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Effects of Cooling Rate and Aging Temperature of CuCrZr Alloys for Fabrication of ITER First Wall

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1. Introduction

The first wall of the International Thermonuclear Experimental Reactor (ITER) is multilayer components consisting of plasma facing armor materials, heat sink materials and structural materials [1]. The joining of three different materials has been critical issue in the fabrication of ITER first wall. For a successful fabrication of such complex components, the diffusion welding method is favored. Hot isostatic pressure (HIP) is one of the promising diffusion welding methods that allows uniform distribution of the pressure and good dimensional tolerances [2]. The precipitation strengthened CuCrZr alloys are being considered as potential heat sink material for the shielding blanket of ITER first wall, due to its high strength and high thermal conductivity at a high temperature [1,3]. However, the mechanical properties of CuCrZr are sensitive to the thermal history [4].

The first HIP process for the joining of CuCrZr/stainless steel (SS) is carried out at high temperature of 1050℃ for 2hrs. However, for security reasons such as a high pressure of the HIP vessel, the HIP quenching operation is not possible. Therefore, a supplementary solution annealing procedure has been inserted into the heat treatment process just after CuCrZr/SS HIP joining treatment in order to have a sufficient fast cooling of the CuCrZr. Fast cooling is needed in order to avoid the formation of too large precipitates, and so, a CuCrZr with good material properties. A subsequent HIP process to join the Be tiles to the CuCrZr is also needed in order to age-harden the CuCrZr. Although a increase of the HIP temperature is desirable for a improvement of a HIP joining strength, the maximum temperature to be applicable to the Be/CuCrZr joint HIP procedure is limited by an over-aging of CuCrZr [4].

In this study, the effect of the cooling rate and aging treatment on the mechanical properties of CuCrZr is investigated to optimize the HIP joining conditions.

2. Experimental procedure

The CuCrZr alloy used in this study was produced by the KM Europa Metal, and it has the following chemical composition (wt.%): 0.79% Cr, 0.11% Zr and Cu balance. The Cr and Zr contents fulfill the ITER requirements. The CuCrZr is machined in the form of block with dimensions of 60 x 60 x 70 mm and canned with 2 mm SS304 plates. Thermocouples (K type, Φ 1.6) are placed in 2 parts with 30 mm in depth (the mid height of CuCrZr block): one (P1) is located in center of CuCrZr block, the other (P2) is located 10 mm point from the side part.

The solution annealing of CuCrZr specimens has been performed at 980℃ for 30 min. Various cooling modes have been realized: water quenching (WQ), rapid gas cooling (RGC), slow gas cooling (SGC) and air cooling (AC). The cooling rate is measured between two points (P1&P2), and average cooling rates are determined in the temperature range of 980-500℃. After a solution annealing, the specimens have been aged at temperatures of 400, 440, 480, 500, 550, 580, 600 and 620℃ for 2hrs, respectively.

The mechanical properties are measured by the Vickers hardness and tensile test, and the fracture surface of the tested specimens is observed by a scanning electron microscopy (SEM). The Vickers hardness is measured with test loads of 4.903 N and 5 seconds loading time at room temperature. Tensile tests are preformed at a cross-head speed of a 5 mm/min, at room temperature and 250℃. The tests are performed on cylindrical specimens with a gauge length of 30 mm and a diameter of 3 mm.

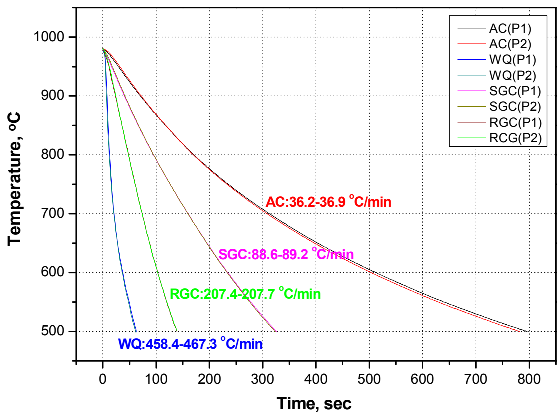


Figure 1. Variation of cooling rate with four different cooling conditions: WQ, RGC, SGC and AC.

3. Results and discussion

The variation of the cooling rate with four various cooling conditions are shown in Fig. 1. The average cooling rates determined in the temperature range of 980-500℃ were as follows: 458℃/min at WQ, 207℃/min at RGC, 88℃/min at SGC and 36℃/min at AC. The cooling rates between the P1 and P2 part were very similar. However, in the case of WQ, the difference of the cooling rate was 9℃/min.

For all the cooling conditions, the Vickers hardness showed the maximum hardness at 440℃, and improved with an increase of the cooling rate. The values were from 110 to 130 Hv at 440℃.

The tendency of a strength variation was similar to that of the hardness results. The ultimate tensile strength and yield strength of the CuCrZr showed maximum values at the aging temperature of 440℃ regardless of the testing temperature, and exhibited exactly the same trend with respect to the testing temperature when the cooling rates changed. In the case of the elongation results, the elongation values were higher than 15 %, the minimum value recommended by ITER, for all the tested samples. However, we could not find a clear tendency about the cooling rate and aging effects. The effect of the aging temperature on the yield strength of the CuCrZr solution annealed and cooled with different cooling rates is shown in Fig. 2: (a) and (b) were tested at room temperature and 250℃, respectively. The dotted red lines are the minimum value recommended by ITER. The yield strength of the aged CuCrZr was higher than 150 MPa at 250℃ up to the aging temperature of 600℃, regardless of the cooling rate. It is suggested that the HIP temperature of the Be/CuCrZr joint could be increased to 600℃ based on the results obtained.

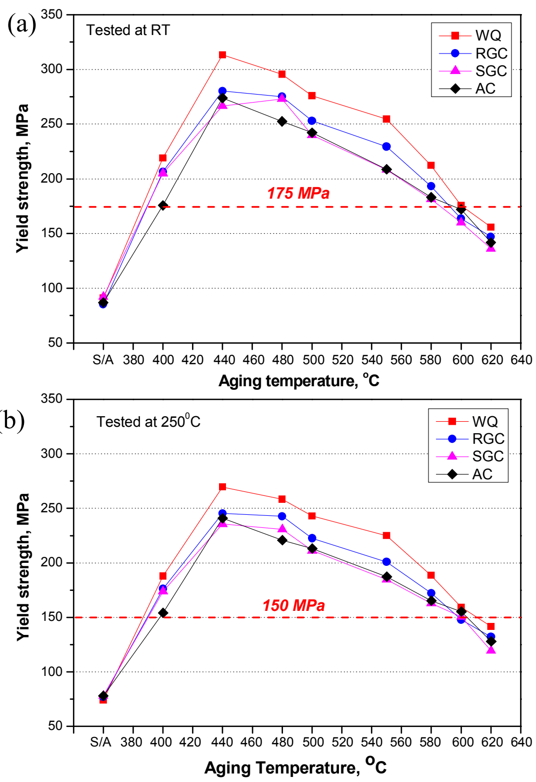


Figure 2. The effect of aging temperature on the yield strength of the CuCrZr alloy cooled with different cooling rates: tested at (a) room temperature and (b) 250℃.

Fig. 3 shows the surfaces of the fracture by SEM of different tensile samples after tests at room temperature and 250℃. For all the tested samples, whatever the manufacturing processing (cooling rate and aging temperature) or the testing temperature, the fracture surface morphologies were rather irregular, and exhibited the same mechanism of a fracture: inter-granular fracture with clear dimples associated with a ductile cavity growth. The dimple sizes of tests at room temperature were smaller when compared with those of tested at 250℃.

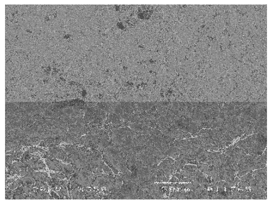
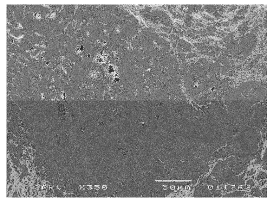
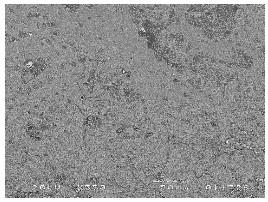
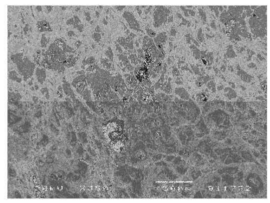
	RT	250℃
WQ		
RGC		

Figure 3. SEM microstructure of fracture surfaces of specimens aged at 580℃ and tested at room temperature and 250℃.

4. Conclusion

The effect of the cooling rate and aging temperature on the mechanical properties of CuCrZr was investigated to optimize the HIP joining conditions without a significant degradation of the CuCrZr alloys. The hardness and strength of the aged CuCrZr were increased with an increasing cooling rate. The strength of the aged CuCrZr was the highest at 440℃ and then gradually decreased up to 620℃ regardless of the cooling rate. The yield strength was lower than the minimum requirement values when the aging temperature was higher than 600℃ which could be the upper limit of the HIP temperature. Therefore, the effective HIP temperature for the Be/CuCrZr joint can be employed up to 600℃.

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