PROPERTIES AND STRUCTURE OF ELECTRODEPOSITED COPPER LAYERS IN PARTS OF THE TTF MAIN COUPLER

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Abstract

For TESLA type power coupler, the influences of heat treatments on properties and structure of electrodeposited copper layers are investigated. Experiments show that heat treatment of 350-400°C improves RRR; heat treatment at 550°C is acceptable for copper layer with the thickness higher than 20μm; 820 °C, 5 min reduces the RRR rapidly and causes Condo Effect.

INTRODUCTION

TESLA input coupler has to transmit RF pulses from the waveguide at room temperature to the coaxial input port of the superconducting accelerating structures at superfluid helium. For TESLA-500, the pulsed power requirement is 230 kW for a 950 μS long beam pulse of 9.5 mA[1]. Hence the transmission line parts must have the combined properties of low thermal conductivity to prevent the heat conduction from room temperature, and high electrical surface conductivity for keeping the RF losses as low as possible. This is solved by copper plated stainless steel. The thickness of the electrodeposited copper layer keeps in the range of 10-20μm, which is thin enough to prevent the heat conduction. For keeping the RF surface losses low enough, the requirement for the copper layer is RRR>30.

Problems will arise for DESY type TESLA coupler, if the final steps of its assembly are done by brazing in a UHV furnace. During the heat treatment, the diffusion of the stainless steel components pollute copper layer and reduce RRR. Similar problems have been subjects of references [2] [3], however, their results are not transferable to our applications due to the bigger thickness of its copper layers.

On the other hand the heat treatment has also a positive influence on RRR, because of degassing of copper layer and reduction of lattice defect density during heat treatment. Understanding of the processes and optimization of the annealing parameters for definite layer thickness was the aim of our study. Some experimental results and calculations for the heat treated Cu plated samples are presented below.

MICROSTRUCTURE

Copper coated stainless steel sample consists of three layers: coated copper layer, intermediate Ni flash or Cu flash and stainless steel base, as shown in Fig.1. The influence of heat treatment can be seen by microstructure: as-received copper layer has porous structure; the grain growth due to recrystallization of copper by heat treatment can be seen on Fig 1b. The grain growth become significant for the samples heat-treated at 820°C.

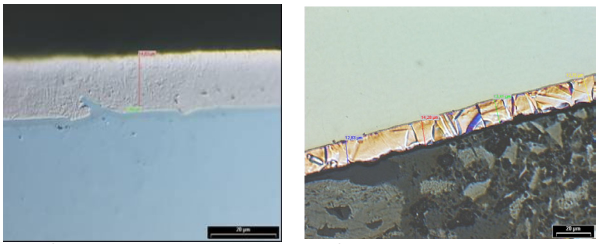
a. before annealing
b. after annealing at 400 °C, 1h

Figure 1: Microstructure of NiFl20μmCuPyro samples (as received and after heat treatment) magnification 500:1.

DIFFUSION

The diffusion of Fe or Ni atoms into the copper layer can be estimated by the second Fick´s law [4]:

$$\frac{\partial C}{\partial t} = D \times \frac{\partial^2 C}{\partial x^2} \qquad (1)$$

C - concentration of diffusing atoms, D - diffusion coefficient, t – time, x – coordinate

Some calculations of Ni and Fe diffusions in copper for different thickness of the flash layer are given in Fig. 2. It shows that for 820°C, 5 min annealing, the penetration depth of these atoms becomes comparable with the thickness of copper layer, so that it will greatly pollute the copper layer.

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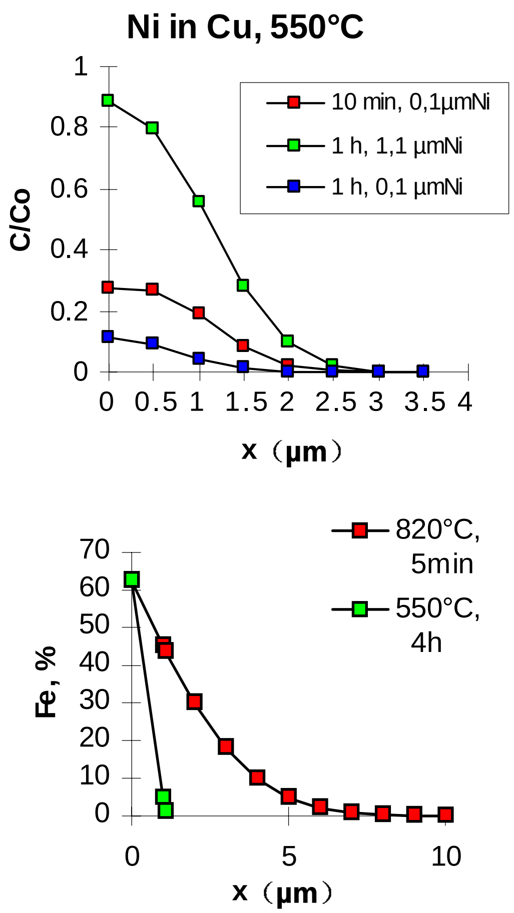

Figure 2: Distribution of Ni and Fe in copper layer after different heat treatments

RESIDUAL RESISTIVITY RATIO RRR

RRR Measurement Method

RRR is defined as the ratio of the resistances of metal at room temperature and at 4.2K. Method assuming the parallel connection between the copper layer and the stainless steel base was applied in order to estimate the RRR of coated copper layer. The copper layer resistance R_{cu} is estimated by the formula:

$$R_{cu} = \frac{R \bullet R_{st}}{R_{st} - R} \tag{2}$$

Where R is the total resistance of copper plated steel; R_{st} is the resistance of pure steel after the copper is removed by diluted nitric acid HNO3.

The resistances of the copper plated steel and the steel base after removing the copper layer can be easily measured at room temperature and 4.2K, and then the resistances of copper layer at room temperature and 4.2 K can be estimated by formula (2).

Samples and Heat Treatment

The samples with the copper layer of 5-100 μm and different flash layers were prepared and heated treated at 350°C, 450°C, 550°C and 820°C with different treatment duration.

Results

- The annealing (820°C, 5 min.) reduced the RRR in most cases.
- 350-400°C improves RRR significantly, while the influence of 550°C annealing is dependent on the treatment time. Fig. 2-3 shows the RRR dependence on annealing duration and copper layer thickness at the annealing temperature 550°C.

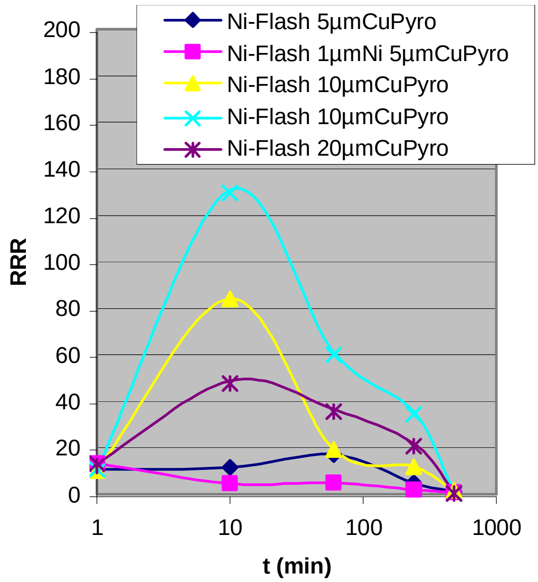

Figure 3: RRR versus annealing time (annealing temperature 550 °C)

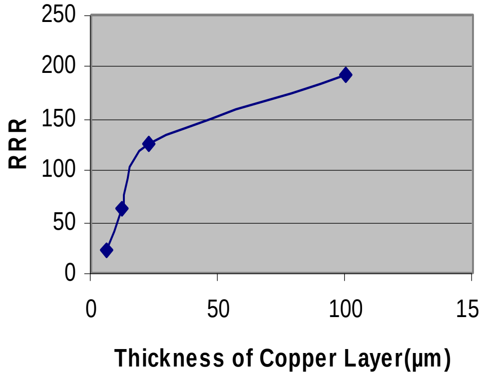

Figure 4: RRR dependence on the thickness of copper layer (after annealing at 550 °C, 10 min)

RESISTIVITY – CONDO EFFECT

One interesting feature was observed on the temperature dependence curve of the copper layer's resistivity. The resistivity of metal rises normally with temperature. But for the samples annealed at 820°C for 5 minutes a minimum at the resistivity plot was observed (Fig.5).

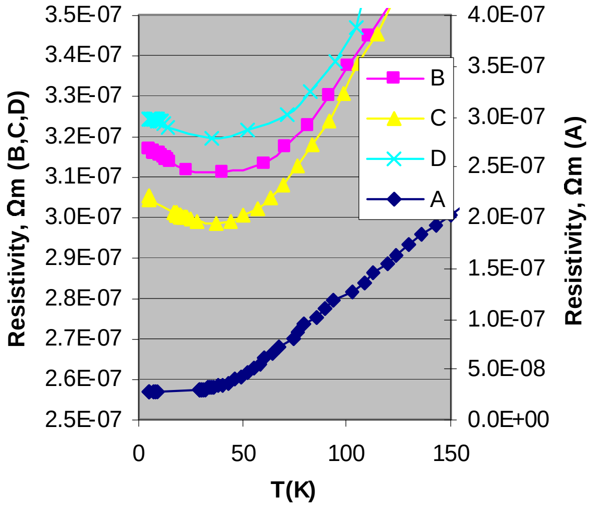

Figure 5: Temperature dependence of the resistivity on samples annealed at 820 ^{o}C, 1 h (A: before annealing).

This may be caused by Condo-Effect. An additional contribution appears in electrical resistivity, if the material contains magnetic impurities. This contribution is roughly proportional to lg (1/T).

$$\rho = \rho_o + \rho_{id} + \rho_1 \times \ln \frac{1}{T} \qquad (3)$$

The exchange interaction between spins of the electrons and magnetic moments of the impurity atoms during the scattering is the reason of this additional term. The combination of the second and third terms in the equation (3) causes the minimum at the resistance curve. This result in our cases shows that the heat treatment of 820°C for 5 minutes causes the diffusion of magnetic atoms (probably Fe or Ni atoms) into the copper layers. Many samples have shown such effects. It shows that the diffusion of magnetic elements from stainless steel play a critical role on reducing the RRR of coated copper layer.

THERMAL CONDUCTIVITY

Thermal conductivity, which determines the efficiency of heat transfer for high energy guide, is also an important parameter of copper plated steel for TTF coupler.

With RRR value, the thermal conductivity can be roughly estimated with one electron gas model (Wiedemann -Franz law)

$$\lambda \cdot \rho = L \cdot T \qquad (4)$$

Lawrence constant L(Cu)=2.23x10^{-8} W Ω/K^{2})[5].

In the temperature range of 2-25K, the temperature dependence of ρ becomes weak, so we suppose $\rho \approx \rho_{res}$ (residual resistivity). Then,

$$\lambda \approx \frac{L \cdot T \cdot RRR}{\rho(293K)} \qquad (5)$$

From Fig. 6, it can be seen that in the region of 2 - 25 K, the estimation is close to the experimental result.

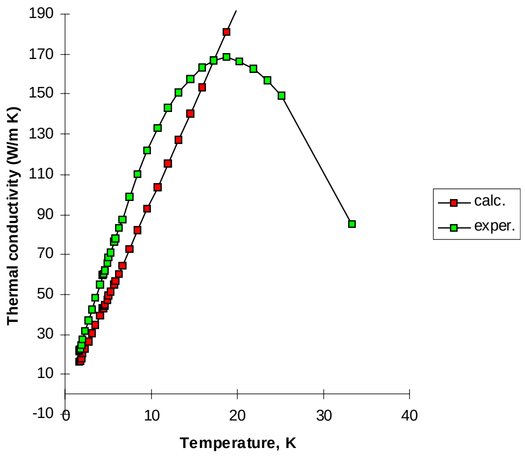

Figure 6: Thermal conductivity of CuFl20µmCuPyro sample after heat treatment by 550°C, 10 min

SUMMARY

Investigations on the influence of heat treatment on the properties and structure of copper coated stainless steel are done. The investigations show that

- Heat treatment at 350-400°C in most cases improve the RRR due to the reduction of gas content and crystal defects; at 550°C, the RRR is dependent on heating duration; at 820°C, 5 min, RRR decreases rapidly.
- Condo effect was observed on the sample heat treated at 820°C, 5 min.
- Thermal conductivity of copper layer can be estimated by Wiedemann-Franz law. In 2-25K, the theoretical value is roughly close to the experimental results

ACKNOWLEDGMENTS

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