Study on Characteristics of Dissimilar Material Joints for ITER First Wall

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Abstract. The first wall (FW) of ITER blanket includes beryllium (Be) armor tiles joined to CuCrZr heat sink with stainless steel (SS) cooling tube and backing plate in order to improve plasma performance and reduce thermal stress. Since these joints must withstand thermal and mechanical loads caused by the plasma and electromagnetic force, it is important to evaluate the strength and thermal fatigue life of the joints. Qualification tests of the FW fabrication technology are performed in order to qualify the joining technologies. The Japan Domestic Agency (JADA) has fabricated the qualification mock-up with a hot isostatic pressing (HIPing) technique and carried out the materials testing and the non-destructive examinations. When the dissimilar materials joints are subjected to external force and thermal load, the stress distribution shows singularity and large stress concentration at the interface edges caused by discontinuity of the elastic properties. The characteristics of stress singularity were analyzed for the Be/CuCrZr and SS/CuCrZr joints. The results of tensile test showed that the Be/CuCrZr joint fractured at the interface because of large stress concentration at the interface edges. For the SS/CuCrZr joint, however, the joint fractured at CuCrZr apart from the interface. There was insignificant stress concentration at the interface edges, because those elastic properties are almost same. Since Charpy impact strength of the SS/CuCrZr joint was inferior to the CuCrZr, elasto-plastic finite element analyses were also carried out to clarify the deformation characteristics and fracture of the tensile and Charpy specimens. Those fracture behavior were caused from the plastic deformation properties of both materials.

1. Introduction

The first wall (FW) of ITER blanket is composed of beryllium (Be) armor tiles, CuCrZr heat sink and stainless steel (SS) cooling tubes and backing plates to improve plasma performance and reduce thermal stress. Beryllium is selected as reference armor material because of low plasma pollution, oxygen getter capability and acceptable erosion lifetime. Since the ITER applies various plasma experimental operations, the blanket modules will be exposed to the strong electromagnetic load in case of plasma disruptions, as well as the heat radiation and neutron load. In order to obtain high heat transfer capability and sufficient strength of the components, these materials are bonded metallurgically and firmly. Namely, dissimilar materials joints should be indispensable for the in-vessel components. Moreover, these joints must withstand the thermal, mechanical and neutrons loads under the cyclic mode of operation, while providing an acceptable design lifetime and reliability.

Toward the procurement of ITER FW, each Domestic Agency needs to demonstrate its capability to fabricate the FW through the fabrication of a representative mock-up including most of the technical specifications, material testing and non-destructive examinations to qualify the joining technologies required for the ITER FW. And then, the mock-ups are tested under the representative heat load conditions to prove the soundness of the joints. The qualification of the FW fabrication technology is very important for maintaining the ITER operation reliability enough, because the FW is exposed to the severe environment stated above. The Japan Domestic Agency (JADA) has fabricated the mock-up with a hot isostatic pressing (HIPing) technique and carried out the materials testing and the non-destructive examinations, such as ultrasonic examinations, helium leak and pressure tests, in accordance with the specifications proposed by ITER organization [1,2]. All examinations and materials tests showed that the mock-up was defect free and satisfied for the specifications. This paper describes the fabrication technique of the mock-ups in JADA, characteristics of stress distribution and strength of the joints in consequence of the mechanical properties of their materials.

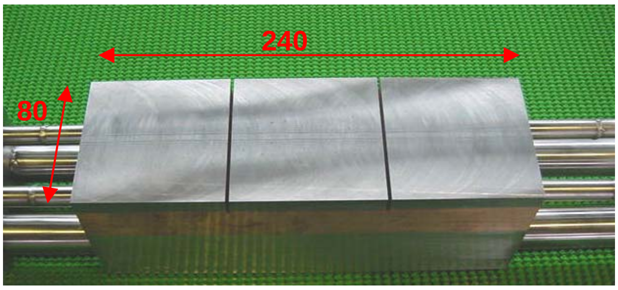

FIG. 1. Fabricated qualification mock-up in JADA.

2. Fabrication of FW Qualification Mock-ups

FIGURE 1 shows the fabricated qualification mock-up in JADA. The mock-up included three Be tiles size of 80×80×10 mm thick. The gap between the tiles was 2 mm. As for the beryllium tiles, S65C vacuum hot pressed (VHP) block has been selected. Because of some anisotropy of mechanical properties of the VHP block in longitudinal and transverse directions (relative to pressing axis), the Be tiles were cut from VHP block in accordance with parallel to the direction of pressing.

The used CuCrZr was 15 mm-thick plate. Since CuCrZr alloy is a precipitation hardening material, it is proposed to be used in the solution annealed and aged state in the FW. For the heat treatment of CuCrZr, the solution annealing temperature should be high enough to make re-solution of alloying elements and a sufficiently high cooling rate is necessary to keep the alloying elements in supersaturated solid solution. Cooling rates lower than the critical one would induce an early precipitation of coarse particles. In the fabrication of FW, important processes are HIPing conditions of the SS/CuCrZ, CuCrZr/CuCrZr and CuCrZr/Be joints, because the joining processes accompany with the heat treatment of CuCrZr and affect the strength of CuCrZr and the joints. For simultaneous HIPing of SS/CuCrZr and CuCrZr/CuCrZr in the fabrication, the HIP and after-HIP heat treatment conditions have been investigated taking the FW fabrication process into account. From the previous development of HIPing technique [3-7], the HIP condition for joint between dispersion strengthen copper and SS was temperature of 1050ºC, pressure of 150 MPa and holding time of two hours. However, the temperature of 1050ºC corresponds to a eutectic point of the CuCrZr alloy and the CuCrZr may melt at this temperature. Therefore, temperature of 1045ºC, pressure of 150 MPa and holding time of two hours is adopted as the possible HIP joining condition for the SS/CuCrZr and CuCrZr/CuCrZr in this fabrication.

Though the CuCrZr needs fast cooling such as water quenching in the solution anneal treatment, the fast cooling cannot be applied in the HIP furnace and precipitation of coarse particles will be induced. Hence, the re-solution annealing after the HIPing was performed in other furnace with forced convection cooling in order to get high cooling rate. While the solution annealing is normally performed at temperature of 980 ºC, the CuCrZr was not getting sufficient strength, because the solution temperature was not high enough to make re-solution of the precipitation. Therefore, temperature of the re-solution annealing increased to 1045 ºC same as the temperature of HIPing to make re-melt of the coarse precipitation. Consequently the tensile properties of the CuCrZr satisfied the specifications.

The HIPing process of Be joining onto CuCrZr is regarded as the aging process for CuCrZr. An optimum aging treatment to obtain sufficient strength is temperature of 450-480ºC for several hours [8]. High temperature of HIPing between Be and CuCrZr is desirable to get enough strength joint, however, brittle intermetallic phases between Be and CuCrZr are formed. The temperature selection and prevention of intermetallic phases formation are key issues for obtaining sufficient mechanical strength of CuCrZr and the joint. As the diffusion barriers to prevent intermetallic phases forming, Cr coating of 1 μm and Cu coating of 10 μm thickness on the Be surface to be bonded were carried out with PVD technique. From these points of view, the HIPing condition of 580ºC and 1 hour was selected after some study.

3. Characteristic of Stress Distribution in Dissimilar Materials Joints

3.1 Stress Singularity at Interface Edge

Since the FW is subjected to severe stresses caused by material mismatch of thermal expansion and electromagnetic force, it is important to evaluate the strength of the joints. When the dissimilar materials joints are subjected to external force, the stress distribution shows singularity due to discontinuity of materials properties at the interface edges. These stresses may lower the strength of joints. Bogy et al. have been investigated the stress singularity using an application of the Mellin transform in conjunction with the Airy stress function. Elastic stress at an interface edge is expressed by the following equation [9].

$$\sigma_{ij} \propto r^{-\lambda}$$

Where r is distance from the bonding edge and λ is order of singularity as shown in *FIG.2*. When the r diminishes, the stress increases and shows singularity. The stresses under mechanical and thermal loading had been evaluated for the bonded quarter-planes joint. The analysis was carried out for the SS/CuCrZr and Be/CuCrZr using those materials elastic properties. The stresses are obtained as following equations [10].

$$\sigma^1{}_{ij}(r,\theta) = K^1{}_{ij}(\theta) r^{-0.02} + \sigma^1{}_{0ij}(\theta) \quad \text{for SS/CuCrZr joint}$$

$$\sigma^2{}_{ij}(r,\theta) = K^2{}_{ij}(\theta) r^{-0.08} + \sigma^2{}_{0ij}(\theta) \quad \text{for Be/CuCrZr joint}$$

Where (r,θ) is plane polar coordinates, $K^k{}_{ij}$ are stress intensity factors and $\sigma^k{}_{ij}(\theta)$ are thermal stress terms. If the loading is only external force, the $\sigma^k{}_{ij}(\theta)$ disappears. The stress singularity depends on their combination of the materials and configuration of joints. The results show that the order of stress singularity for Be/CuCrZr joint was 0.08, however, the singularity was small for the SS/ CuCrZr joint, because those elastic properties are almost same.

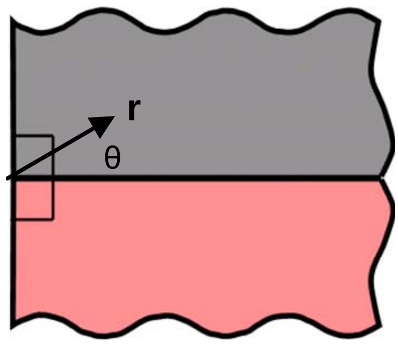

FIG.2. Model for bonded two-wages.

3.2 Thermal Stress Distribution of Bonded Plate

In a two or three materials joint, thermal stress develop after a change in temperature due to the different thermal expansions of the materials. As an example, the thermal stress was evaluated for the Be/CuCrZr joint with the thickness of 10 mm of Be and 70 mm of CuCrZr plate using those materials properties as shown in *FIG.3*. The loading was a homogeneous increase in temperature of 500 ºC. The thermal expansion of the CuCrZr plate is larger than that of the Be plate. Consequently, bending of the bonded plate is generated and compressive stress develop at the CuCrZr plate and tensile stress at the Be plate. *FIGURE 4* is the thermal stress distribution in the center of the joint. A jump at the interface in stress component parallel to the interface is developed. If the Be plate has some defects near the interface, this tensile stress can lead to crack propagation.

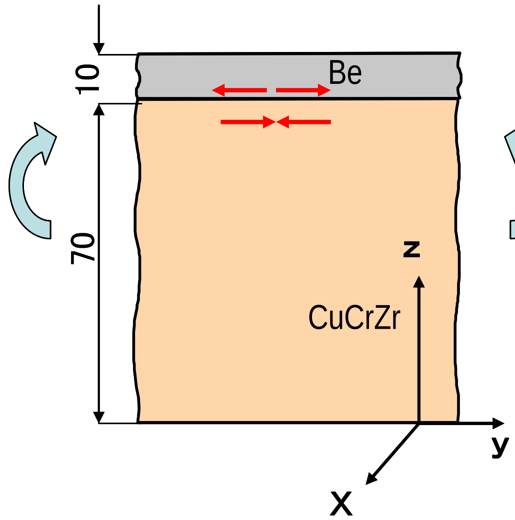

FIG. 3. Configuration of bonded plate.

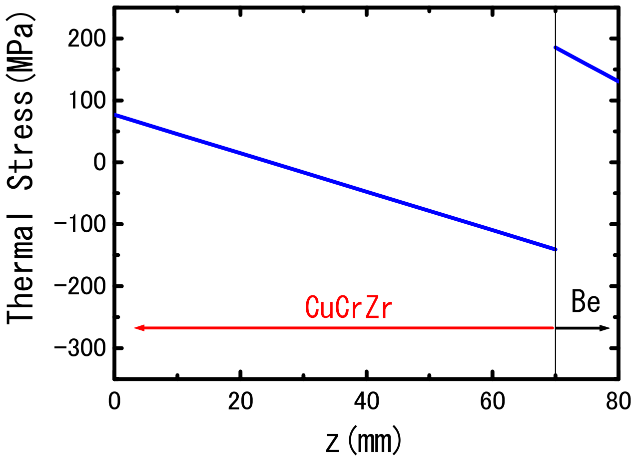

FIG. 4. Thermal stress of bonded plate.

4. Strength of Joints

As the destructive examination tests of the joints for the qualification of the mock-up, tensile, shear, 4-points bending, Charpy impact and fracture toughness tests were conducted in accordance with the specification proposed by ITER organization [2]. In this section, the results of the tensile, Charpy impact test and the relevant analyses with elasto-plastic finite element method (FEM) are described to make clear the deformation and fracture behavior of the specimens.

4.1 Tensile Properties of Joints

FIGURE 5 shows the fractured tensile specimens. The specimens of Be/CuCrZr joint fractured at the bonding interface, while their strength is over 80% of the CuCrZr. The degradation of tensile strength for the Be/CuCrZr joint is attributed to the stress singularity as mentioned in section 3.1 or its low bonding strength. On the other hand, the tensile specimens of the SS/CuCrZr joint fractured at the CuCrZr region apart from the interface. The tensile strength of SS/CuCrZr joint was the same as the CuCrZr base. In order to clarify the deformation and fracture behavior of the tensile specimens, elasto-plastic

Be/CuCrZr *SS/CuCrZr*

FIG. 5. Fractured tensile specimen.

FEM analyses were carried out using stress-strain curves of the SS and CuCrZr base metals as shown in *FIG. 6*. As can be seen from *FIG. 6*, the deformation stress of SS is weaker than that of CuCrZr at small strain range but stronger at large strain range. *FIGURE 7* shows distributions of axial stress on the interface near the edge for the SS/CuCrZr joint. In this figure, the stress were compared with a ratio of distance from the edge, r, to the radius of the specimen, w, in respect of elastic and elastic-plastic analyses for nominal strain ε=0.2-0.75 %. The stress singularity, which is designated by a slope of the stress distribution around the interface edge, existed slightly for elastic analysis and was 0.0203. This value is well in accordance with the theoretical result of 0.02 as shown in section 3.1. As the strain was advanced to the plastic range ε=0.2-0.5 %, the stress singularity decreased because of varying those mechanical properties.

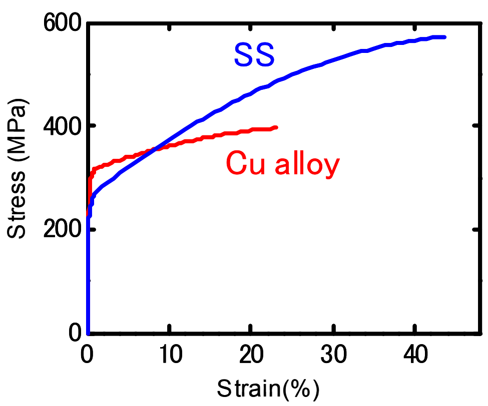

FIG.6. Stress-strain curves used.

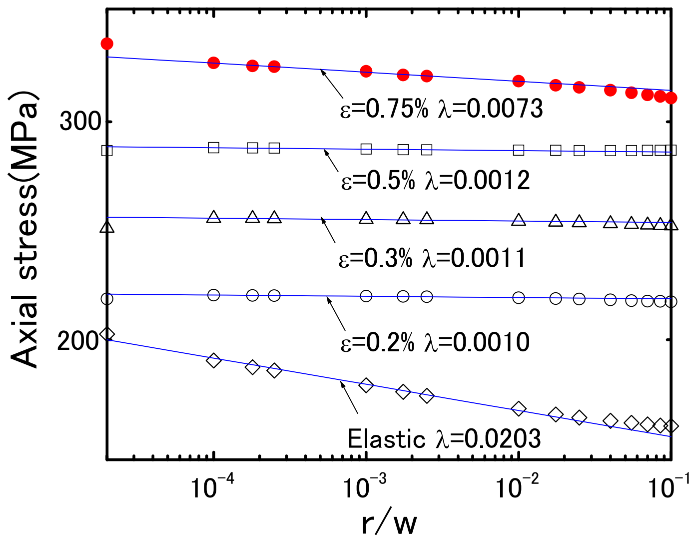

FIG.7. Stress on interface near edge.

FIGURE 8 shows contours of the Mises stress and plastic strain distribution for 0.5 and 10% of nominal tensile strain obtained by the elasto-plastic FEM analyses [11]. In case of 0.5% nominal strain, the stress and strain of SS near the interface were small due to tri-axial tensile stress, because the deformation of SS was constrained from the CuCrZr owing to the fact that the stress-strain curve used for the FEM modeling shows that the SS is slightly weaker than the CuCrZr at this strain range. For 10% nominal strain, however, the deformation of CuCrZr near the interface was constrained from the SS and the stress and strain were small near the interface contrary to the case of 0.5 % nominal strain. The maximum strain occurred at the CuCrZr side apart from the interface and the strain of CuCrZr was larger than that of the SS, because the SS is strong rather than the CuCrZr at the large strain range. These calculations support the experimental observation that the tensile specimen fractured at the CuCrZr from the interface.

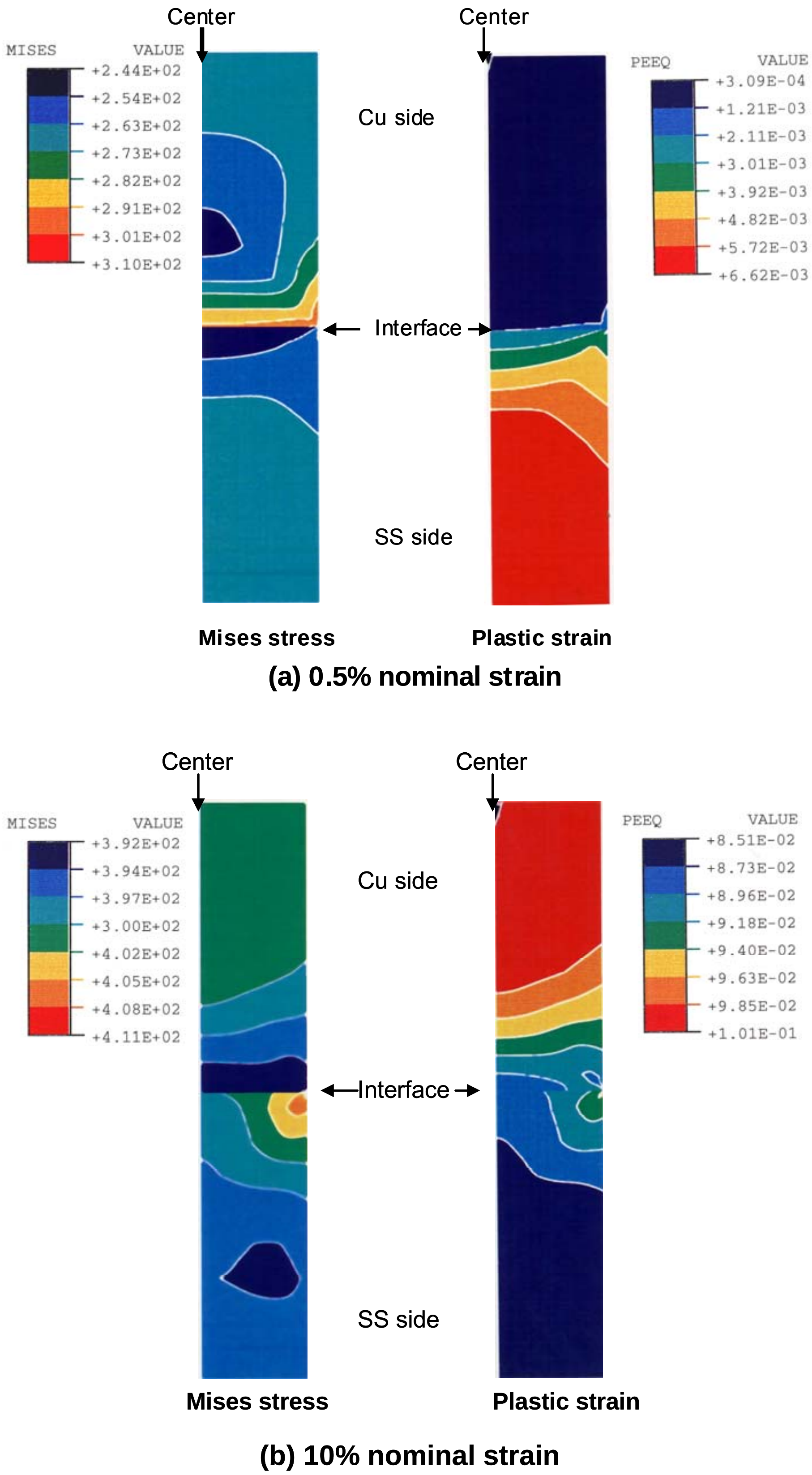

FIG. 8. Results of FEM analysis for tensile test in case of 0.5 and 10% nominal strain.

4.2 Charpy Impact Strength of SS/CuCrZr Joint

Charpy impact test was conducted using 7.5x10x55mm size of V-noched Chapy specimen. The notch of 2mm depth was introduced with the interface located at the center of the notch root. The specimens fractured at the CuCrZr near the interface of joint as shown in *FIG.9* and the impact strength was about 39 J/cm^2, which was significantly lower than that of CuCrZr base of approximately 140 J/cm^2.

In order to clarify the degradation of Charpy impact strength of the joint compared with CuCrZr base, elasto-plastic FEM analyses were performed [11]. The FEM analyses were of three-points bending of the Charpy specimen for the SS/CuCrZr joint and whole CuCrZr base. As a result of the FEM analyses, plastic strain distributions near the notch root of specimens for the SS/CuCrZr joint and whole CuCrZr are shown in *FIG.10*. Concerning the SS/CuCrZr joint, the plastic strain concentrated at the CuCrZr near the interface compared with whole CuCrZr. This strain concentration arose from that the CuCrZr is weaker than the SS as the fracture of the tensile specimen, while the deformation of whole CuCrZr specimen developed uniformly at the notch root. The Charpy absorbed energy consists of its deformation and generation of fracture surfaces. The deformation energy of the joint is lower than that of the whole CuCrZr. Therefore, the degradation of Charpy impact strength of the joint was attributed to the strain concentration, which was caused by the plastic deformation properties of both materials.

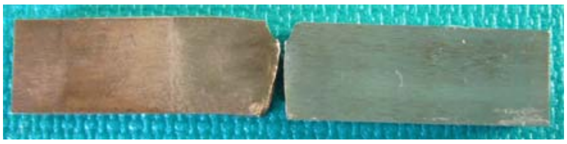

FIG.9. Fractured Charpy impact specimen of SS/CuCrZr joint.

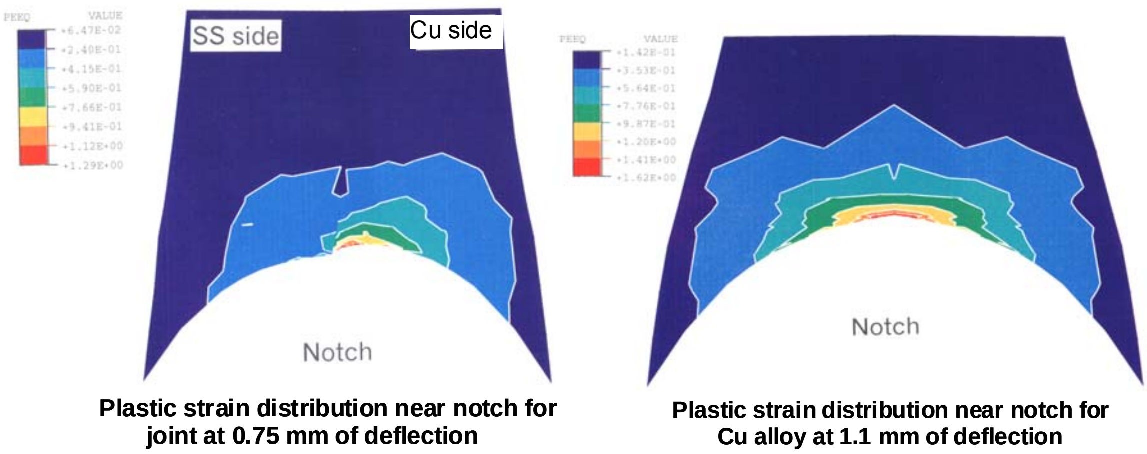

FIG.10. Plastic strain distributions near notch root of Charpy Impact Specimen.

5. Summary

The JADA has fabricated the qualification mock-up using the HIPing and carried out the materials testing and the non-destructive examinations to qualify the joining technologies. The conditions of the HIPing and the heat treatment were contrived for sufficient strength of the joints and CuCrZr. All examinations and materials tests showed that the mock-up was defect free and attained sufficient strength.

When the dissimilar materials joints are subjected to external force and thermal load, the stress distribution shows singularity and large stress concentration at the interface edge caused by those elastic properties. Concerning the SS/CuCrZr joint, however, the singularity was small and the tensile specimen fractured at CuCrZr, because the elastic properties between SS and CuCrZr are almost same. Nevertheless, the singularity of Be/CuCrZr joint was serious matter. More investigations on the effect of cyclic heat load on the strength and thermal fatigue life are important for Be/CuCrZr joint.

Acknowledgement

This report was prepared as an account of work by or for the ITER Organization. The Members of the Organization are the People's Republic of China, the European Atomic Energy Community, the Republic of India, Japan, the Republic of Korea, the Russian Federation, and the United States of America. The views and opinions expressed herein do not necessarily reflect those of the Members or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the ITER Joint Implementation Agreement.

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