Induction Brazing Analysis of EAST Fast Control Coil Conductor

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To achieve much higher operation parameters of EAST device, some key components are upgraded. Fast control coil as one of the key components is updated by using novel stainless steel mineral insulation conductor and the turns are increased to 4, which means the coil's operation environment becomes more severe and larger loads will be encountered. The coil joint is apt to be destroyed in view of the potential defects during the fabrication. Given the numerous advantages, the induction brazing is being considered for the conductor joint connection. The copper mock up is used to carry out the feasibility analysis. Based on the structural size of copper tube, the brazing parameters are calculated and a 2 turns splitting induction coil is designed. Some influence factors effecting the induction efficiency are analysed. It will provide guidance for choice of power supply and the optimization design of induction coil. In addition, the induction experiment is launched and comprehensive joint performance tests are subsequently performed. The test results indicate the joint overall performance could satisfy the basic engineering design requirement, but also some defects are found and more study should be carried out and to further improve the brazing quality.

Key words: EAST, Fast Control Coil, Induction brazing, Current frequency, Eddy current

1 Introduction

In order to achieve the goal of higher parameters operation, some important components of Experimental Advanced Superconducting Tokamak (EAST) are upgraded. Fast control coil as the main component to maintain the vertical stability of plasma should also be updated. For the upgraded fast control coil, the ITER-like (International Thermonuclear Experimental Reactor) novel magnet of stainless steel mineral insulation conductor is used to withstand the strong radiation rooted in plasma [1,2,3,4,5]. And the turns of the coil are increased from 2 turns to 4 turns for the purpose of carrying more current. In the meantime, for the sake of avoiding electromagnetic shielding and improving the control capability, the fast control coil is mounted at the internal wall of vacuum vessel, which means high temperature, strong electromagnetic load and severe neutron radiation [6,7,8]. Thus, the conductor joint is more apt to be destroyed under this worse operation environment especially the existence of fabrication defects. Therefore, the problem of how to connect the conductor joint effectively attract a lot of concern during the upgrade of fast control coil. Induction brazing is a kind of welding technology that is widely used in the aerospace industry, its principle is utilizing the induction eddy current caused by the induction coil to braze the base metal. Given the prominent advantages of induction brazing, such as lower brazing temperature, non-contact and higher brazing efficiency[9,10,11,12,13], it is proposed for the connection of fast control coil joint. The conductor of fast control coil contains three layers, they are the outer layer jacket, middle layer insulation of magnesium oxide and the inner layer copper free conductor, as shown in Fig. 1 and Fig. 2. Where we mainly study the in-duction brazing of copper conductor.

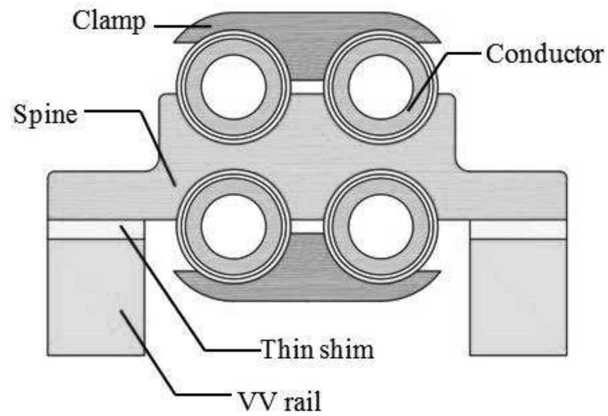

Fig. 1 The structure of fast control coil

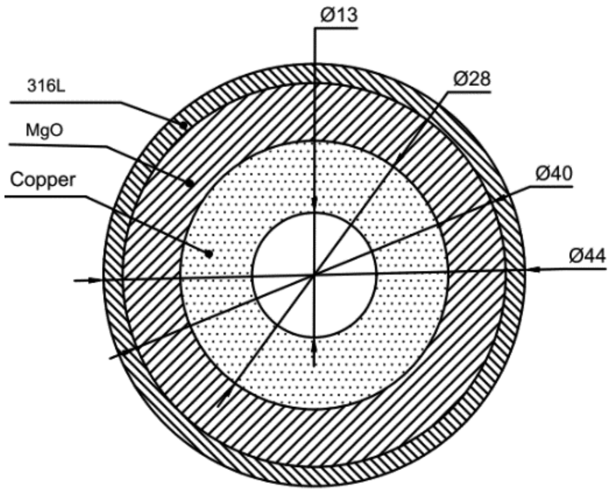

Fig. 2 The structure and parameters of coil conductor

2 The parameter calculation of induction heating

A piece of equivalent copper tube (shown in Fig. 3) is used to carry out the parameter calculation of induction heating. Assuming the hollow metal tube placed in an alternating magnetic field. And h is the length of the tube, d is the thickness, R_a is the average radius of cross section, ρ is the electrical resistivity, dh is the differential line element along the length direction of copper tube. For the copper tube of EAST fast control coil, its inner and outer radii are 6.5 mm and 14 mm respectively, the thickness in the radial direction is 7.5 mm. If the copper tube needs to be heated to the temperature of 850℃ in 35 seconds, the induction heating power needed can be calculated in equation (1), the value is about 3869 W. In the actual brazing condition, considering the heat radiation and dissipation along the axial direction, a conservative value of 5804 W (1.5 times of the original value) is used to assure the power supply has enough margin to satisfy the brazing requirements. Once we have known the heating power, the eddy current induced by the varied magnetic field can be calculated according to the equation (2). Corresponding to the heating power, the eddy current in the copper tube is about 31.65 kA. The equivalent inductance for the selected copper tube can be calculated based on the equation (3). Combing the inductance with the copper electrical resistance, the impedance and induction electromotive force of copper tube can be easily obtained. The maximum induction electromotive force is about 1.8 V. Finally, the required magnetic field of induction coil can be calculated based on the equation (5). In order to the induction heating device can also be used for the in-vessel coils of China Fusion Engineering Test Reactor (CFETR), a much higher peak magnetic field of 0.34 T is needed for the induction coil (assuming the current frequency is 1500 Hz).

$$\Delta\theta = \frac{P \cdot \Delta t}{C \cdot m} \tag{1}$$

$$P = \rho \frac{2\pi I_e^2 R_a}{hd} \tag{2}$$

$$L = K \frac{\mu \pi \mathrm{R}_\mathrm{a}^2}{h} \tag{3}$$

$$\varepsilon_\mathrm{m} = \sqrt{2} Z_m \cdot I_e \tag{4}$$

$$B_m = \frac{\varepsilon_m}{2\pi^2 f R_a^2} \tag{5}$$

Where:

$\Delta\theta$ temperature increment of copper tube from room temperature [T],

Δt time increments [s],

m mass of copper tube [kg],

C specific heat of copper tube (3.9×102) [J/kg·℃],

I_e eddy current in the copper tube [kA],

K coefficient related with the ratio of R_a / h and is about 0.8,

ε_m maximum induction electromotive force [V],

Z_m impedance [Ω],

B_m maximum magnetic density [T],

f current frequency [Hz].

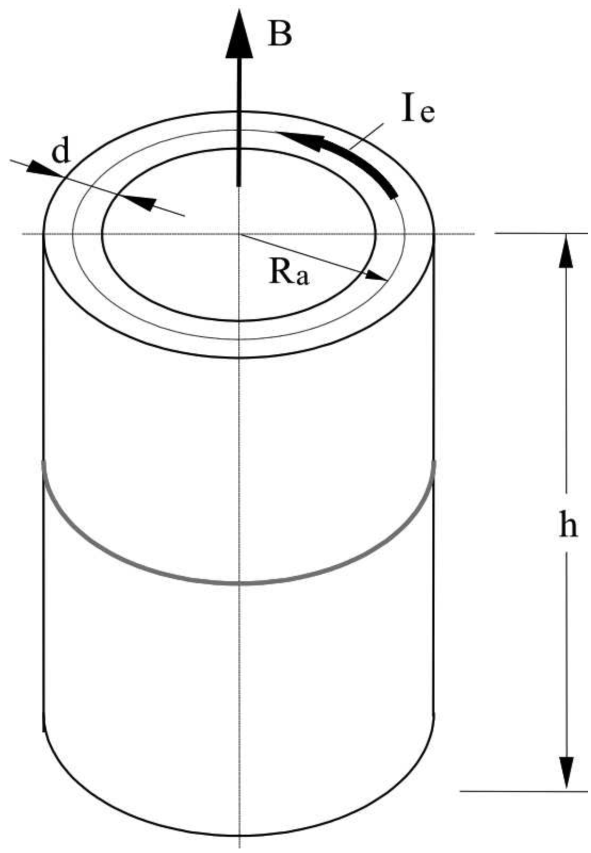

***Fig. 3** The calculation model of base metal*

3 The induction brazing design

The design scheme of induction coil is shown in Fig. 4. The induction coil is winded by hollow copper conductor and contains two turns in a small contact gap with the base metal. The heat distribution in the copper tube during the brazing process is related with the cross-section shape of induction coil. Compared with the circular cross section, the rectangular section could generate more uniform heat distribution in the base metal. Thus, the cross section of induction coil is designed in rectangle. As to the connection mode of copper pieces, butt joint is used. However, the strength of copper tube in the brazing region is not robust enough in the connection mode of butt joint. To void the possible damage caused by the hoop stress, a 10 mm-long sleeve with the thickness of 1 mm is housed at the connection region. Besides, a hole with 2 mm diameter is machined, through which the solder wire is filled into the brazing joint during the brazing process. In order to guarantee the capillarity of brazing filler metal, a small clearance in the range of 0.02~0.1 mm is proposed at the contact interface of copper tubes. If the clearance is too small, the fluidity of the filler metal between the joints would be blocked. On the contrary, the capillary action will work effectively and it is hard to fill the joint completely. With respect to the selection of filler metal, due to the good toughness and electroconductivity, BCu80PAg is selected as the brazing filler metal. In addition, the ingredient of phosphorus in the filler metal can bring down the melting point of copper. And the ingredient of silver can lower the melting temperature of copper-phosphorus.

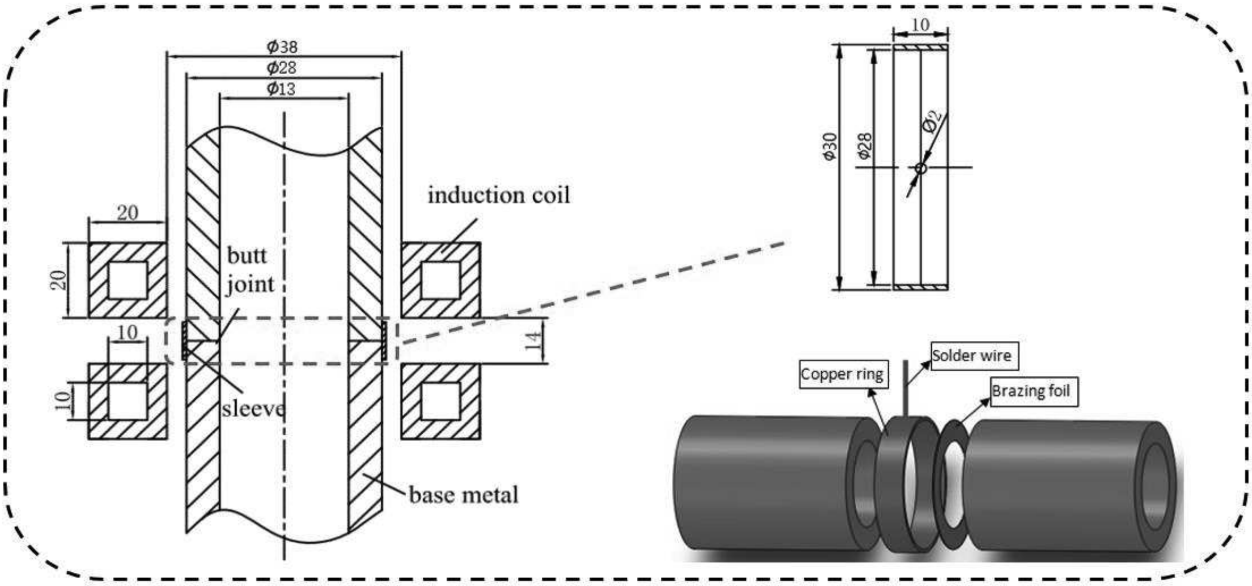

Fig. 4 The brazing scheme of the conductor joint

4 The analysis of induction brazing

4.1 The affecting factors of induction brazing

The equation (6) indicates that the induction heating power is in positive correlation with the magnetic density and current frequency. Therefore, the heating power can be improved by either increasing the magnetic density or amplifying the current frequency.

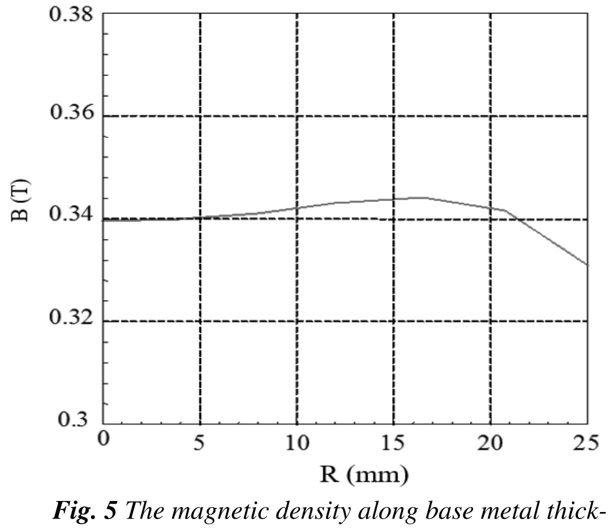

Fig. 5 The magnetic density along base metal thickness direction

For the induction coil with fixed turns, the magnetic density can be changed by adjusting the current flowing through the coil. Based on the design of paragraph 3, when the alternating current with the valid value of 10 kA is carried by the induction coil, the magnetic density along the brazing metal radial direction is shown in Fig. 5. The magnetic density within the thickness region is more than 0.34 T, which can satisfy the design requirements. The current frequency corresponding to the magnetic field of 0.34 T is 1500 Hz. The current frequency can be increased to improve the heating efficiency. However, it will affect the penetration depth of eddy current in the base metal as shown in equation (7). Where two different current frequency of 1500 Hz and 15000 Hz are selected, and the detailed induction heating process are analysed respectively. In addition, the induction heating is also affected by the heat conduction and irradiation, which are considered in the analysis.

$$\overline{P} = \frac{1}{T}\int_0^T pdt = \frac{\pi d}{4\rho} B_m^2 \omega^2 R_a{}^2 h = \frac{\pi^3 d}{\rho} B_m^2 R_a{}^2 f^2 h \qquad (6)$$

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}} \qquad (7)$$

Where:

$\overline{P}$ average thermal power [W],
T current period [s],
p instantaneous power [W],
ρ electrical resistivity [Ω ·m],
d thickness of copper tube [mm],
B_m maximum magnetic density of induction coil [T],
ω phase angle [°],
R_a average radius of copper tube [mm],
h length of copper tube [mm],
f current frequency of power supply [Hz],
δ penetration depth [s],
μ magnetic permeability [-].

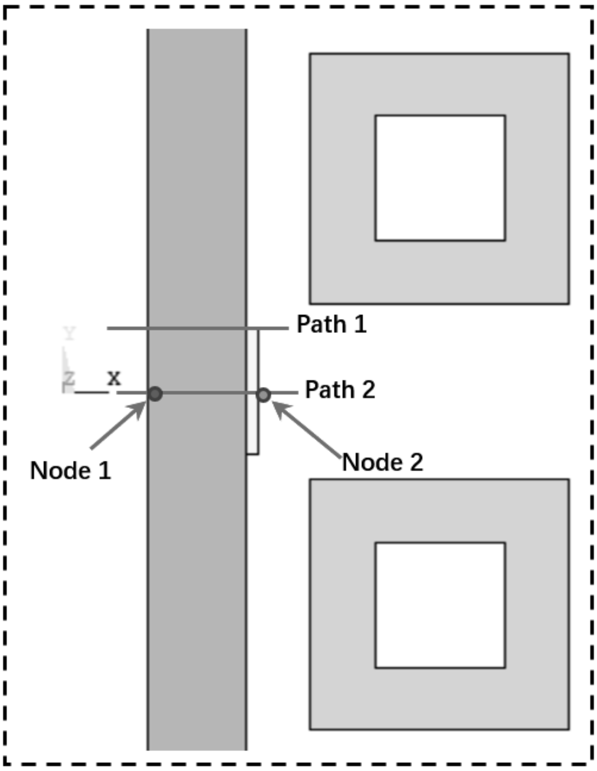

Fig. 6 The description paths and nodes

4.2 The influence of current frequency

In order to describe the variation of heat and temperature versus time conveniently, two typical paths and nodes are selected as shown in Fig. 6. The heat distribution of copper tube under the current frequency of 1500 Hz and 15000 Hz are shown in Fig. 7 and Fig. 8. No matter the current frequency is 1500 Hz or 15000 Hz, the joule heat at the outer layer is always larger than that in the inner layer. It is due to skin effect, which will cause the eddy current mainly congregate at the outer layers of the copper tube. Besides the nonuniformity of heat distribution in the radial direction, the heat distribution in the axial direction is also nonuniform. It can be seen the brazing region near to the induction coil (e.g. line 1) generated more joule heat than the middle region (line 2). If the current frequency is 15000 Hz, the heating efficiency is much higher. It only takes less than 9 seconds to heat the copper tube to the expected temperature. While if the current frequency is 1500 Hz, it needs 35 seconds to heat the copper tube to the same temperature. Although the larger frequency means higher heat generation, it is not always the larger the better. The larger current frequency will deteriorate the nonuniformity of temperature distribution. The temperature distribution of copper tube under different current frequency is presented is Fig. 9. When the current frequency is 15000 Hz, the skin effect will become more severe and the maximum temperature difference in the radial direction is about 30°C, which is apt to cause large thermal stress [14]. While if the current frequency is 1500 Hz, the maximum temperature difference is only about 6°C. One reason is that the skin effect is weakened under the relatively smaller current frequency, the other reason is more time for the heat conduction.

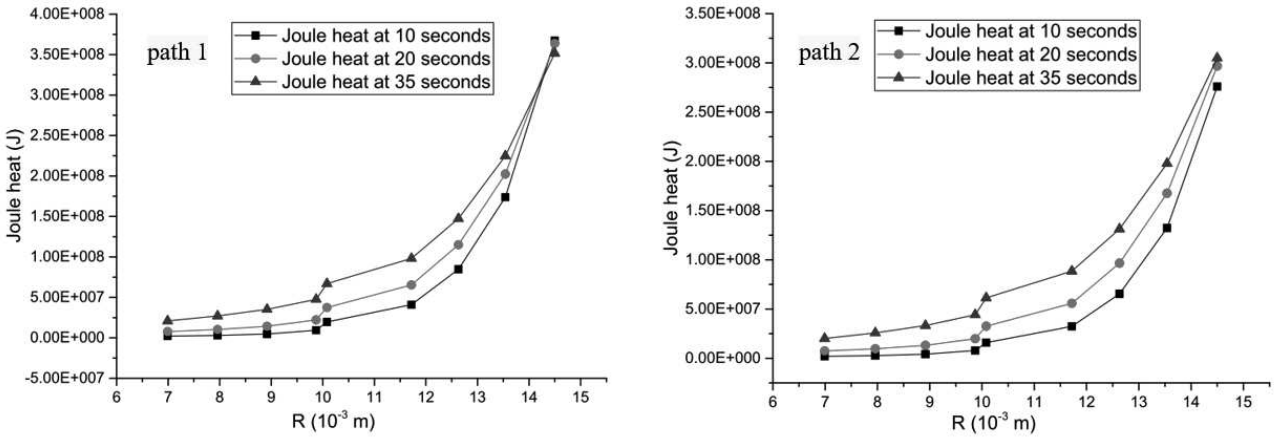

Fig. 7 The distribution of Joule heat under the frequency of 1500 Hz

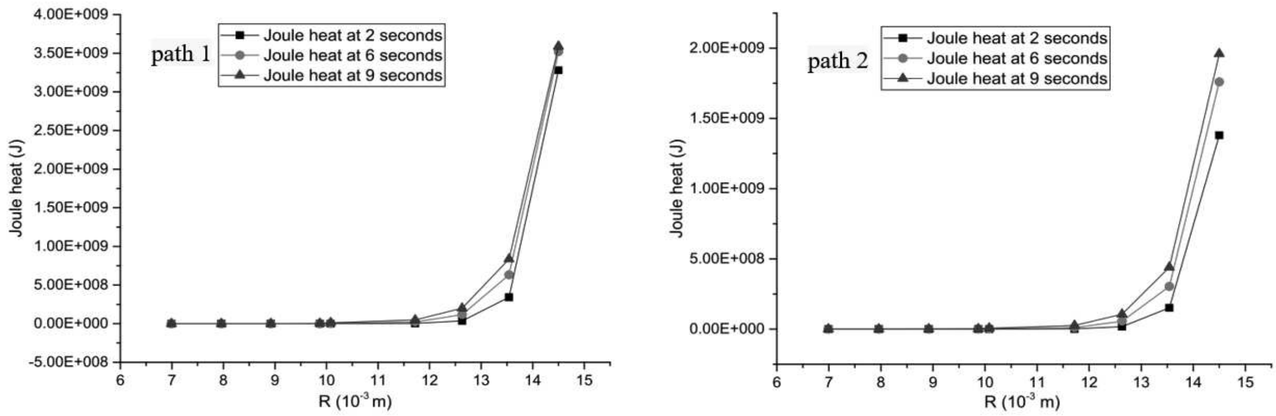

Fig. 8 The distribution of Joule heat along path 1& path 2 under the frequency of 15000 Hz

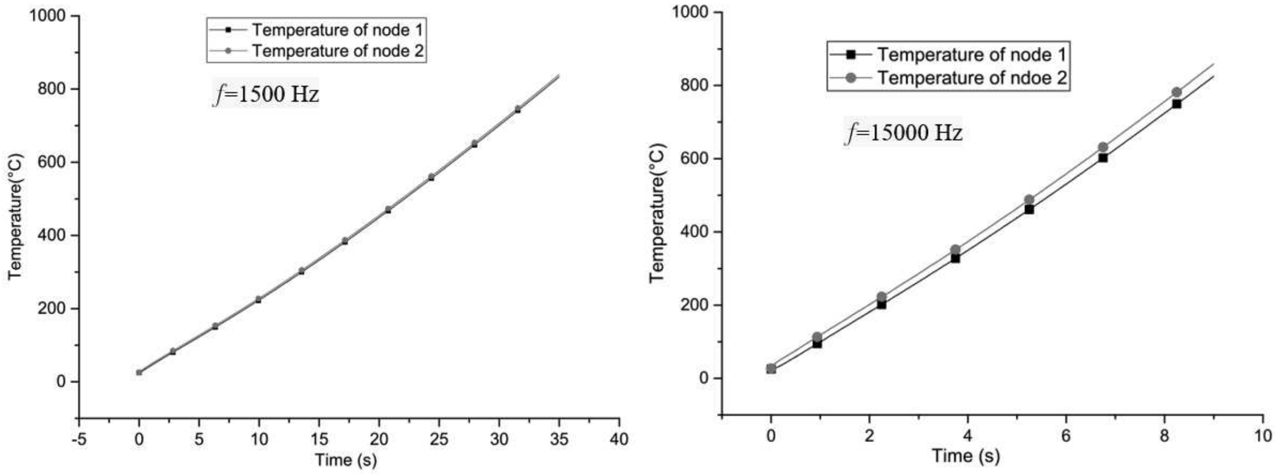

Fig. 9 *The temperature variation of node 1& 2 during the induction heating process*

4.3 The analysis of heat conduction and radiation

The thermal conductivity coefficient of copper conductor is related with the temperature, it will drop down a little bit with the temperature rising. The changed thermal conductivity coefficient is applied to the electromagnetic-thermal coupling analysis by recycling iteration. During the analysis 70 load steps are created and solved using different thermal conductivity coefficient. In view of the excellent heat conduction performance of copper tube, it will significantly mitigate the skin effect under the proper heating time. From Fig. 8 we can see if the heating time is 35 seconds, it will not generate large temperature difference at the inner and outer layer of copper tube, which is mainly attribute to the extinguished heat conduction performance. In addition, heat radiation is inevitable during the brazing process. Fig. 10 and Fig. 11 show the temperature distribution of copper tube without and with radiation respectively. If the heating frequency is 15000 Hz, it will result in the temperature decrement of 10°C in 9 seconds under the effect of radiation. If the heating frequency is 1500 Hz, the temperature decrement caused by radiation is up to 35°C in 35 seconds. Thus, radiation is a nonnegligible factor during the medium frequency induction brazing. And during the determination of heating power, the weaken effect of radiation on heating efficiency should be considered.

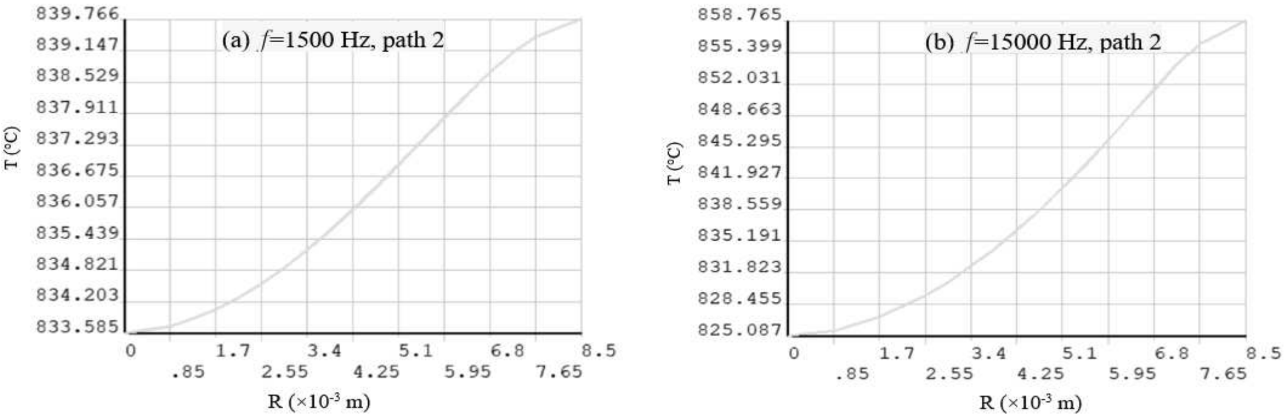

Fig. 10 *The temperature distribution at the time points of 35 second &9 second*

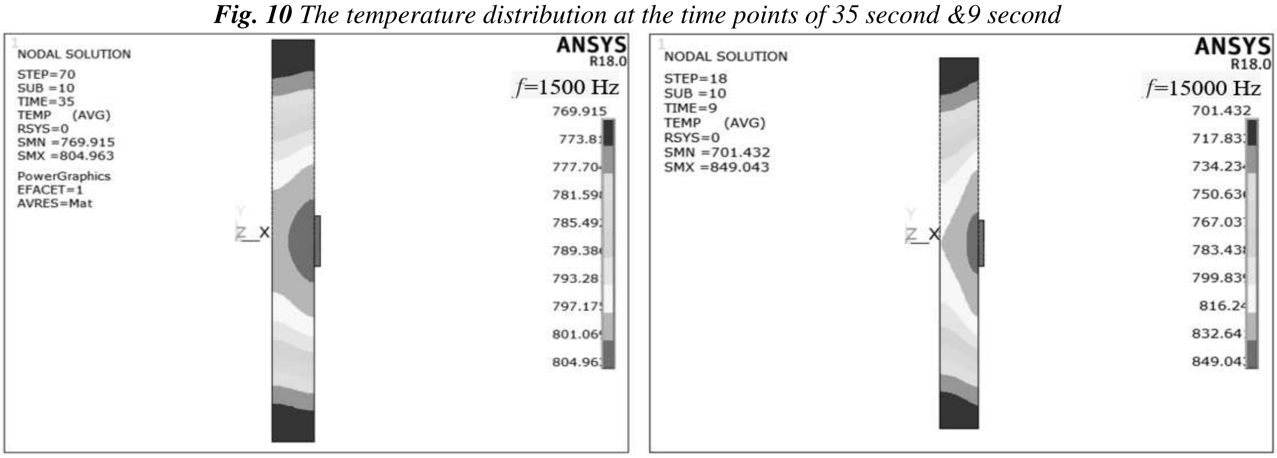

Fig. 11 *The temperature distribution under the condition of radiation*

5 Brazing experiment

In order to verify the feasibility of induction brazing, a split induction coil with 2 turns and the power supply with the power of 80 kW are used to perform the brazing experiment. An appropriate and feasible brazing procedure is very important to make sure the filler metal distributed evenly and worked with the base material absolutely. Based on the designed structure and the prepared instruments, the brazing procedures can be divided into four steps. The quality of the brazed joint is largely determined by whether the clearance between the two base metals are well satisfied. So that the filler metal can interact with the base metal better to join the two parts. As mentioned in paragraph 3, the most appropriate clearance between the base metals should be kept in 0.02 mm ~ 0.1 mm. Thus, the first step for brazing is using the polisher to polish the section of the joint part and keeping the clearance in required range. The second step is clearance. Since the inner and outer surfaces of copper tube usually contains oxide coating and dirt, the brazing region should be cleaned by abrasive paper and then washed by using the solution of acetone or alcohol. Not only the base metal, the filler metal should also be cleaned in the same procedure. The third step is to assemble the joint for brazing. The copper sleeve is to be assembled from one end of the copper conductor. A piece of ring-shaped brazing foils with the thickness of 0.3 mm needs to put at the joint position. Finally, the other end of the joint is assembled and the two ends of the sample to be pressed to the appropriate clearance. The last step is to braze the joint, during the brazing the argon is used as the protection gas. After finishing the brazing, the non-destructive test, tensile test and leakage test were implemented respectively. The inner surface of the brazing joint is shown in Fig. n, it indicates that the inner surface has good finish and no protrusion happened. The X-ray test is presented in Fig. 12, the test results show that the joint clearance is not filled completely by the brazing filler. The tensile test was done subsequently. The fractured sample is shown in Fig. 12. Though the joint was not filled completely, the fracture didn't happen on the joint position. The ultimate tensile strength is 217 MPa, which is a little lower than the base copper conductor (~ 240 MPa). Finally, the spraying method was selected to check the leakage performance of the brazing conductor sample. The results showed that the leakage of the brazing conductor was less than 10^{-10} Pa · m^3 · s^{-1}, which could satisfy the leakage requirements.

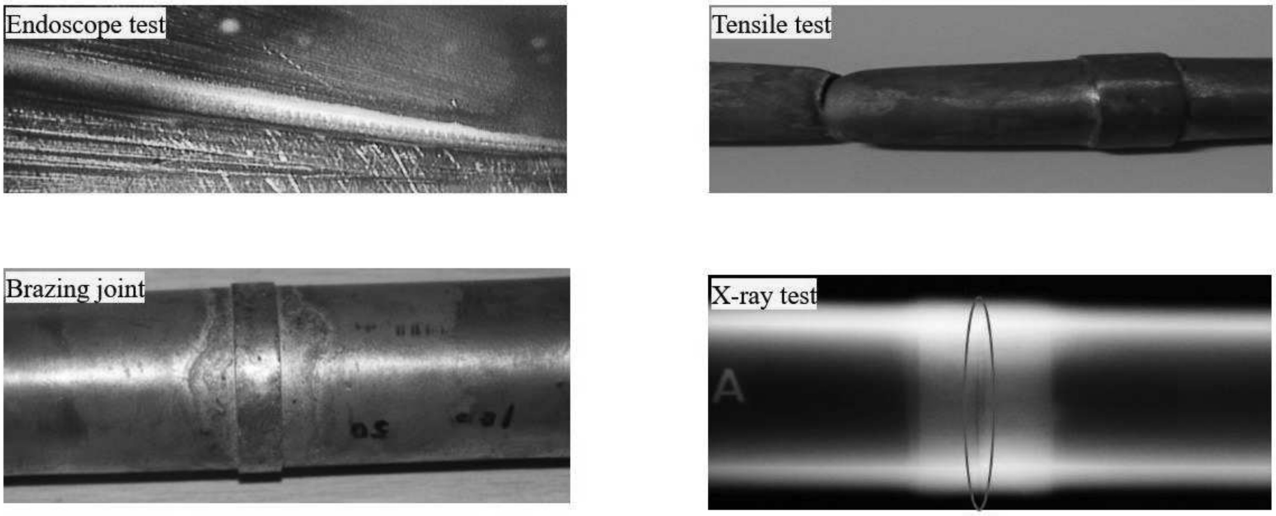

Fig. 12 *The test results for brazing joint*

6 Conclusion

During the upgrade process of EAST fast control coil, the induction brazing is attempted for the connection of conductor joint. A piece of copper tube is selected to carry out the study of induction brazing. The preliminary induction heating parameters are calculated and a 2 turns split induction coil with rectangular section is designed. A sleeve with the length of 10 mm is housed at the butt joint to enhance its strength. The BCu80Pag is selected as the filler metal and it will be filled into the joint through the hole on the sleeve by hand during the brazing process. The recommended valid value of current is 10 kA. Combining with the current frequency of 1500 Hz, it will induce up to 0.34 T magnetic density, it can not only satisfy the brazing requirement of EAST fast control coil but also be capable for the brazing of CFETR in-vessel coils. Some key factors affecting the induction brazing are analysed. The high frequency current will result in severe skin effect on the copper tube, it has potential hazard to cause large thermal stress during the brazing. Compared with the high frequency current, if the current frequency is rated as 1500 Hz, it will have deeper penetration depth and is much preferable for the copper tube. The joule heat generated during the induction brazing will change the thermal conductivity coefficient of copper tube. The varied heat conduction is applied to the coupling analysis model by dividing the heating process into numerable time sub-steps. Although the temperature going up will lead to the decrement of copper thermal conductivity coefficient, it can still effectively decrease the temperature difference between the copper tube inner and outer layers if accompanying proper heating time. The radiation will cause evident temperature decrement especially under the relatively longer brazing time. It is nonnegligible if medium induction brazing is adopted. The comprehensive performance tests indicate the induction brazing could satisfy the basic engineering design requirement, but more efforts should be made to improve the joint mechanical performance and reduce the defect in the brazing seam.

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