Improvement of Thermal Conductivity by Anodized Copper Coating

M.H. Mahmood, Suryanto, F.I. Haider

Abstract*— This paper presents an investigation into the effects of the anodized copper coating on the performance of heat transfer. The investigation was made by an experimental thermal test on copper pipes coated with a copper oxide. The coating was performed using anodization in oxalic acid bath contains 0.1M oxalic acid at ambient temperature and applied voltage of 9 volts. The anodized coating consisted of cupric oxide with an average grain size of 45 nm and an average thickness of 10 micrometers. Results show an enhancement of heat transfer performance after the anodized coating. The thermal resistance of anodized copper samples was less than those of the non-anodized one. The cause of the decreasing in thermal resistance after the coating was due to the increase of the heat transfer surface area. The coating increases heat transfer coefficient 10 times higher than the uncoated surfaces. This invention can contribute to developing the design of heat exchangers, by reducing the size of equipment, which considered as one of the most important Industrial challenges.

Keywords: Anodized Copper Coating; Copper; Heat Transfer; Thermal Resistance

1. INTRODUCTION

Copper alloys are the most common material used in the manufacturing of heat exchangers, hot water tanks, and cooling towers, because of their good heat transfer and corrosion resistance properties. Corrosion resistance and heat transfer are related together in selecting material for applications used in heat transfer through fluid environments. The corrosion resistance of copper and its properties in heat transfers are better than many other competitive metals used in such environments. The nearest metals of copper in the specification are aluminum and stainless steel. Aluminum as compared with Copper, it has 62% of copper's thermal conductivity [1]. In addition, aluminum is unsuitable for use in untreated water environments, because it corrodes at pH less than 7.0 and releases hydrogen gas, which may cause hazardous industrial events [2]. Stainless steel is the second closest metal to copper's specification with similar corrosion resistance, but, it has a very low thermal conductivity, only 4% of that of copper's [1]. Moreover, the latest study shows coppers and copper alloys having higher anti-microbial properties as compared to that of stainless steel [3]. For all the above reasons, copper alloys become associated with particular types of cooling equipment that normally used in water environments.

Anodization is an electrochemical process that converts the metal surface into a durable, corrosion-resistant, oxide finish. Copper is suited for anodizing, although other nonferrous metals, such as Aluminum, magnesium, zinc, and titanium, also can be anodized. Anodizing can be considered as one of the corrosion protection methods. It is industrially known as the beauty of corrosion. It protects metal surfaces, in spite of its being a kind of metal corrosion. A careful control of corrosion parameters can develop more effective corrosion protective film of metal oxides [4]. When copper alloys come in contact with water, it directly forms a copper oxide films. This film is considered a corrosion protective film because it prevents coppers from further oxidation. This research studies the effects of surface grain size of anodized copper coating on heat transfer performance. Cupric oxide, CuO is an important transition metal oxide used for developing high-temperature superconductors [5]. The performance of heat transfer through anodized copper coating was investigated using thermal tests by subjecting the samples to cooling and heating zones. The cooling zone was controlled at a temperature of 20 o C.

Grain size is an important characteristic of materials because of its reverse relation with surface area. This is because of the partition of material surface particles into a smaller size and different shapes which increase the total surface area. Therefore, a high surface area can be achieved by reducing the surface grain size. Nanotechnology opened a new hope to enhance strength, corrosion resistance and heat transfer performance of metals [6, 7]. The Nanoscale grain size of the metal surface can enhance the characteristic properties of the metals, by the enhancing of the surface to volume ratio and increasing the quantum effect which controls the material properties.

Previous researcher [8] studied the developing a cupric oxide, CuO coating to be used as electrical substitution detector with a high absorbing cavity for working at liquid nitrogen environment. In this study, thermal properties of the anodized copper coating was investigated to evaluate coating with good thermal conductivity of 370 $Wm^{-1} K^{-1}$. The effective thermal conductivity of coated copper was increased 25 times higher than the non-anodized samples at heating load of 250 W.

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M.H. Mahmood, Department of Manufacturing and Material Engineering, International Islamic University Malaysia, PO Box 10, 50728Kuala Lumpur, Malaysia

Suryanto, Department of Manufacturing and Material Engineering, International Islamic University Malaysia, PO Box 10, 50728Kuala Lumpur, Malaysia(email: surya@iium.edu.my)

F.I. Haider, Department of Manufacturing and Material Engineering, International Islamic University Malaysia, PO Box 10, 50728Kuala Lumpur, Malaysia

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2. EXPERIMENTS

Effect of the anodized coating was investigated using thermal experimental system Figure1. The testing system consists of high purity copper pipes 99.99%, with a dimension of 3.18 mm outside diameter, 0.81 mm wall thickness, and 1.55 mm inside diameter. The pipe was passed through three sections, evaporation, adiabatic and condensation. The evaporation section was heated by an electrical heater mantel, while the condensation section was cooled by direct contact with a constant-temperature cooling bath. To measure the skin temperatures of the pipe, eighteen temperature indicators were distributed in the six paths at the three sections as illustrated in Figure 1.

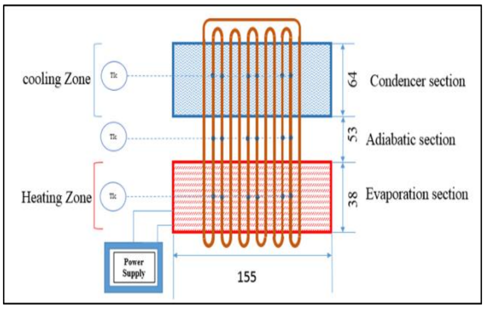

Fig. 1: Thermal experimental system

The working fluid in this study was distilled water at operating temperature range from 20 to 100 °C. The evaporator sections consisted of tubes heated up using a power supply. The power supply was started to heat the tubes when the cooling zone temperature settled at the steady-state temperature of 20 o C. The cooling zone reaches the steady state after about 15 min due to the time delay in responding. The data of temperatures difference and heating loads in the heating section were recorded. Average readings of temperature differences were taken for each of the six paths to get a more accurate result. The thermal tests were performed for anodized and non-anodized copper samples. The thermal resistance of anodized coated and non-coated samples was calculated according to the following equation [9]

$$R= \frac{(\Delta T)}{Q} \qquad (1)$$

Where; ΔT is the temperature difference and Q is the input power. Nano anodized copper coating was fabricated on in the inner surface of the copper substrate by anodization in 0.1M oxalic acid ($H_2C_2O_4$) at ambient temperature and 9 v applied voltage [10], [11]. As it is hard to characterize oxide coating in the inner surface of tiny diameter copper pipe, therefore anodized coating was fabricated on flat copper foil to investigate its characteristics. The morphological structure of the coated surface was characterized using X-ray diffraction (XRD), and field emission scanning electron microscopy (FESEM). XRD results show that nanostructures of cupric oxide, CuO have grown as represented by two obvious peaks at 38.7^o and 43^o. Anodized copper coating shown in Figure 2 has an average grain size of 45 nm and a thickness of 10 micrometers.

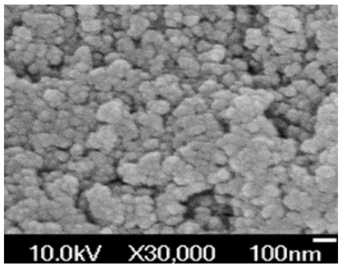

Fig. 2: FESEM image of anodized copper sample

The surface Nanoscale grain size properties can enhance metal characteristics, as a result of the enhancement of the surface to volume ratio, which increases the quantum effects which controls the material properties. The following relation clarifies the effects of surface grain size on the heat transfer specific surface area.

$$\mathrm{SSA} = \frac{6}{\rho \times d} \qquad (2)$$

Where SSA is the Specific Surface Area, ρ is the particle material density and d is the particle size diameter.

To evaluate the capability of heat transfer through the anodized coated sample, effective thermal conductivity was calculated at specific heat flux according to the following equations;

$$\mathrm{Keff} = \frac{Q \times \mathrm{Leff}}{(\Delta T \times \mathrm{Ac})} \qquad (3)$$

$$\mathrm{Leff} = \frac{\mathrm{Le}}{2} + \mathrm{La} + \frac{\mathrm{Lc}}{2} \qquad (4)$$

Where; Keff is the effective thermal conductivity W/Mk, Ac is the total cross-section area of the tested samples cm^2, Leff is the total effective length, Le, La, Lc are the lengths of the evaporation, adiabatic, and condensation sections of copper tested samples.

$$q = \frac{\mathrm{Keff}}{\mathrm{Leff}} / (\Delta T \times \mathrm{Ac}) \qquad (5)$$

$$\text{Heat flux } q = \frac{Q}{\mathrm{Ac}} \qquad (6)$$

3. RESULTS AND DISCUSSION

From the experimental testing result, it was observed that the thermal resistance for the anodized copper samples was lower than this for the non-anodized samples. Moreover, thermal resistance for the anodized samples was decreased with the increase of the input heating load from 25 to 250 Watt, as shown in Figure 3.

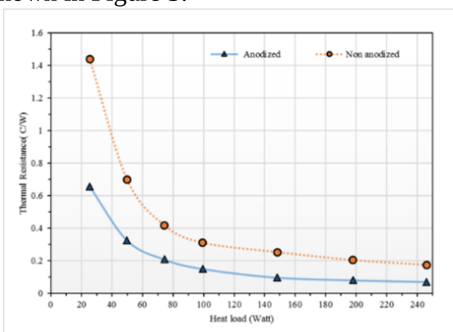

Fig. 3: Thermal resistance as a function of the heating load for anodized and non-anodized samples

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The coating surface area was increased by the Nano anodized coating. The total surface area is partitioned into smaller parts, depending on the grain's size and shape. Therefore, the surface area is dramatically increased at the Nanoscale grain sizes. The increasing of surface area improves the surface characteristics, including heat transfer, by enhancing the surface to volume ratio. For more investigation, the microstructures morphology of anodized coating was investigated by testing heat transfer through anodized and non-anodized copper sheet of 0.5 × 0.5 × 0.012 cm dimensions. The average surface grain size of the anodized and non-anodized samples was 45 nanometer and 10 micrometers respectively. Average coating thickness was 10 micrometer. The result shows that the heat transferring was about nine times higher through the anodized coated samples than the non-anodized samples, at the same temperature difference. This result is due to the increase of the thermal conductivity by increasing heat transfer active surface area for Nano anodized coated samples. Thermal conductivity is the essential property of materials which expresses its ability to transfer heat. The linear relation between active surface area and thermal conductivity for anodized copper is illustrated in Figure 4.

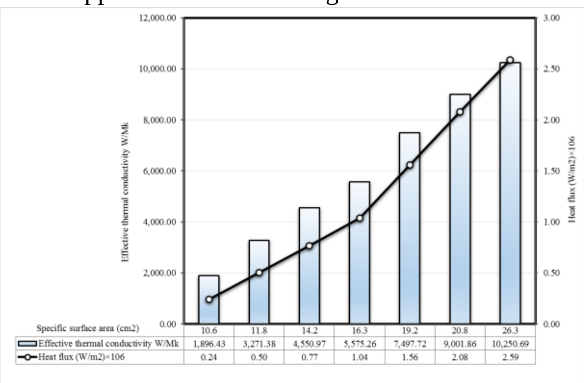

Fig. 4: Effective thermal conductivity (W/Mk) as a function of Heating flux (W/m^2) and specific surface area (cm^2)

Previous result analysis referred to the improvement in the heat transfer through anodized samples compared with the non-anodized samples. This improvement was due to the increasing of the surface area for the anodized samples at Nanoscale grain size. The increasing of surface area after copper anodization can contribute for developing the heat exchangers design and reduce the equipment's size, which could be an important Industrial challenge.

4. CONCLUSION

Thermal resistance for the anodized copper samples was lower than this for the non-anodized samples. Thermal resistance for the anodized samples was decreased with the increase of the input heating load. The surface area is dramatically increased at the Nanoscale grain sizes where the total surface area is partitioned into smaller parts, depending on the grain's size and shape. The increasing of surface area improves the surface characteristics, including heat transfer, by enhancing the surface to volume ratio.

Heat transferring through the anodized coated samples was enhanced by about nine times higher than the non-anodized samples, at the same temperature difference. This enhancement was due to the increase of the thermal conductivity by increasing the active surface area of heat transfer for Nano anodized coated samples.

The anodized copper coating can contribute to developing heat exchangers design by reducing the size of equipment, which considered as one of the most important Industrial challenges.

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