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A COMPREHENSIVE ANALYSIS OF RADIAL THERMAL CONDUCTIVITY OF GRAIN-ORIENTED ELECTRICAL STEEL BASED ON THE INTERACTIVE APPROACH

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Abstract

The grain-oriented (GO) electrical steel coil has highly anisotropic conduction properties. These properties arise because, in one direction, thermal conductivity is that of the bulk conduction properties of electrical steel. In another direction, the conductivity is a fraction of bulk properties due to the thousands of laminations comprising a coil. There are two principal directions in which heat can be transferred in a coil, axially and radially. The temperature profile of a coil is determined by the proportion of total heat transferred in each direction. An electrical steel coil usually consists of thousands of laps, and each lap is a composite of steel and MgO coating on both surfaces. The heat entering the coil normal to the strip plane, i.e., radially, passes through coating, steel and the gas occupying the inter-lap gaps, and therefore, a high thermal resistance is associated with radial heat transfer. The conductivity of such a composite will be dependent upon the number of laminations and the thickness of individual layers. A series of experiments were conducted to measure the coil conduction in the radial direction to provide data for future research.

1. Introduction

Grain-oriented (GO) electrical steel is a specialty kind of steel used to produce outstanding magnetic properties including high permeability and most importantly low energy loss when magnetized under AC conditions in devices such as transformers, motors, reactors, and inductor cores [1, 2]. The superior properties of the GO are due to the abnormal grain growth that developed during secondary recrystallization during the high-temperature coil annealing (HTCA) process [3, 4].

The GO steel is produced in highly complicated processes with multiple steps to achieve steel with desirable magnetic properties. Generally, GO steel production starts from conventional steelmaking, then continuous casting, slab reheating at 1150°C, hot rolling to 2-3mm gauge, short annealing and pickling of the steel sheet after hot-rolling and a single-step cold rolling with large sheet thickness reduction. The next stage of the process is decarburizing annealing follows cold working to release residual stresses in the steel strip due to thickness reduction and enable recovery primary recrystallization and nitriding after changes in the crystalline structure of the metal [2]; this is performed in a wet hydrogen atmosphere for decarburizing purposes. The superior grain structure develops during the HTCA in a dry hydrogen atmosphere where the secondary recrystallization and the abnormal grain growth occur [5]. During the HTCA process, purification of the steel removal of AIN precipitates and formation of the forsterite (glass film) layer also occur.

The development of the magnetic properties of electrical steel is achieved during the high-temperature coil annealing process. It is a crucial stage in GO production, which requires careful control of heating rates and gas composition. The high-temperature annealing process is performed after decarburizing annealing. The final process step is stress relief annealing and thermal flattening which removes the stresses induced in the thin strip when it is stacked bore vertically in the HTCA process, flattens the strip to make it suitable for transformer laminations and applies a tension coating to reduce electromagnetic losses and provide insulation.

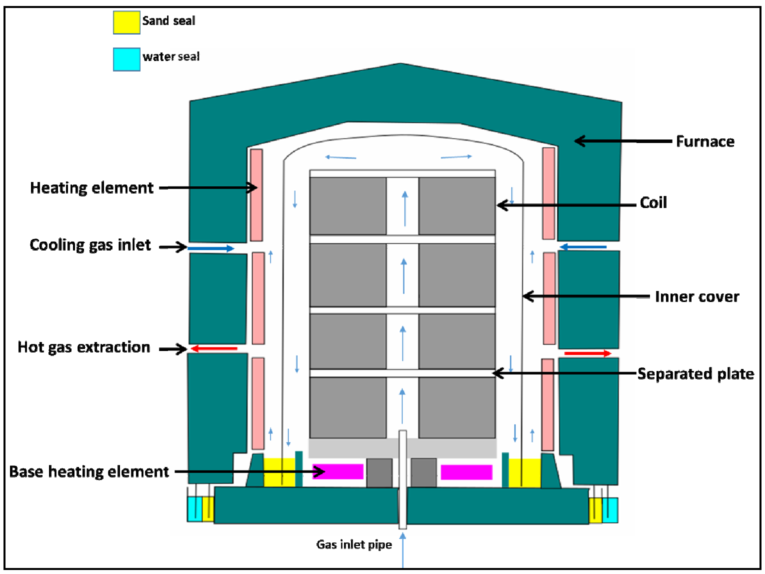

Figure 1. A schematic diagram of the HTCA furnace loaded with the GO steel coils.

At Cogent Power Orb Electrical Steels, part of the Tata Steel group, the HTCA process is conducted in electrical multi-stack annealing furnaces. The process begins by stacking the steel coils onto an empty base. Protective covers are placed over the stacks and settled in a sand seal, which helps enclose the circulating protective atmosphere. Then a flow of deoxidizing gas starts to purge the air from the space under the inner covers and the furnace bell. Figure 1 shows a schematic diagram of the furnace with the steel coils charge and inner covers.

1.1. Heat transfer in HTCA furnaces

The predominant heat transfer mechanism in HTCA furnaces is thermal radiation emitted from electrically heated elements installed at the wall of the furnace. The inner covers receive heat from the electrical elements and reradiate it inside to the coil surface, heat is then conducted through the coil wall to the bore. The geometry and method of heating cause most of the heat entering the coils to be transferred normally to the strip plane and in a radial direction [6, Figure 2].

1.2. Thermal conductivity of electrical steel coils

There are two principal directions in which heat can be transferred in a coil, axially and radially. Therefore, steel coil has highly anisotropic conduction properties [7]. This means that in one direction, conductivity is that of the bulk conduction properties of electrical steel. In another direction, the conductivity is a fraction of the bulk properties due to the thousands of laminations comprising a coil. It is difficult to find appropriate thermal data for electrical steel. The bulk thermal conductivity of electrical steel with a silicon concentration of 1.5% is 33W/m.C [8]. Figure 3 shows the heat transfer mechanisms between the heating elements and the steel coil. Radiation is the dominant heat transfer mechanism through the annealing process.

The gap between any two successive laminations is filled with gas and MgO coating layers. Figure 3 shows the heat transfer mechanisms between two successive laps.

The heat enters the coil normally to the strip plane, i.e. radially, passes through MgO coating, steel, and the gas occupying the inter-lap gaps. Therefore, a high thermal resistance is in the radial direction of the coil. The conductivity of such a composite depends on the number of laminations and the thickness of individual layers.

In the present study, a series of experiments were conducted to measure the coil conduction in the radial direction to provide new data in the field of grain-oriented electrical steel research.

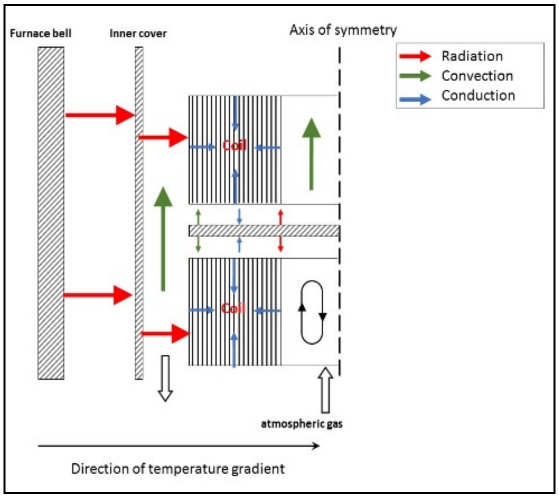

Figure 2. Heat transfer mechanisms inside the annealing furnace.

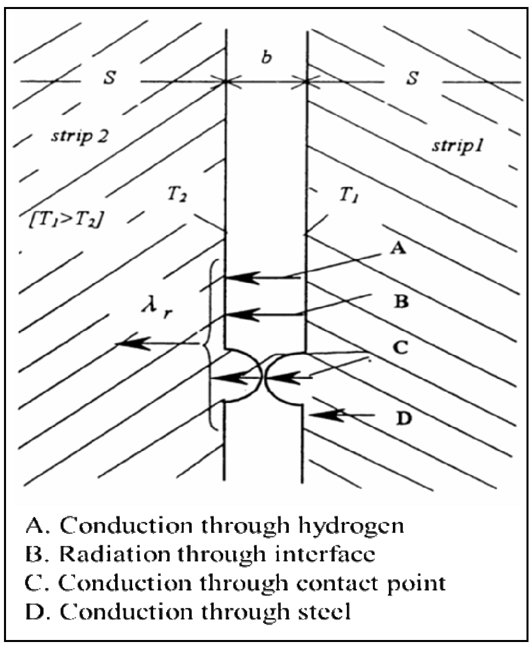

Figure 3. Heat transfer mechanisms between the coil laps.

2. Experimental Setup

The furnace used during the thermal conductivity tests in this research was the Carbolite GPC 1300 furnace. It is a laboratory simulator for the HTCA furnaces at Orb Electrical Steels. It is comprised of a conventional laboratory muffle furnace, fitted with a stainless-steel retort, a control unit for the gas process, and a programmable logic controller. In order to make the furnace useable with Orb's bulk gases and useful for a variety of annealing treatments, Advance Furnace Technology (AFT) has modified the gas process control system originally supplied by Carbolite (but designed for higher pressure gas supply) providing a gas saturator which increases the scope of the furnace.

The incoming gases are tapped off the mains and thus do not require bottled gasses. The gases used are reducing process gases N_2 and H_2 that are used in the HTCA furnace. The standard Carbolite GPC furnace has an upper working temperature of 1300°C. However, this is without a retort being present. A retort will reduce the temperature to 1200°C. The retort is heated using a Kanthal AF resistance wire, which is coiled and supported in ceramic element carriers on either side of the heated chamber.

The retort is rectangular with an apex roof section. Its internal dimensions are ~ 400mm in length, ~ 270mm in width, and ~ 180mm in height. Due to the apex section, the central roof section has a maximum height of 195mm. The furnace has a programmable logic controller (Eurotherm 2408).

The furnace is equipped with two R-type (platinum-13% rhodium/platinum) thermocouples used to control the single zone temperature. They are situated on the outside and to the rear of the retort. This has a rapid response to the temperature as it is close to the electric windings but the inside retort will be lagged behind the displayed temperature. The temperature of the samples inside the furnace can be measured using K-type thermocouples through a hole in the center of the removable door. The thermocouple is then connected to a data logger as shown in Figure 4.

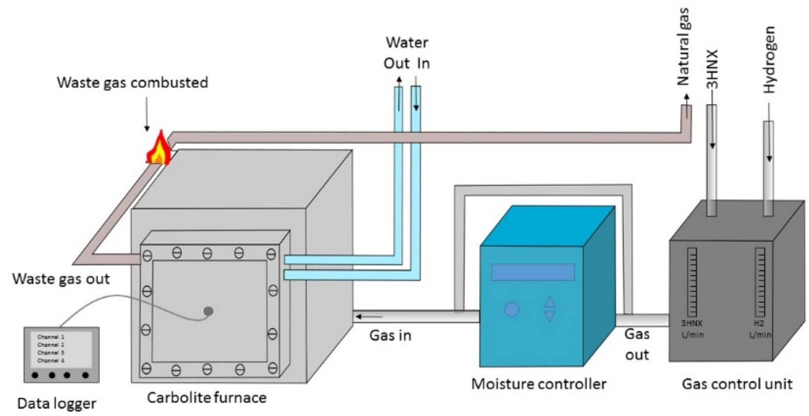

Figure 4. Schematic diagram of Carboilte GPC 1300 furnace and its attachments.

2.1. Methodology

The application of heat in the radial direction results in the formation of a temperature gradient. This gradient can be used for the calculations of radial conductivity using Fourier's rate equation:

$$q = kA\left(\frac{dT}{dx}\right), \tag{1}$$

where k, the radial thermal conductivity is calculated for the material in the presence of the protective atmosphere gases of the annealing process, which affect the conduction properties of the composite as the gas fills the space between the individual coil laps.

Samples of the stack of MgO-coated steel discs were used to simulate the successive layers of the electrical steel coil during the annealing process. The samples were prepared carefully to ensure promoting one-direction heat transfer throughout the disc, Figure 5B, therefore enabling measurement of thermal properties in one specific direction and independent of other directions.

Specimen discs were punched from the MgO-coated steel strip and assembled into a stack to simulate successive laps in a coil. The discs were 90mm in diameter and thickness of ~0.3mm. The test specimen was assembled by stacking a known number of selected discs into a cylinder, the total sample height was approximately 10mm.

Several layers of high-quality insulation materials, that can work at high temperatures up to 1400°C, were used to prevent heat transfer through the edges parallel to the sample plane which would affect the measurements of the radial thermal conductivity. More insulation material was used to insulate the bottom of the sample.

Thermocouples type K TBSLL129 was used. This type of thermocouple is a metal-sheathed cable with thermocouple conductors that are insulated from each other and the sheath by highly compacted magnesium oxide. The thermocouples were led out of the furnace and connected to a data logger, Figure 4. The thermocouple at the top of the reference material was placed a few millimeters from the exposed end to allow the temperature to diffuse within the material into a uniform distribution, Figure 5A.

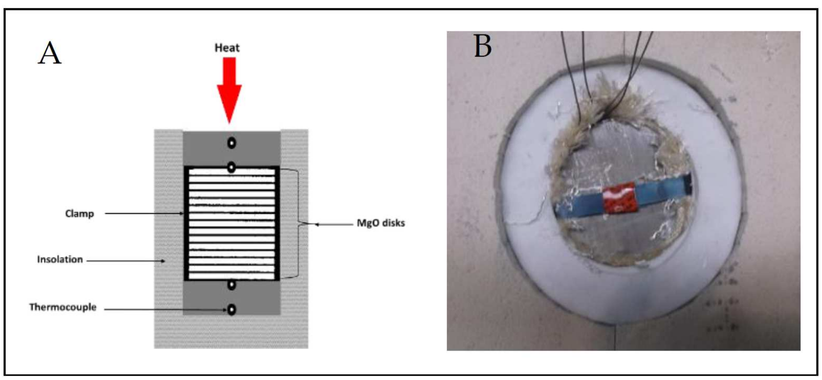

Figure 5. Samples configuration.

The thermal couple reader used was a Eurotherm nanodac. The compact panel mount unit offers four universal inputs for data recording. Therefore, the four channels were used to record the temperature readings from the thermocouples inserted in the sample, Figure 5. The fifth thermocouple was used to monitor the furnace temperature, and it was connected to another data logger for temperature recordings.

A container was designed from fire brick to hold the stack of discs, the insulation material, and the reference material together. The fire brick was used for its high-temperature rating, low thermal conductivity, and good physical resistance to the HTCA media. Banding wires were used to hold the sample elements together, and a force was applied during banding to ensure good contact between the laminations.

The heat was applied to the top end of the stack and so a temperature gradient was raised in the top reference material. Heat is conducted through the samples, and a temperature gradient is produced in the upper reference material, specimen stack, and lower reference material. The recorded temperatures were used to calculate the temperature gradient and the results were substituted into equation (1) with the heat flux to produce the conductivity in the axial direction of the specimen.

2.2. Reference material

In order to measure the conductivity of a stack of lamination, heat flux in the stack must be known, as is described by equation (1). To achieve this, a reference material of known conductivity and dimensions was used. This technique of measuring thermal conductivity is known as the comparative technique [9, 10].

In the present research, discs of AISI 321 stainless steel alloy were used as reference material. The alloy was chosen because its thermal conductivity is characterized over the temperature range of interest [11], as shown in Figure 6. Moreover, its thermal conductivity is similar in magnitude to the bulk thermal conductivity of the steel discs to ensure heat transfer at a similar rate in both materials [9]. The alloy melting point is 1400-1425°C. Both reference materials were 90mm in diameter having a thickness of 5mm.

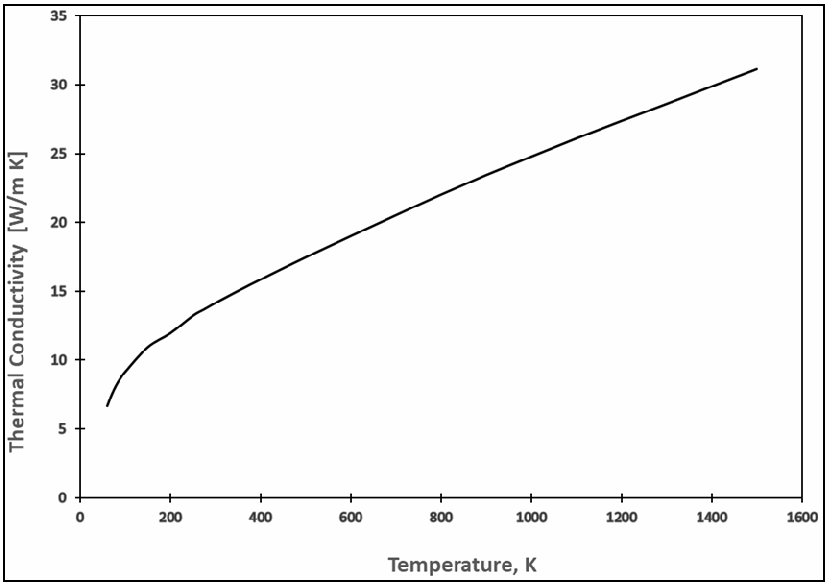

Figure 6. Thermal conductivity of AISI 321 stainless steel.

3. Results and Discussion

3.1. HTCA thermal profile

The thermal profile of an annealing cycle is shown in Figure 7. The process starts with slow heating to 700°C in an atmospheric gas of N_2. The coil batch is held at 700°C for approximately 6 hours in a process called *soaking*, the atmospheric gases in this process are H_2 and N_2. Then, the temperature is raised to 1200°C and the steel coil batch is soaked again at 1200°C in an atmosphere gas of H_2. The cooling process is then conducted, and the furnace is removed at 300°C, where the coil batch is left to cool naturally.

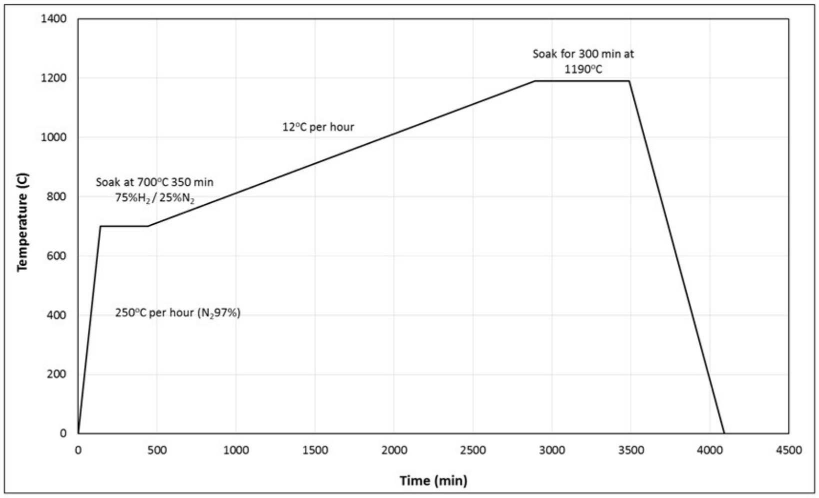

Figure 7. Thermal profile of an actual annealing process of GO electrical steel.

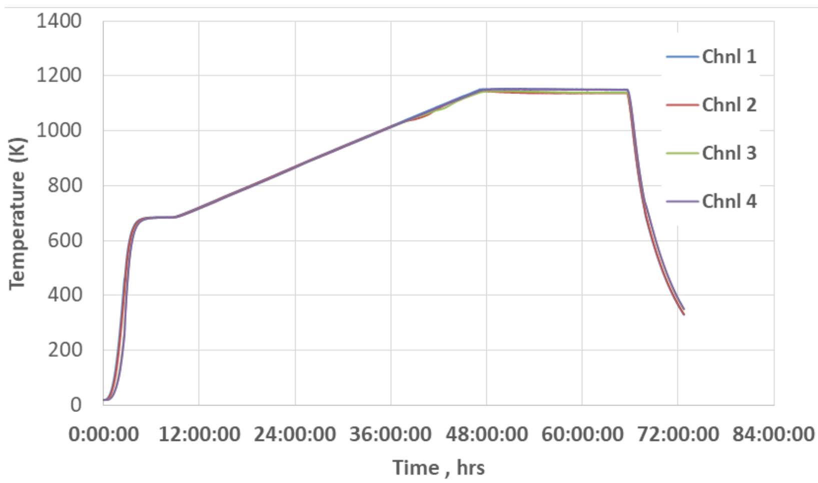

Figure 8. Temperature profile of the sample.

The temperature data collected from the Carbolite furnace through the thermocouples is shown in Figure 8. The channels represent the location of the thermocouples through the stack. The recorded temperatures were used to calculate the temperature gradient and the results were substituted in equation (1) with the heat flux to produce the conductivity in the axial radial direction. The heat flux was measured using a reference material with known thermal conductivity and dimensions.

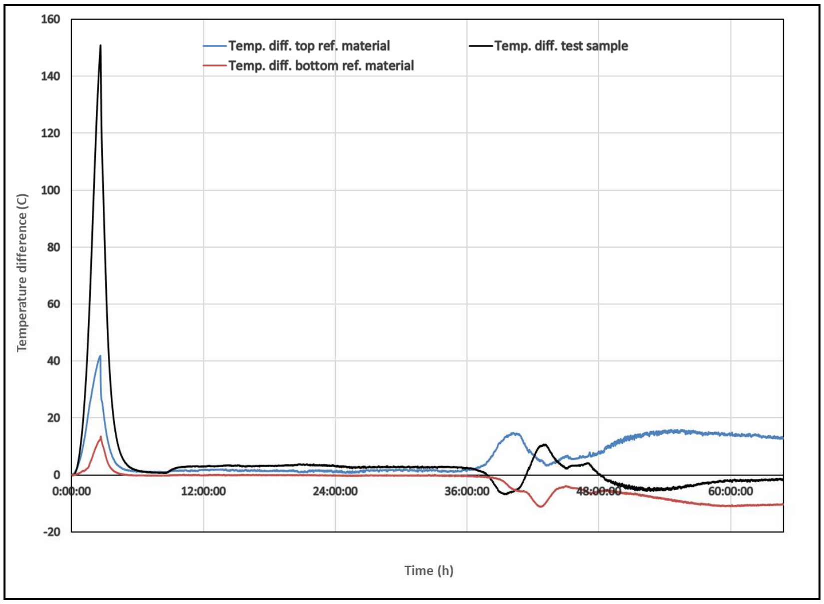

Figure 9. Temperature differences through the sample.

Figure 9 shows the temperature differences profile through the test sample. The differences were calculated throughout the top reference material, the stack of discs, and the bottom reference material. It can be observed from the chart that the temperature difference profiles are decreasing from the top of the sample configuration to the bottom. This is due to the heat energy transfers in one direction through the sample with less heat loss or gains to the edges. However, the temperature difference on the discs was higher due to the laminations and low thermal conductivity in the direction normal to the laminations, thus the temperature at the top of the stacks stayed higher than at the bottom of the stack. However, the difference starts decreasing after a few hours of the cycle as the gas in the gaps becomes hotter and the sample thermal profile is approaching the steady state where the properties do not change with time but may change with location throughout the sample. Therefore, we can see that the temperature difference on the discs is still the highest for the reasons mentioned earlier.

The random behavior of the profiles after about 36 hours of the heating cycle was not expected and could be caused, possibly, by the failure in the insulation materials. The failure caused the heat transfers to the bottom reference material consequently the temperature profile on the two ends of the stack is affected due to receiving heat in two directions (top and bottom). Therefore, data beyond this range was considered invalid, and the thermal conductivity was calculated for up to 900K.

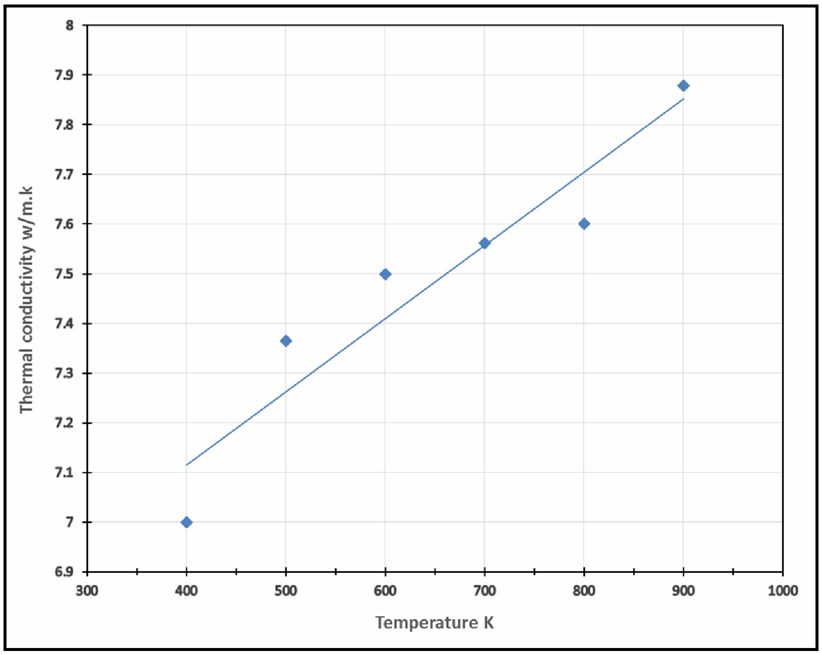

Figure 10. Radial thermal conductivity of 0.3mm high permeability electric steel.

Figure 10 shows the normal-to-plan thermal conductivity of the steel discs against temperature measured through the test sample. It can be observed that the thermal conductivity in the radial direction is less than that in the axial direction for a standard grain-oriented electrical steel, which was reported in the literature. The radial conductivity is on average, 0.29 of the axial coefficients. The only available literature on measuring the radial thermal conductivity of electrical steel is presented in [6], which shows that the radial conductivity is sixth of the axial conductivity.

4. Conclusions and Remarks

In the present study, the radial thermal conductivity of the grain-oriented electrical steel was measured experimentally using a Carbolite furnace that applies exactly the same annealing process as in a furnace used for production.

This new data of radial thermal conductivity of the HGO electrical steel with gauge 0.3mm fills a current need for the material properties to aid in the development of steady-state and transient thermal numerical analysis models for heat transfer through the steel coil that can be used to inform and optimize industrial high-temperature batch annealing cycles. The results show that the radial thermal conductivity is on average 0.29 the bulk thermal conductivity of the typical grain-oriented electrical steel.

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