Study with Magnetic Property Measurement of Amorphous HB1 Material and its Application in Distribution Transformer

Yeong-Hwa Chang, Chang-Hung Hsu, Ching-Pei Tseng

a Department of Electrical Engineering, Chang Gung University, Tao-Yuan, Taiwan, R.O.C.
b Department of Electric Machine, Fortune Electric Ltd, Co., Tao-Yuan, Taiwan, R.O.C.
c Department of Physics, Institute of Nuclear Energy Research, Tao-Yuan, Taiwan, R.O.C.

Corresponding author: Mr. C.-H. Hsu, Tel.: + 886-3-4526111-237; Fax: + 886-3-4526111 ext 237; E-mail: chshiu@fortune.com.tw

Abstract: - In this paper, crystallization behavior effects on magnetic property of Fe–based amorphous HB1 alloy alloys were studied. DSC and TGA techniques were used to study the thermal properties, phase formation during primary crystallization and magnetic properties. According to measurement results, the lowest core loss occurs with an annealing temperature at 360°C, soak for 2 hours and under a DC magnetic field density 800A/m. Finally, at the same specifications and rated power, experimental results of the magnetic loss are presented for the amorphous alloy HB1 core transformer and commercial SA1 core and silicon steel core transformer. It can be seen that the amorphous HB1 core transformer can provide better performance in the aspect of core loss and exciting power.

Key-Words: - Amorphous materials; Annealing; Curies temperature; Core loss; Exciting power; Transformer

1 Introduction

In last two decades, Fe-based amorphous core transformers have been used widely in industry. It is interesting that their use in electrical power distribution systems as improved energy efficiency was increasingly needed in earths. Because of this material in industry is considering material of the low loss, the lights of reduction of CO₂ gas discharge and preservation of the environment [1, 2]. Due to the progress of physical and magnetic techniques, the soft ferromagnetic materials have many excellent properties of high saturation magnetic flux density, high permeability and low losses. In [3, 4], for amorphous alloy core, being capable of the magnetization saturation induction, hyteresis loss and noise, is suitable for transformer application in industry. Between 320°C and 350°C of annealing temperature, the different annealing procedure relate with noise variation for amorphous alloy was discussed in [5].

In additional, the transformers were fabricated by amorphous SA1 cores combined with superconductivity winding in [6]. Application and survey issues aspect of the transformer, it is clearly that not only the winding of the superconductivity stability, but also focused on core loss performance for amorphous core was also concerned. Therefore, there are many unavoidable disadvantages existing in amorphous materials. It is obvious that the alloy has increased difficult the manufacturing procedure, such as low saturation induction, high brittleness and fracture, high hardness, low core lamination staking factor and low thickness under post annealing procedure [7]. The most of important factor with physical property variation relate to annealing elevated temperature control can be desired, because it was directly effect on magnetic characteristic of the material. In [8], a 1kVA transformer of Fe-based amorphous alloy Fe₇₈Si₉B₁₃, in order to achieve knowing the material magnetic property, the crystallization temperature, Curies temperature and material structure changed physical properties were used DSC, TGA and XRD. The annealing temperature is set to be 380°C with an applied DC magnetic flux density 800A/m, so that the best core crystallization point can be obtained. Finally, the transformer manufacturing was followed by detection results. However, until now, for Fe-based amorphous alloy SA1 material, the different annealing temperature effect on material structure change, magnetic loss and saturation induction variation has not yet discussed very clearly. Therefore, this paper presents the transformer core of the annealing elevated temperature factor, such as material magnetic property and their application. In Section2 introduced the material magnetic property of Fe-based amorphous HB1 alloy. In Section3, the transformers design and implementation are introduced in detail. Section 4, Application of the amorphous material SA1 was manufactured a core
for transformer, compared commercial silicon steel core with magnetic property in detail. The conclusion is given in section 5.

2 Magnetic properties of High Saturation Induction Analysis with Amorphous HB1 Material

2.1 Activation energies from the DSC measurements

In order to find out the crystallization processes occurring in the sample of amorphous alloy SA1, differential scanning calorimetry (DSC) was performed in Fig. 1. The DSC scans is recorded at 5 \(^\circ\)C/min, DSC results show two exothermic peaks at 457 \(^\circ\)C and 477 \(^\circ\)C which clearly represent two crystallization temperatures corresponding to activation energies of 26.84J/g and 72.51J/g, respectively. In Fig. 2 is an amorphous alloy HB1 crystallization experiment by DSC. The DSC scans is recorded at 5 \(^\circ\)C/min, DSC results show two exothermic peaks at 463 \(^\circ\)C and 477 \(^\circ\)C which clearly represent two crystallization temperatures corresponding to activation energies of 41.13J/g and 91.47J/g, respectively.

2.2 Curie temperature and saturation magnetization

Differential scanning calorimetry (DSC) is considered to be a convenient and relatively accurate method for measuring the thermal phase transition of materials. In particular, it gives effective observations of the crystallization of amorphous alloys. However, sometimes it can also be used to measure the Curie transition temperature. The magnetic Curie transition involves a small change in enthalpy, and this heat flow results in a detectable peak. When magnetic material under heat treatment procedure, it is clear that physical phenomenon of the annealing temperature achieving Curies temperature (\(T_c\)) can be observer, which the material of magnetic property will be change form ferromagnetic to paramagnetism. At this time, the magnetization intensity will be slowly disappearing. The Curie temperature of the SA1 materials was measured by TGA. Therefore, according to measured results of the Curies temperature of the amorphous HB1 material was occurred at 341.6\(^\circ\)C.

The Curie temperature of the SA1 materials was measured by TGA in Fig. 4. Therefore, according to measured results of the Curies temperature of the amorphous HB1 material was occurred at 385.6\(^\circ\)C.
3. Transformer Design and Implementation

3.1 Transformer design parameters

In general, the transformer of magnetic induction and the impedance voltage ratio are essential to be determined for the design of transformers. These parameters are determined from estimates of suitable values for the magnetic induction $B_m$, the full load of exciting current density in the transformer winding. That depend on the way of transformers will be used, the next determine parameter are winding space factor and the stacking factor, respectively. Beside, the primary and secondary windings parameter must be considered the window area. The winding space factor is defined by the ratio between the total conductor cross-section area and the window area. The full-load conductor of winding current density is limited by conductor resistance loss and heat dissipation. The core stacking factor is defined by the ratio between the ferromagnetic material cross-section area and the total core cross-section area.

With the thickness of a sheet of grain oriented silicon, it is normally higher than 0.9. The thickness of amorphous alloy ribbon is smaller than conventional silicon steel material. This thickness of amorphous alloy with its uneven surface, it can be seen that giving the amorphous material a space factor of only higher than 80% compared with 95% achieved with silicon steel were addressed. In this paper, this reference material of the amorphous alloy HB1 was produced by Hitachi Corporation, Japan. Some parameter of the Fe-based amorphous alloy and important design parameter are describing as follow. To determine the core dimensions for the amorphous alloy core geometry shown in Fig. 8. The core design dimension of rectangular and circular of cross section area is show as amorphous core and silicon steel core in Fig. 6(a) and Fig. 6(b), and Fig. 6(c), it is sketch of winding design parameter. The core cross-section area of core is calculated as

$$A_c = \frac{10^4}{4.44 \times B_m \times f \times \delta} \times \frac{V}{N}$$

(1)

where $f$ is the power frequency, $B_m$ is magnetic flux density in tesla, $\delta$ is core stacking factor, the $V/N$ is volts per turn ratio, respectively. Fig. 6(c) illustrates the winding distribution. The voltage per turn of the winding is calculated as
where $E_{kVA}$ is the capacity of transformer, $S$ is the number of phase, $\alpha_1$ is rolling thickness of primary winding, $\alpha_2$ is rolling thickness of secondary voltage, $\alpha_3$ is insulation space between primary and secondary winding, $L_{m1}$ is average length of inside winding, $L_{m2}$ is average length of outside winding, $w_l$ is high of winding. In practice, the height of primary winding and secondary winding are the same.

Let $\%IR$ be denoted as resistance voltage percentage

$$\%IR = \frac{P_w}{E_{kVA}} \times 100$$

where the $P_w$ is winding loss. The impedance voltage percentage is define as following

$$\%IZ = \sqrt{\left(\%IX\right)^2 + \left(\%IR\right)^2}$$

Until now, both of winding and core of electrical and magnetic parameter has been decides. The core loss $P_c$ is calculated as

$$P_c = P_{watt/kg} \times G_{ei} \times D.F.$$  

where $P_{watt/kg}$ is the watt per unit ribbon, depending on the core operation frequency, and $G_{ei}$ is the core weight. It is noted that the core loss will be slightly higher than its rated value of ribbon because of the process of cutting and crimping. In this paper, particularly, $D.F$ is defined as the core destroy factor of three phase transformer 1.3, for single phase transformer $D.F$ is define as 1.1. The winding loss is define $P_w$, including the loss of winding resistance and stray loss, is calculated in the following

$$P_w = I_p^2 \times R_p + I_s^2 \times R_s + W_{stray\_loss\_p} + W_{stray\_loss\_s}$$  

where $I_p$ and $I_s$ are rated winding currents; $R_p$ and $R_s$ are winding resistances (the parameter $R_s$ includes the inner and outer of the secondary winding resistances); $W_{stray\_loss\_p}$ and $W_{stray\_loss\_s}$ are winding stray losses. Finally, the transformer efficiency is calculated as following. The amorphous alloy core of the transformer was fabricated in Fig. 7.

$$\eta = \frac{E_{kVA}}{E_{kVA} + P_c + P_w} \times 100$$  

3.2 Transformer design and implementation flow chart

During design and implementation for three-phase transformer with capacity 1MVA, the flow chart is illustrated in Fig. 8. It is expresses the core of the magnetic detection, general design, manufacture and test procedure for a three-phase transformer. Here, from the lowest to the highest class, four types of
transformer are considered as following:
Type 1: Material property detection by DSC and TGA.
Type 2: Transformer design by equation (1-7)
Type 3: Core and winding manufacture and loss test by Section 4.
Type 4: Transformer performance test is in Section 5.

In this paper, it is point out that indispensability element for three-phase transformer design; manufacturing and testing process were presented. As a result, during core of annealing, transformer loss, efficiency, impedance resistance will be illustrate transformer performance compared with SA1 alloy and silicon steel core.

![Flow Chart of design, manufacture and test for a three-phase transformer.](image)

Fig. 8. Flow Chart of design, manufacture and test for a three-phase transformer.

4. Transformer manufacturing and testing

4.1 The core magnetic characteristics relate with annealing temperature

The annealing temperature control is crucial for the manufacturing of amorphous materials. If the annealing temperature is too high, it will cause localized partial crystallization, and the resulting magnetic crystalline anisotropy will tend to increase the core loss. Otherwise, if the anneal temperature is too low; the residual stress is not adequately relieved. From experimentation results, for the amorphous alloy HB1 ribbon, the annealing temperature is set at 330°C for two hour in an air atmosphere. During the annealing process, a DC current driven magnetic field is applied to further improve the magnetic properties. In this paper, the magnetic field density 800 A/m is utilized to reduce the core loss. According to experimentation results, it can be found that to obtain the lowest core loss the annealing temperature is of 330±10°C for the amorphous alloy HB1 core.

4.2 Transformer loss and magnetic property

The measured core loss related to magnetic induction is shown in Fig. 9, it can be seen that the core loss of HB1 core transformer is less than the conventional SA1 core transformer with each magnetic flux density, Bm 1.2~1.5(T). In addition, for HB1 alloy, the measured core loss is lower than SA1 material respect to each magnetic induction, at least reducing up to 0.04W/kg. Beside, the measured exciting power result of the amorphous alloy respect to magnetic flux density characteristic show as Fig. 10. Form the measured results, the exciting power of HB1 material have lower performance than that SA1 alloy will be obtained. According to Fig. 5, the measured results both of the hysteresis loops and saturation induction for a conventional SA1 material is with Bs 1.56(T), and HB1 material is with Bs 1.64(T), respectively. Especially, for HB1 and SA1 material, there is a higher curve of the exciting power performance than magnetic induction Bm, 1.38(T) and 1.4(T), respectively. In another word, when the induction Bm higher than above mention induction point, the exciting power of the amorphous alloy will soon arisen that than silicon steel core material. Because of amorphous alloy achieves saturation induction, HB1 and SA1 alloy with Bs 1.4(T) and 1.38(T), the exciting power of the amorphous material will rising up very fast.

To achieve better efficiency by using the fabricated amorphous alloy HB1 and SA1 cores transformer, it is suggested to follow the observation that the magnetic flux density is less than 1.4(T) and 1.38 (T). Nerveless, the transformer efficiency will turn to be cost down because of the exciting power has been existing arise very fast phenomenon. The measured noise level results of the amorphous alloy and silicon steel cores shown in Fig. 11. The silicon steel material shows the lower noise levels at all magnetic induction. In addition, the measured noise result of the HB1 core respect to each magnetic induction is all
of lower than conventional SA1 core, at least more 4dB values.

5. Conclusion

This paper presents the design and implementation of a three-phase Fe-based HB1 amorphous alloy core transformer with capacity of 1MVA. Testing the core of material performance, the amorphous phase structure result of Fe-based amorphous HB1 alloy under different temperature has been studied using DSC and TGA. The annealing temperature is set to be 330°C applied with a dc 800 A/m magnetic field so that the lowest core loss of best crystallization can be obtained. Finally, compared with conventional SA1 alloy and silicon steel core transformer, the amorphous alloy HB1 core transformer has better performance for core loss and exciting power can be obtained.

References: