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# The experiment progress of bracket brazing to SSMIC for the ITER ELM prototype coil

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## HIGHLIGHTS

- In this study, the experimental research of brackets brazing to stainless steel jacketed, Mineral Insulated Conductor (SSMIC) of the first Edge Localized Modes (ELMs) prototype coil for ITER has been made.
- The technology for controlling the fluidity of silver-based brazing alloy is developed to meet the bracket brazing.
- Brazing experiments to find the reason for cracks are carried out and the improved brazing technologies to restrain the cracks in the Inconel 625 jacket with silver-based alloy are developed.

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## ABSTRACT

The first Edge Localized Modes (ELMs) prototype coil for International Thermonuclear Experimental Reactor (ITER) has been manufactured in the Institute of Plasma Physics, CAS (ASIPP) at 2014. The all 19 brackets need to braze to the stainless steel jacketed, Mineral Insulated Conductor (SSMIC) for transporting the nuclear heating in the brackets to the water-cooled SSMIC. Silver-based alloy is the only candidate brazing filler for the bracket brazing due to the limitation from melting point temperature and strength. In this paper, firstly, the experimental study for controlling the fluidity of silver-based brazing alloy is developed. And then, the brazing experiment of prototype bracket is introduced to develop the brazing process and some cracks in the Inconel 625 jackets surface appeared unexpectedly. The microstructures and tensile performance study of the cracked Inconel 625 jacket were made to explore the reason for cracks and the improved brazing technologies to suppress the cracks are developed. Finally, the bracket brazing experiment for the first ELM prototype coil is carried out, In spite of this, some cracks also appear in the Inconel 625 jackets.



## 1. Introduction

ITER is an experimental fusion device currently being designed by an international team which includes the United States, European Union, Japan, Korea, India, China and Russia for construction southern France. The ITER subsystem, namely the 'in-vessel coil' (IVC) system, including the ELM and Vertical Stabilization (VS) coil, has being designed by the Princeton Plasma Physics Lab (PPPL) and the prototype coil has being manufactured at ASIPP in China.

The so-called ELM coil, located with the ITER vacuum chamber will provide control of ELMs of the plasma. The ELM coil system consists of (27) 6-turn 'picture frame' coils which provide the ELM control [1]. According to the design requirement from PPPL, the all brackets should be brazed to the SSMIC using the local heating furnaces to avoid slippage between the SSMIC and brackets and ensures the good thermal conduction so that nuclear heating of the brackets to be transports to the water-cooled SSMIC [2]. Fig. 1 shows the middle ELM coil and bracket model.

Due to the mismatch between the coil winding accuracy and bracket machining precision, the local gap may be large which will bring the tremendous challenges for the bracket brazing.

With the help from PPPL and (ITER Organization) IO, the experiment research of bracket brazing to SSMIC technology for ITER ELM prototype coil has been performed at ASIPP. In this paper, at first, the experimental research for selecting and controlling the fluidity of brazing alloy are described to meet the brazing requirement due to the local bigger gap. Then, the experiment of prototype bracket brazing for ELM coil is developed and the microstructures and tensile performance study of the cracked Inconel 625 jacket were made to explain the reason for cracks. The improved brazing

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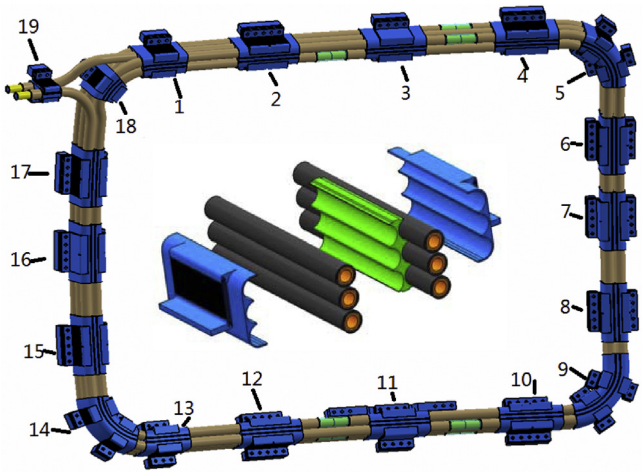


**Fig. 1.** Middle ELM model with bracket model.

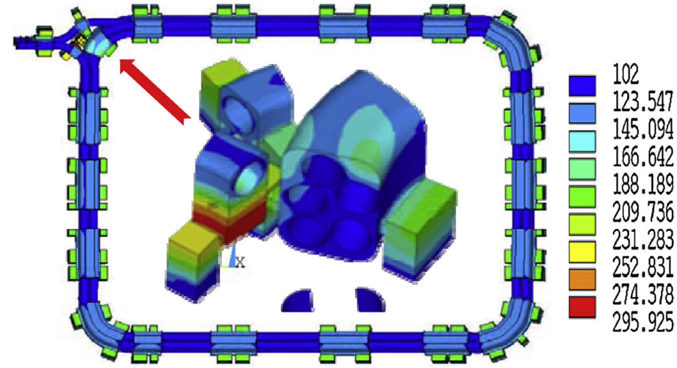


**Fig. 2.** Temperature distribution of ELM coil from unclear heat.

technologies to suppress the cracks in the Inconel 625 jacket are developed. Lastly, the bracket brazing experiment for the first ELM prototype coil is performed and some cracks also appear in the Inconel 625 jackets.

## 2. Brazing alloy and fluidity control experiment

### 2.1. Limitation and selection for brazing alloy

Based on the design requirement and the structure characteristic of the ELM coil brackets, the key technologies for brazing the bracket to SSMIC are as following: one is the lower fluidity control of the brazing alloy to reduce the void fraction and obtain the good thermal conduction; another is enough mechanical strength of the brazing alloy to avoid slippage.

But there are some unavoidable limitations for the brazing alloy selection: one is the melting point of the alloy for CuCrZr tube joint inside the SSMIC; another is the operation temperature of the brackets in the in vessel environment from the nuclear heating. The BCup-5 filler is used for the CuCrZr tube joint brazing where the melting point is 643 °C; another point, the temperature of the brackets from the nuclear heating is nearly to 300 °C from thermal analysis shown in Fig. 2 [3], so the melting point range of the alloy for bracket brazing should be from 300 °C to 643 °C.

According to the Ref. [4], only aluminum and silver based alloy can match the melting point requirement for the bracket brazing. But the shear strength test of the brazing alloy shows that the aluminum based alloy has the strong brittle and lower the shear strength, so the silver based alloy BAg-1 is the only candidate alloy due to the 620 °C melting point and 60 MPa shear strength [5].

### 2.2. Fluidity control for brazing alloy

Generally, the silver based alloy has the strong fluidity characteristic which is not suitable for the big gap brazing of ELM coil bracket structure. So the key problem urgent to resolve is to develop the technology to control the fluidity characteristic of the BAg-1 paste.

In order to control the fluidity of brazing alloy, it is a commonly method to add the high melting point metal powder in the brazing filler to increase the capillary action [6,7]. The experiment study used the pure copper powder with the BAg-1 paste as the filler is carried out. The size of copper powder should match with the brazing gap thickness. In this experiment, 75 um size copper powder is

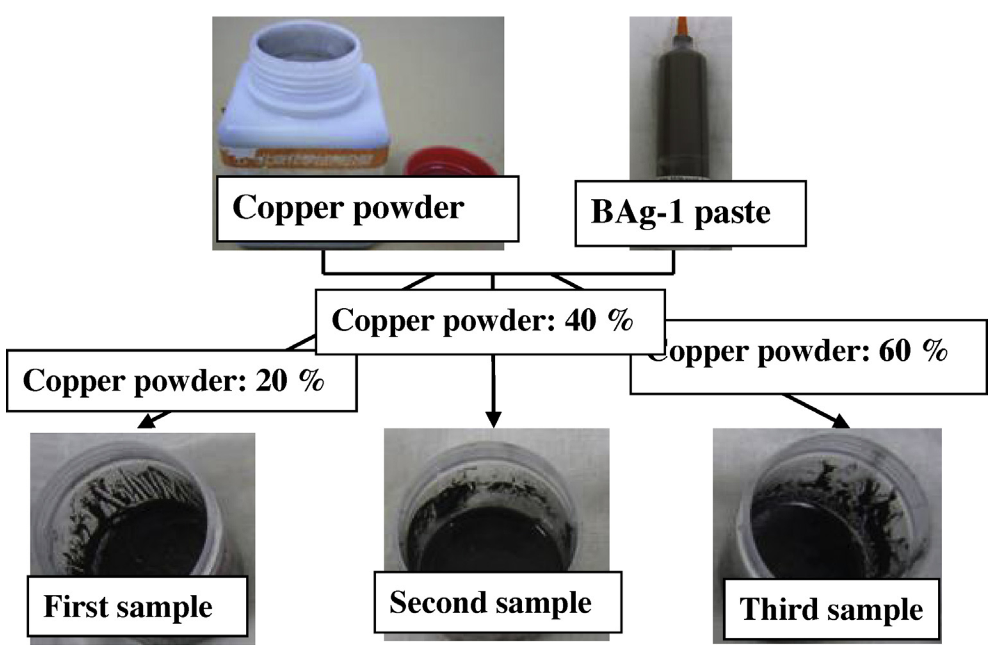


**Fig. 3.** The sample preparation of BAg-1 paste with the pure copper powder.

**Fig. 4.** The experiment result of bracket sample with the pure powder as the filler.

used for the 0.8–1 mm thickness brazing gap. Three brazing filler samples with the 20%, 40% and 60% copper powder proportion in the BAg-1 paste are prepared shown in Fig. 3.

The three brazing fillers with the copper powder is filled into the three bracket samples uniformly and heating in the 640 °C oven for 1 h. According to the brazing results shown in Fig. 4, the brazing is failure and the probably reason is that the copper powder is easy to oxide in the non vacuum brazing environment. So the copper powder is not suitable to be as filler for bracket brazing in the present brazing condition.

It is another method to use the higher melting point silver-based alloy foil such as BAg-6 as the filler. The fluidity experiment results shows that BAg-1 paste has penetrated into the BAg-6 foil and the fluidity area of the melting BAg-6 foil almost no change at 630–750 °C shown in Fig. 5. So the fluidity characteristic of brazing alloys can be controlled effectively at particular temperature.

The further experiment is carried out using the stainless steel bracket sample with six jackets to simulate the real bracket brazing process. The BAg-1 paste with BAg-6 foil is used as the filler and the heating condition is 640 °C for 1 h. The result shows there is almost no void fraction in the bracket cutting surface shown in Fig. 6. X-ray test is carried out in the part of the bracket which shows that there

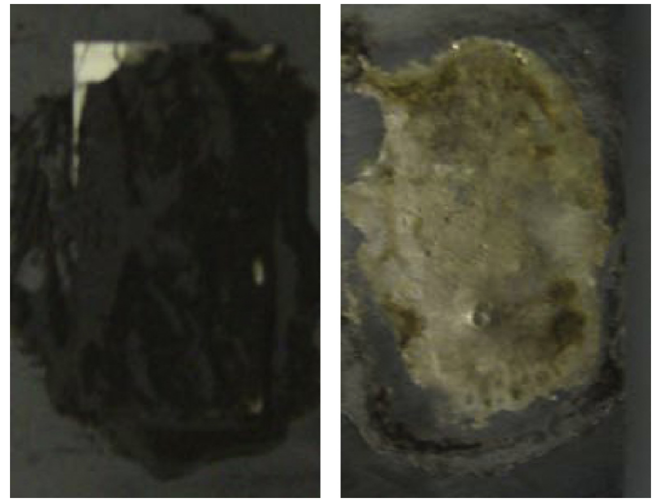

**Fig. 5.** The fluidity character experiment of BAg-1 paste with BAg-6 foil.

is also no void in the all brazing surface. So this bracket sample can obtain the good thermal conduction between the SSMIC and bracket. Fig. 7 is the X-ray test result of the bracket sample.

According to the fluidity control experiment of brazing alloy, the BAg-1 paste with BAg-6 foil filler can meet the bracket brazing requirement to SSMIC at 630–750 °C.

## 3. The prototype bracket brazing experiment

### 3.1. Brazing procedure

In order to develop the bracket brazing procedure for the ELM prototype coil, an Inconel 625 prototype bracket with six SSMICs is prepared. Brazing in the heating furnace is used. The whole brazing preparation procedure includes the following process:

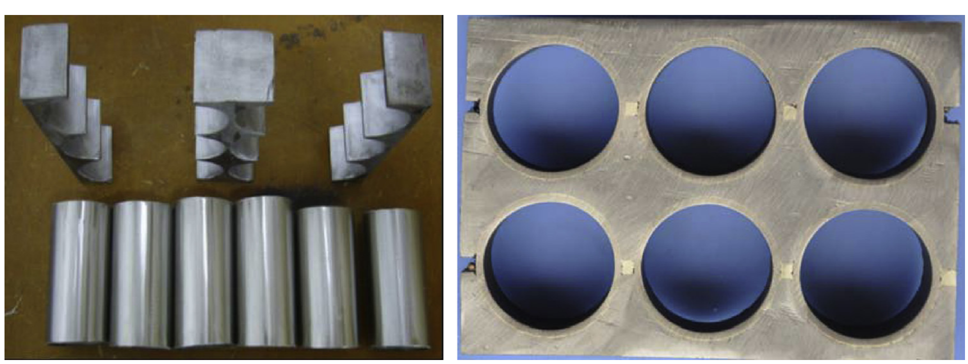

**Fig. 6.** The bracket sample with six jackets and brazing results.

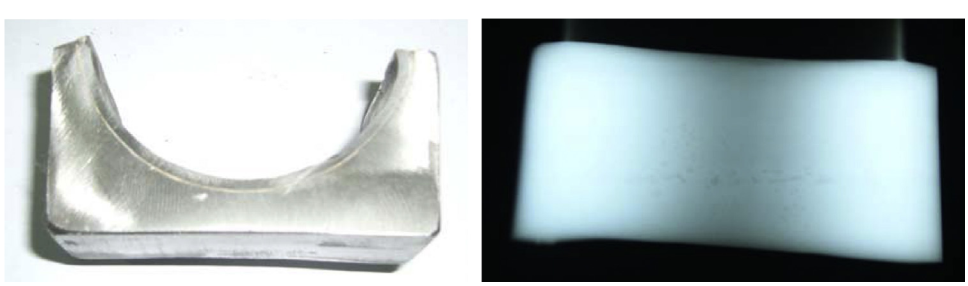

**Fig. 7.** The X-ray test result of the bracket sample.

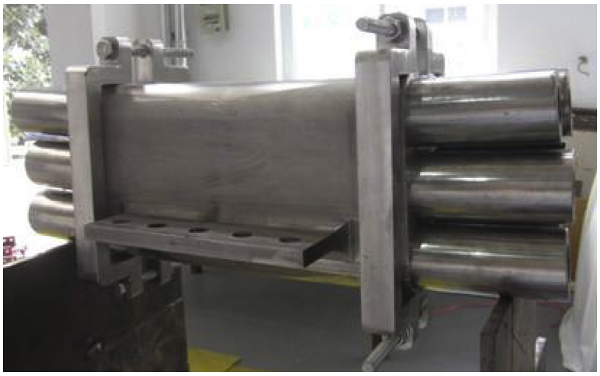

**Fig. 8.** The prototype bracket assembly process.

(1) The treatment process with acetone to remove the oil in the brazing surface;
(2) The filling process with the BAg-1 paste and BAg-6 foil;
(3) The bracket assembly process with SSMICs shown in Fig. 8;
(4) The heating oven assembly process which includes the frame, heating resistor and high temperature adiabatic fibers assembly shown in Fig. 9;
(5) The last is the heating brazing process.

### 3.2. Brazing parameters and results

Since the thermal conductivity of the Inconel 625 material used for bracket and jacket is very poor, so the heating time is much longer by heating transfer in the heating oven. In order to obtain the reasonable heating rate and power, a heating transfer analysis is simulated for the prototype bracket model with six SSMICs. The simulation results show that the whole brackets temperature has reach the brazing temperature 630 °C and the maximum temperature is 700 °C in the middle of bracket with 10 kW heating power after 3 h shown in Fig. 10. So the 10 kW is the reasonable heating power for single bracket brazing due to the not much high temperature difference in the bracket and jackets. Table 1 shows the parameters of the prototype bracket brazing to SSMIC.

**Fig. 9.** The heating oven assembly process for bracket brazing.

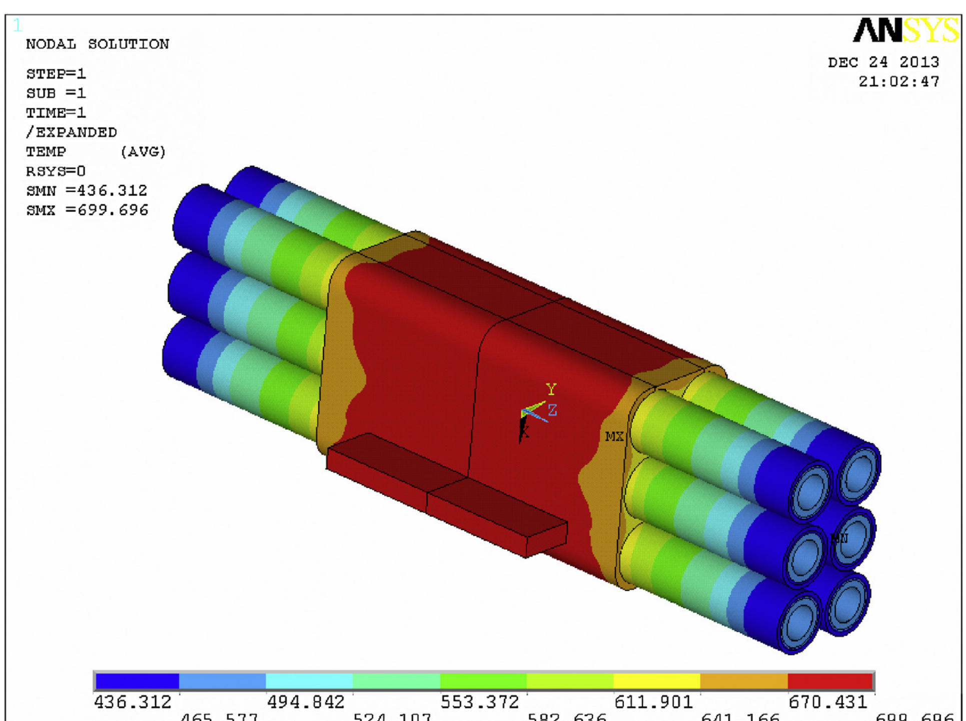


**Fig. 10.** The temperature distribution of the bracket during brazing.

**Table 1**
The main parameters of the prototype bracket brazing to SSMIC.

| Method | Protection gas | Max. temperature | Heating rate | Holding time |
|---|---|---|---|---|
| In furnace one by one | Nitrogen | 700 °C | 3 °C/min | 1 h |

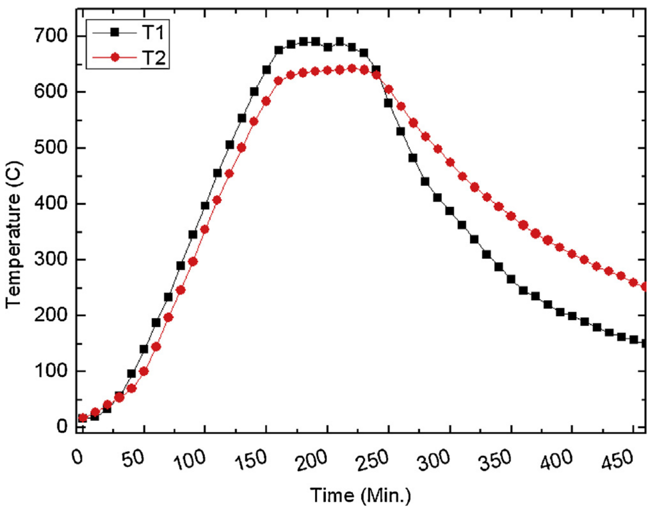


**Fig. 11.** The brazing curve for prototype bracket.

Fig. 11 shows the brazing curve for the prototype bracket. Where T1 is the temperature in the middle of the bracket and T2 is the temperature in the end of the bracket. This brazing curve is almost the same as the simulation result.

The brazing performance seems good by visual, but some cracks appear on all jackets surface unexpectedly. The all cracks seem to spread from inside to the outside shown in Fig. 12.

## 4. Cracks cause analysis

In order to explain the cause of Inconel 625 jackets crack, the microstructure and tensile performance study of the cracked Inconel 625 jacket were made.

Two samples of Inconel 625 are prepared for the microstructure study, one is from the cracked jacket and another is from no cracked Inconel 625 jacket. Fig. 13 shows the grain structure near the cracked and no crack Inconel 625 jacket by the microscope. According to the pictures, for both Inconel 625 samples, lots of precipitates are not only along the grain boundaries, but also distributed in the grain and more twins can be seen in the cracked grain structure.

Through the observation of the fracture surfaces of the cracked Inconel 625 jackets shown in Fig. 14, it can be concluded that the oxidized brazing alloy had precipitated on the fractured surface.

Further study has been carried out by Scanning Electron Microscopy (SEM) technology. According to the SEM image and the EDS test results shown in Fig. 15, it can infer that most of the precipitates are MC.

The tested tensile of the cracked Inconel 625 jacket is also performed to evaluate the mechanical performance after brazing with the silver-based alloy. The UTS of the brazed jacket from the bracket sample is only about 50 MPa compared to the more than 900 MPa for the raw Inconel 625 jacket. This tested tensile jacket sample were separated from bracket sample brazing to SSMIC by heat to higher temperature (>850 °C and longer than 1 h).

Based on the microstructures and tensile performance study of the cracked Inconel 625 jacket, it is clear that the Inconel 625


**Fig. 12.** The cracks in the jacket surface.

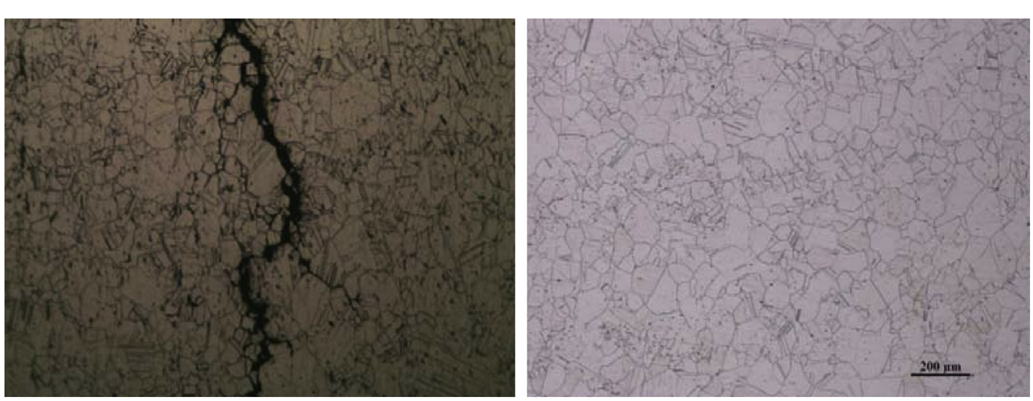


**Fig. 13.** (a) Grain structure near the crack and (b) grain structure of Inconel 625 jacket without brazing.

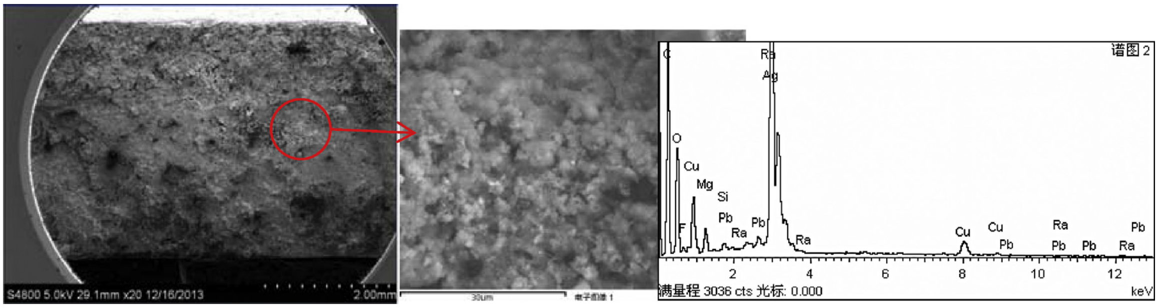


**Fig. 14.** Oxide brazing alloy precipitated on the fractured surface.

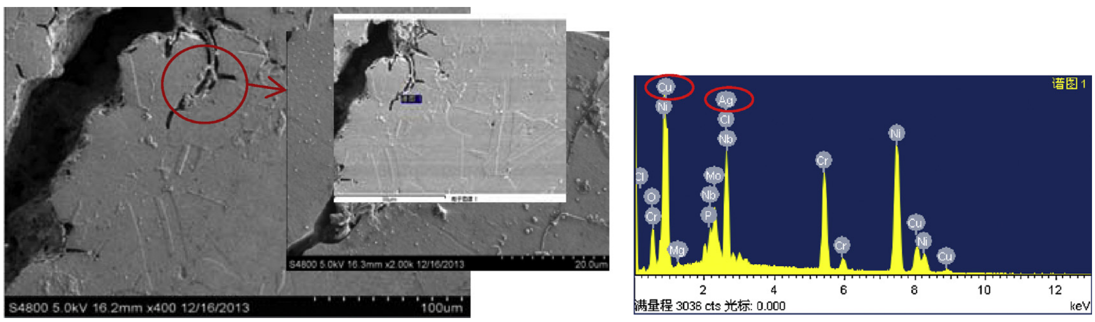


**Fig. 15.** Microstructure of cracked Inconel 625 jacket (observed by SEM).

material would become brittle and mechanical properties would decrease after the higher and longer temperature heating with the silver-based alloy. The conclusion has been certified by some literatures. According to the Ref. [8], it reported that the Inconel 625 aged at 760 °C for 300 h, the material would become brittle, and the tested Charpy Impact Absorbed Energy decreased from 149 J to 19 J. Further analysis is also performed by IO, some conclusions made is that: the silver-based alloy containing the lower melting point metal may induce the Inconel 625 metal cracking combined the high stress which is the most probably origin of the crack [9]. Fig. 16 shows the specimen of silver-based Inconel 718 showing the stress-corrosion cracking.

With the exception of the internal cause above, the external cause is also an important factor for the crack. We think that the larger thermal stress from the inner CuCrZr copper tube is maybe the main inducement due to the larger thermal expansion property. The mean thermal expansion of the CuCrZr copper tube is 18.8 m/K compared to 14 the m/K for the Inconel 625 in the 600 °C (Fig. 16).

In order to verify this assertion, six ELM conductor samples were prepared to braze to the mockup bracket. Among them, four conductor samples with the brazing alloy are cooled by Nitrogen gas in the CuCrZr copper holes to suppress the thermal expansion during the cooling process. The remaining two conductor samples are not cooled by Nitrogen gas in the CuCrZr copper holes in which one sample is without brazing alloy and the other is with brazing alloy. The meaning compression in the all jackets surface is about 8 tons (mean 3 MPa). The other brazing procedure is the same as the prototype bracket brazing process. The experiment sample is shown in Fig. 17. The brazing experiment results show that only the sample which is not cooled by Nitrogen gas with the brazing alloy appears the crack. So it verifies that the larger thermal expansion from CuCrZr conductor tube is the main inducement for the crack in the Inconel 625 which makes large thermal stress on the jacket during cooling process.

According to the crack analysis, the inner cause is that the Inconel 625 material would become brittle and mechanical properties would decrease after the higher and longer temperature heating with the silver-based alloy; the external cause is the larger thermal stress from the inner CuCrZr copper tube. If the materials of Inconel 625 jacket and the silver-based alloy cannot be changed, it is an effective method to suppress the crack in the Inconel 625 jacket by cooling the CuCrZr copper tube during brazing process.

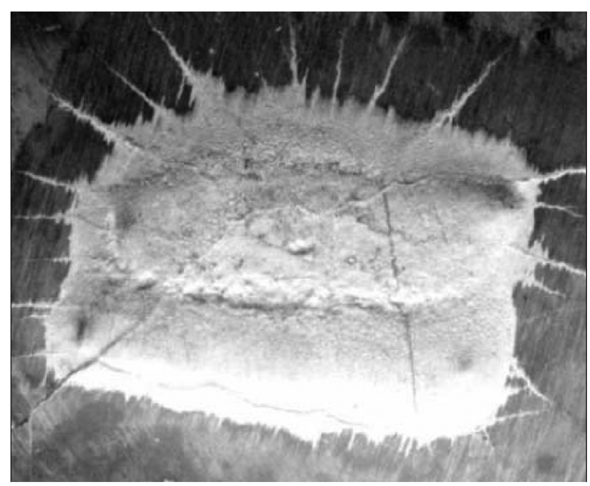

**Fig. 16.** Specimen of silver based Inconel alloy 718 showing stress-corrosion cracking [9].

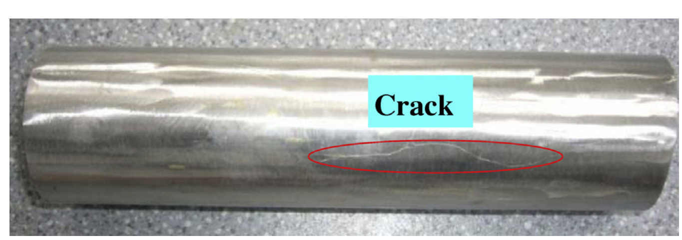


**Fig. 17.** The sample crack.

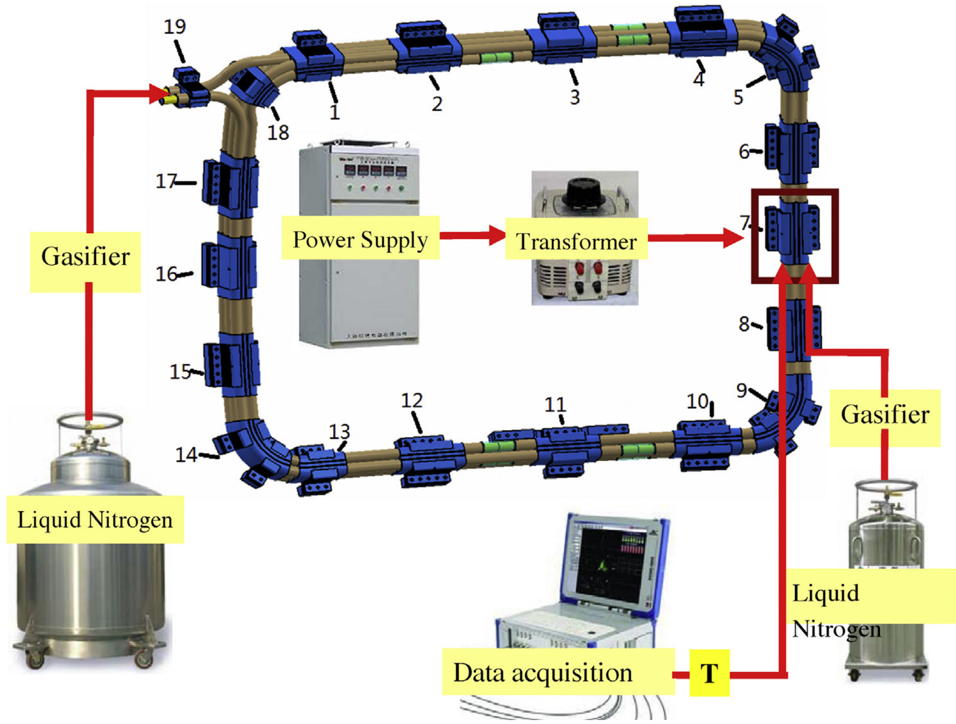


**Fig. 18.** Sketch map of the single bracket brazing process.

## 5. Bracket brazing for prototype ELM coil

Based on the prototype bracket brazing experiment and crack analysis, the bracket brazing activity to SSMIC for ELM prototype coil is performed on the April of 2014. The brazing method in the heating oven is used for all brackets one by one. The all procedure for bracket brazing includes the filling brazing alloy process, pre-loading clamps and welding the housing process, heating oven assembly process and the bracket heating process. The brazing parameters are the same as in Table 1.

The whole systems for bracket brazing include the power supply control system, data acquisition system, protection gas system and CuCrZr copper tubes cooling system. Fig. 18 shows the sketch map of bracket brazing process for the ELM prototype coil.

The typical bracket brazing curve for the prototype ELM coil shown in Fig. 19. Where T1 and T2 is the air temperature in the top and bellow of the bracket, T3–T6 is the bracket temperature in the different location.

Unfortunately, there are also some unexpected cracks appear on the jackets surface shown in Fig. 20 even if some technologies are improved for the brazing process.

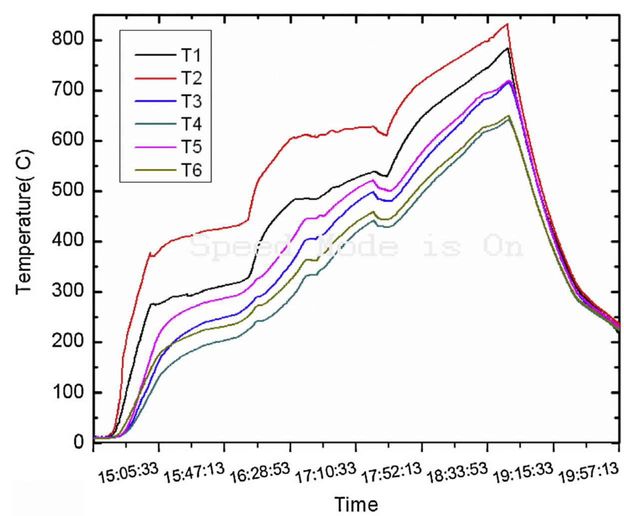


**Fig. 19.** The typical bracket brazing curve for the prototype ELM coil racks in the jacket surface.

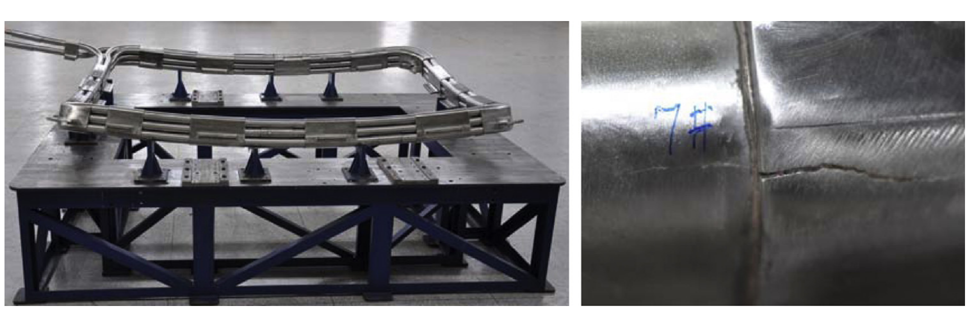


**Fig. 20.** The ELM prototype coil and the cracks in the jacket surface.

## 6. Summary

The bracket brazing technology has been developed and applied with the silver-based alloy for the ELM prototype coil at ASIPP. So far, the biggest problem is the crack in the Inconel 625 jacket. The microstructure and tensile performance study of the cracked Inconel 625 jacket reveal that Inconel 625 material would become brittle and mechanical properties would decrease after the higher and longer temperature heating with the silver-based alloy.

On the premise that the ELM coil and bracket design are not changed, the feasible improved technology for bracket brazing to suppress the cracks in the jackets in the further progress maybe is: using the induction heating method instead of heating furnace to reduce the brazing time.

## Acknowledgements

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