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Effects of pressure and temperature on the effective thermal conductivity of oriented silicon steel iron core under atmospheric condition

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ABSTRACT

A set of experimental devices was designed and built to investigate the effects of average temperature of lamination, contact pressure, and lamination number on the effective axial thermal conductivity of silicon steel multi-stacked material in the loading and unloading processes under atmospheric environment. Specimens are stacked by oriented silicon steel sheets, the content of silicon is approximately 3.3%, and thickness is 0.23 mm. Average temperature is in the range of 200–800 °C, and contact pressure is between 0.16 and 16.68 MPa. Experimental results indicated that: effective axial thermal conductivity presented an obvious relationship with the average temperature and contact pressure of lamination but showed independence from the lamination number. Effective axial thermal conductivity is more sensitive to contact pressure in the loading process than in the unloading process. The correlation equations of effective axial thermal conductivity have an accuracy of 15%.

1. Introduction

Thermal conductivity is a critical parameter for thermal management and is frequently encountered in engineering applications, such as heat treatment, microelectronic, and insulating materials [1–5]. Many functional materials have been developed to improve the energy efficiency of electronic devices. The widely concerned material is oriented silicon steel, which is a type of multi-layer cladding materials [6]. Silicon steel sheets are the preferred engineering materials for transformer core, microelectronic, and electrical equipment because of their low weight, low iron loss, high magnetic sensitivity, and excellent corrosion resistance [7]. Transformer cores are mainly divided into two types, namely, wound and laminated cores. They are all considered a type of multi-stacked materials [8], and the wound core is superior to laminated core in terms of short circuit endurance and overload capacities. However, the production process is more complex for wound core than for laminated core. The mechanical stress increases iron loss and reduces magnetic performance during the winding process. Thus, annealing treatment is performed to eliminate harmful residual stress. Furthermore, the magnetic performance of wound core is sensitive to temperature and winding pressure during annealing treatment. Therefore, a system study of axial thermal transfer in cores should be conducted to improve production efficiency.

Maxwell and Rayleigh investigated the thermal property of composite material with matrix and certain spherical particles [9], thereby facilitating the study on thermal conductivity of multilayer composites. Many studies have focused on the effects of diverse coating on effective thermal conductivity [10–12]. Meanwhile, several scholars have conducted the interfacial effect study at micro scale [13,14]. However, the main reason that caused the marked difference in the thermal conductivity between multilayer composites and corresponding bulk materials is unclear. The effects of structural imperfections and phonon scattering at the interface are main contributors [15,16]. The measurement and analysis methods of thermal conductivity of diverse materials have been proposed and developed [17–19]. However, the effect of laminating factors on the effective axial thermal conductivity of multi-stacked materials has not been extensively discussed. Thus, analyzing and confirming the effective axial thermal conductivity of multi-stacked materials are challenging.

In this study, the relationship among contact pressure, average temperature, lamination number, and effective axial thermal conductivity is experimentally studied. Empirical correlation

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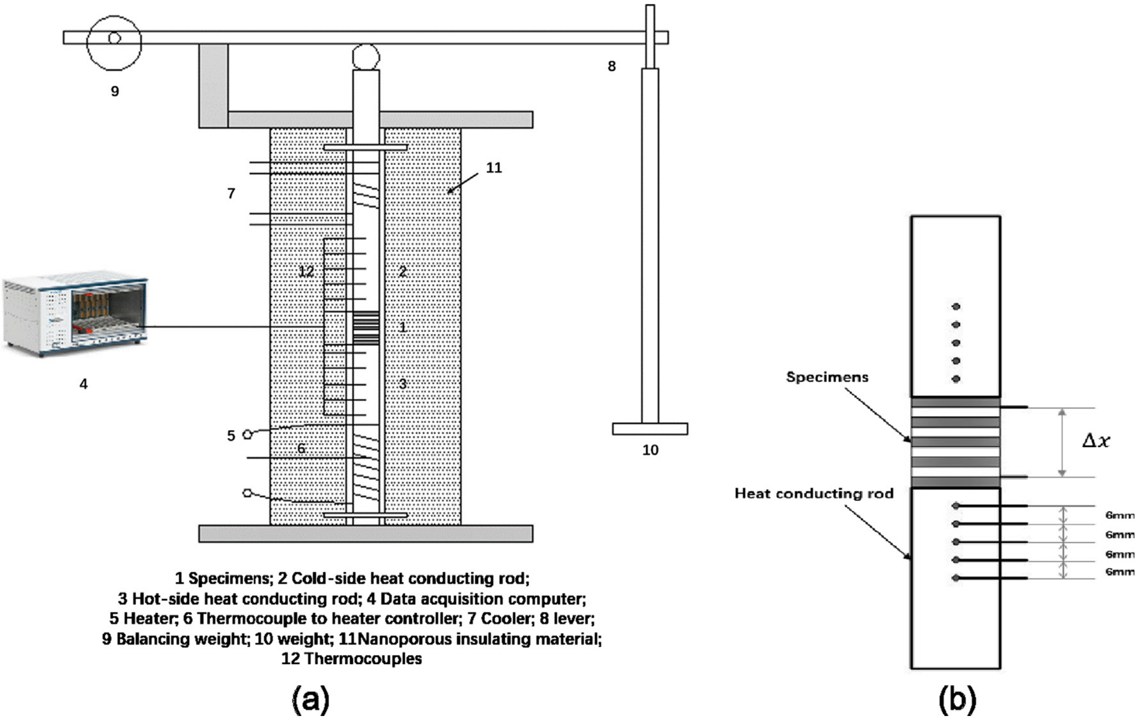

Fig. 1. Schematic diagram of (a) experimental device and (b) locations of the thermocouples.

equations are also established to calculate the approximate axial thermal conductivity with a relative error of 15%.

2. Experimental facility

A complete set of experimental devices is designed and built, as shown in Fig. 1(a). The lever and load are used to control and maintain the contact pressure between the specimens and thus provide a pressure value between 0.16 and 18 MPa. Type-k thermocouples are inserted into the heat conducting rod and specimens through a small hole to measure the temperature distribution at the center line. The detailed locations of the thermocouple are shown in Fig. 1(b). The outer parts of the heat conducting rod and specimens are covered with nanoporous insulating material, the thickness of insulating materials is 60 mm, and the thermal conductivity of the nanoporous insulating material is in the range of 200–700 °C, as shown in Table 1. A rough calculation shows that the average lateral heat flux loss is 1.6% smaller than the heat flux along the axial direction in all the experimental conditions. Therefore, the heat flux in the specimens is a one-dimensional heat transfer when the lateral heat transfer is ignored. NI PXIe-1078 computer with NI TB-4353 card is used for data acquisition. The hot-side heat conducting rod is heated by resistance wire, and temperature is automatically controlled by a PID unit. The cooler system is installed in the upper part of the cold-side heat conducting rod. The system is connected to a water tank with a constant temperature of 20 °C.

The microstructure of multi-stacked silicon steel sheets, which is stacked by five sheets of silicon steel, is shown in Fig. 2(a). Fig. 2(b) shows the clear microstructure and mutual interface of each silicon steel sheet. The chemical compositions of each layer are shown in Fig. 2(c). The peak of carbon element is caused by the spraying of carbon layer in the electron microscope experiment, and the interface is supposed to be the air layer. The silicon steel sheet comprises Fe–Si matrix and magnesium carbonate and phosphate coating. The chemical compositions of heat conducting rods are shown in Table 2. The heat conducting rods are made of stainless steel SUS 304, and the temperature-dependent conductivities are listed in Table 3.

The detailed experimental processes are shown in Fig. 3. First, we set the contact pressure of specimens at the lowest value and the target temperature and start the heating furnace. Then, we record the moment that the heater reaches the target temperature and the system reaches a steady state. Thereafter, we increase the load to a high level and record the moment that the heat transfer reaches another steady state. The second step is repeated to obtain experimental data under different loads. After the load reaches the maximum value, we start the unloading experiment and decrease the load gradually. We record the temperature distribution of specimens and heat conducting rod at each step when the temperature change of every thermocouple is less than 0.2 °C in 30 min. This criterion is essentially used to ensure the stability of temperature and the reliability of data.

3. Error analysis

We assume that the heat transfer along lamination specimens is one-dimensional because the heat loss through the nanoporous insulating materials is negligible. Thus, the temperature distribution along the heat conducting rod is linear under steady-state condition. We can calculate effective heat flux through the lamination specimens. Effective axial thermal conductivity, K_{eff}, can be obtained by Eqs. (1) and (2) as follows:

$$K_{eff} = \frac{q\Delta x}{\Delta T} = \frac{q\Delta x}{T_H - T_C}, \tag{1}$$

$$q = \frac{q_H + q_C}{2} = \frac{1}{2}\left(-k\frac{dT_{Hr}}{dz} - k\frac{dT_{Cr}}{dz}\right), \tag{2}$$

where q is the average heat flux in the hot- and cold-side heat conducting rods ($W{\cdot}m^{-2}$); T_H and T_C are the temperatures of specimens close to the hot- and cold-side heat conducting rods (°C), respectively; T_{Hr} and T_{Cr} are the temperature distributions in the