzed by X-ray diffraction (XRD, Bruker D8 Advance) with  $\text{Cu-K}\alpha$  radiation at 40Kv and 40mA. The microstructure of amorphous alloy strip was observed by 3D-microscopy with large depth of field (VHX-100). The soft magnetic properties of the  $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$  amorphous cores were measured by MATS-2010SD test device.

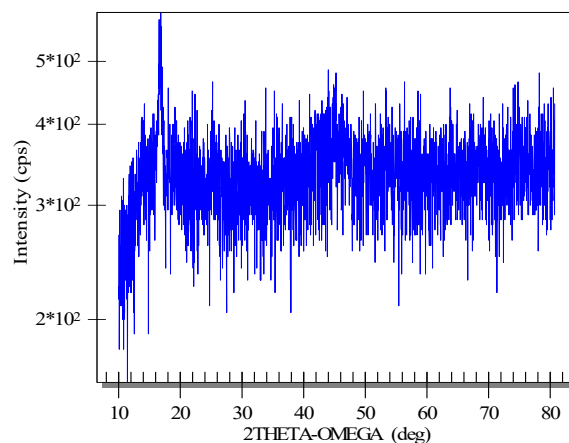
**Table.1** Chemical composition of amorphous alloy strip

Chemical element	Fe	Si	B	C	S
Content(mass fraction) /%	91.14	4.98	2.92	0.085	0.011

### 3. Results and discussion

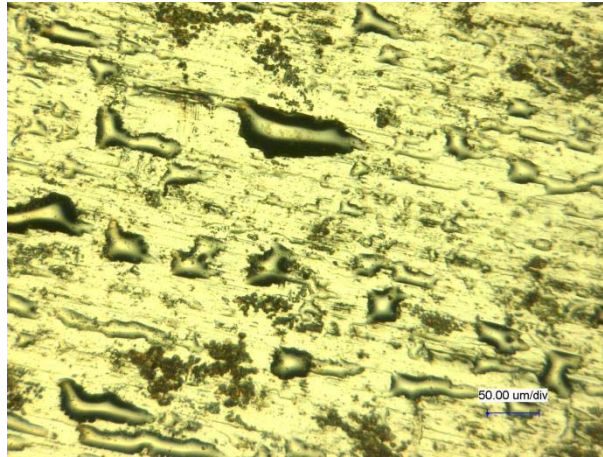
#### 3.1 Structural analysis of $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$ amorphous alloy strip

Fig.1 shows the XRD pattern of the  $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$  amorphous alloy strip. From the XRD results of the  $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$  amorphous alloy strip, the diffraction peak is a diffuse peak and there is no sharp diffraction peak corresponding to the crystal, which showed that the  $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$  alloy strip is amorphous structure.



**Fig.1** XRD pattern of the  $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$  amorphous alloy strip

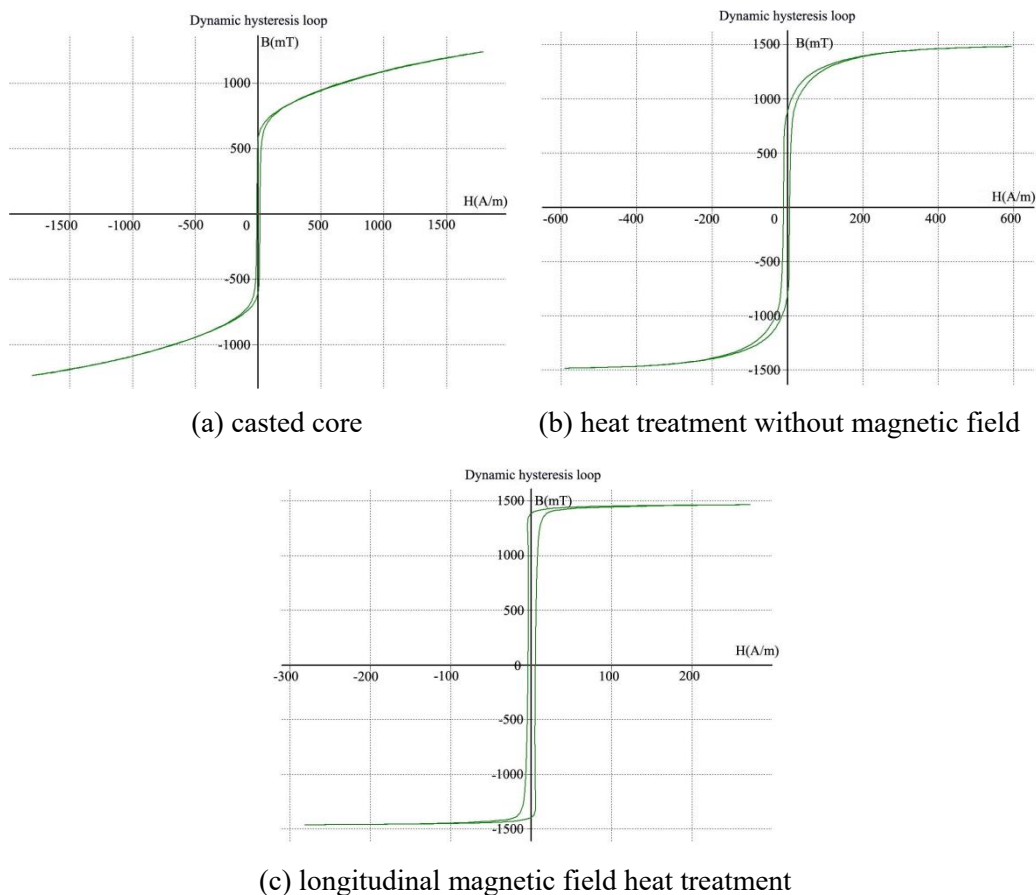
The microstructure of amorphous alloy strip is shown in figure 2. We can see that a small amount of pores, impurities and pits on the surface of the amorphous alloy strip.



**Fig.2** Microstructure of the  $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$  alloy strip

### 3.2 The effect of longitudinal magnetic field heat treatment on the soft magnetic properties of the amorphous cores

Figure 3 shows the dynamic hysteresis loop of the amorphous cores in the different states at  $f=50\text{Hz}$ .



**Fig.3** The dynamic hysteresis loop of the amorphous cores in different state ( $f=50\text{Hz}$ )

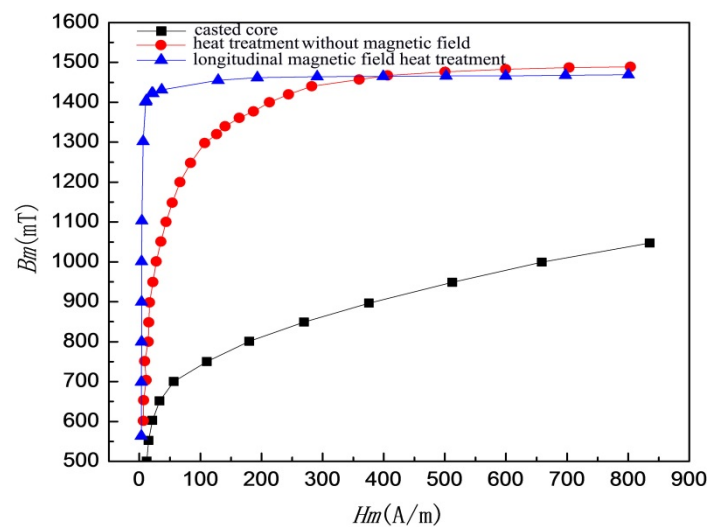
It can be seen from Fig.3 (a), (b) and (c) that the amorphous cores are more easily saturated after heat treatment. When  $H_m=800\text{ A/m}$ , the magnetic induction  $B_m$  of the amorphous cores that in casted core, heat treatment without magnetic field and longitudinal magnetic field heat treatment is 1.04, 1.48 and 1.47, respectively. This is mainly due to the stress caused by the rapid cooling and winding of the

amorphous cores is removed after heat treatment, which makes it easier to magnetize and obtain good magnetic properties. The magnetic parameters of the amorphous cores in different states are given by Table 2.

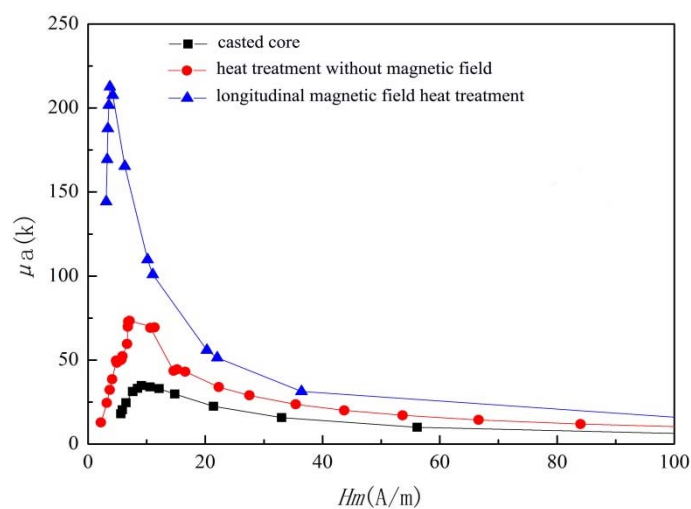
**Table.2** Magnetic parameters of the amorphous cores under different condition( $f=50\text{Hz}$ )

	$B_{800}/\text{T}$	$H_c/(\text{A/m})$	$\mu_m$	$B_r/\text{T}$
casted core	1.04	11.52	34800	0.59
heat treatment without magnetic field	1.48	8.12	73300	0.86
longitudinal magnetic field heat treatment	1.47	5.23	212700	1.39

( $B_{800}$  represents the magnetic induction  $B$  value which was measured at  $H = 800 \text{ A/m}$ )



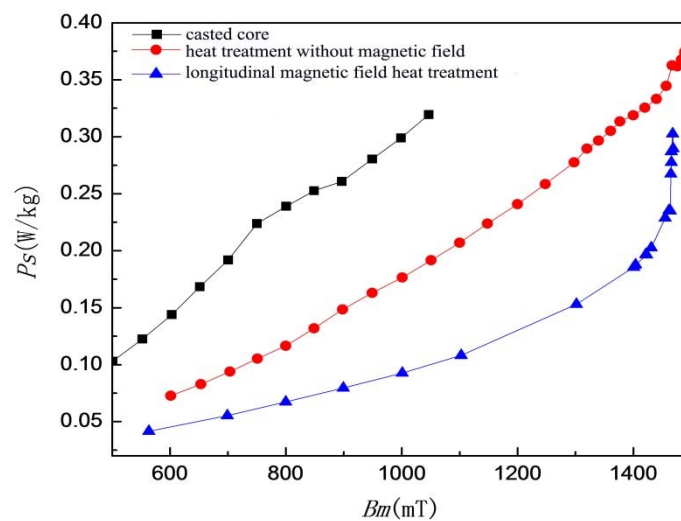
**Fig.4** The magnetization curve of the amorphous cores in different states ( $f=50\text{Hz}$ )



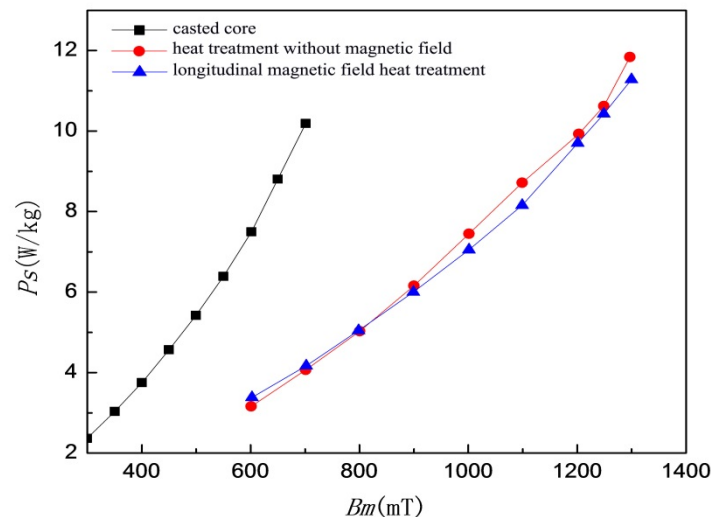
**Fig.5** The permeability curve of the amorphous cores in different states ( $f=50 \text{ Hz}$ )

The magnetization curve and permeability curve of the amorphous cores in different states are shown in Fig. 4 and Fig. 5 respectively. It can be seen from Fig.4, the magnetic induction of the amorphous cores under the casted state is difficult to saturate and the magnetic properties are poor;

The saturation magnetic induction  $B_s$  of the amorphous cores in heat treatment without magnetic field and longitudinal magnetic field heat treatment are 1.48 T and 1.47 T, respectively, and the  $B_s$  are almost the same. This is because the composition of the magnetic material plays a dominant role in the saturation magnetic induction unless the structure has a greater change. But the saturation magnetic induction of the amorphous cores after longitudinal magnetic field heat treatment is close to saturation, when the magnetic field is less than 50A/m. And when the magnetic field is 200A/m, the saturation magnetic induction of the amorphous cores after heat treatment without magnetic field is close to saturation. It can be seen that the magnetizing current can be reduced when the magnetic core works, this can reduce the no-load current for amorphous distribution transformers. The reduction of excitation current is mainly due to the uniaxial anisotropy of the system after longitudinal magnetic field heat treatment increases permeability.



**Fig.6** The loss curve of the amorphous cores in different state ( $f=50\text{Hz}$ )

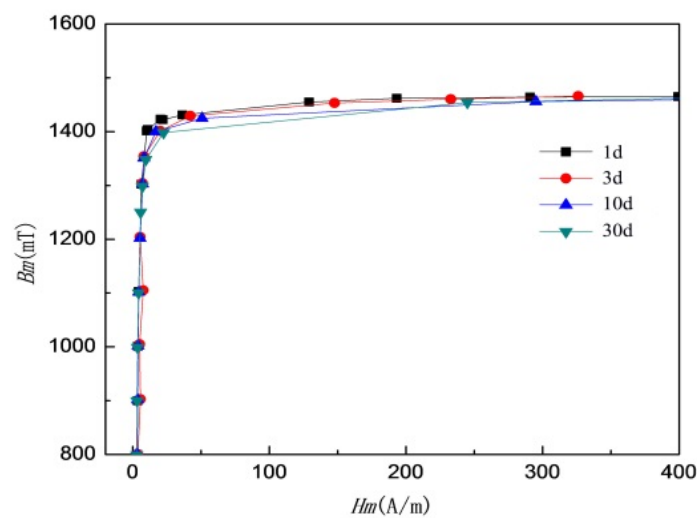


**Fig.7** The loss curve of the amorphous cores in different state ( $f=1\text{kHz}$ )

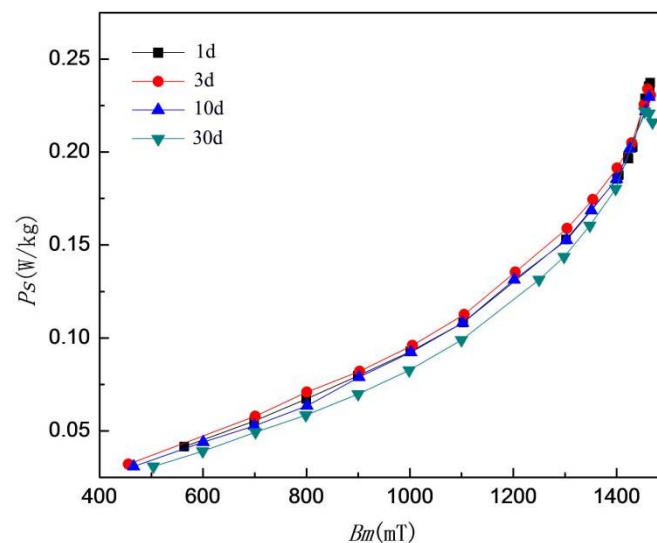
The loss curves of the amorphous cores at  $f=50\text{Hz}$  and  $f=1\text{kHz}$  are shown in Fig.6, Fig.7 respectively. Comparison of the loss curves of the amorphous cores in heat treatment and casted state. When  $f$  and  $B_m$  are fixed, the loss of the amorphous cores after heat treatment is significantly lower than that of the casted state. At  $f=50\text{Hz}$  and  $B_m=1.3\text{T}$ , the loss value of  $P_s$  is 0.278W/kg in the heat

treatment without magnetic field, and the loss value of Ps was 0.153W/kg in longitudinal magnetic field heat treatment, which was 44.9% lower than that of heat treatment without magnetic field. At  $f=1\text{KHz}$  and  $B_m=1.3\text{T}$ , the loss value of Ps was 11.84W/kg in heat treatment without magnetic field, and the loss value of Ps is 11.28W/kg in longitudinal magnetic field heat treatment, which is 4.7% lower than that of heat treatment without magnetic field. Compared with heat treatment without magnetic field, the loss value Ps of the amorphous cores in longitudinal magnetic field heat treatment is significantly reduced at low frequency, while it is almost the same at the high frequency. The reason is that the magnetic core loss is composed of hysteresis loss, eddy current loss and residual loss. In low frequency, the loss of magnetic core is mainly hysteresis loss. In high frequency, eddy current loss and residual loss are the main parts.

### 3.3 The effect of structural relaxation on magnetic properties of the amorphous cores in longitudinal magnetic field heat treatment



**Fig.8** Stability of the magnetization curve for the amorphous cores in longitudinal magnetic field heat treatment ( $f=50\text{Hz}$ )



**Fig.9** Stability of the loss curve for the amorphous cores in longitudinal magnetic field heat treatment ( $f=50\text{Hz}$ )

Figure 8 and figure 9 show the stability of the magnetization curves and the loss curves for the amorphous cores respectively. Structural relaxation phenomenon of iron-base amorphous occurs due to it is a metastable state. It can be seen from Fig. 8 and Fig. 9 that the magnetization curve and the loss curve of the amorphous cores after the longitudinal magnetic field heat treatment are measured at different times are basically identical. This shows that the effect of structural relaxation on magnetic properties of the amorphous cores after longitudinal magnetic field heat treatment is not significant, and the magnetic properties exhibit good stability.

#### 4. Conclusions

(1) The amorphous cores after longitudinal magnetic heat treatment can be obtained rectangular hysteresis loop. The rectangular ratio  $B_r/B_m$  increases from 0.58 in heat treatment without magnetic field to 0.94.

(2) Comparing with the amorphous cores without magnetic field heat treatment, the loss value of  $P_s$  the amorphous cores is significantly reduced at low frequency, while it is almost the same at the high frequency. At  $f=50\text{Hz}$  and  $B_m=1.3\text{T}$ , the loss value of  $P_s$  is  $0.278\text{W/kg}$  in heat treatment without magnetic field and  $0.153\text{W/kg}$  in the longitudinal magnetic field heat treatment, which was 44.9% lower than that of heat treatment without magnetic field.

(3) The effect of structural relaxation on magnetic properties of the amorphous cores in the longitudinal magnetic field heat treatment was not significant, and the magnetic properties exhibit good stability.

#### Acknowledgments

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