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Effect of Alloying Elements on the Creep Properties of Zr Based Alloys

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1. Introduction

Zirconium alloys have been widely used for the fuel cladding and other core components in nuclear reactor and among them Zircaloy-4 has been mainly used as a fuel cladding material for pressurized water reactors (PWR) for a long time. However, since the PWR operating conditions such as a higher burn-up, increased operating temperature and a high pH operation have been implemented to improve the rector efficiency, advanced Zr-based alloys become necessary. Most of the alloying elements were added to the zirconium alloys to increase the corrosion resistance and the creep strength. It is well known that the creep strength of zirconium alloys is affected by alloying elements such as tin[1,2], niobium[3], oxygen[2], carbon[4] and sulfur[5] in a solid solution state. The present work was undertaken to provide the creep behavior of Zr-Cu and Zr-Fe binary alloys and also Zr-Nb-Cu and Zr-Nb-Fe ternary alloys at the rector operation temperature range of 280-330℃.

2. Experimental procedure

The chemical compositions of the Zr-based alloy used in this study are the binary Zr-0.3Cu and Zr-0.3Fe and also the ternary Zr-0.5Nb-0.3Fe and Zr-0.5Nb-0.3Fe alloys. The alloys were solution-treated at 1020℃ for 30 min in a vacuum furnace, hot-rolled after a pre-heating at 590℃ for 10min, and cold rolled three times to obtain a final thickness of 1mm. Between the rolling steps, the cold-rolled sheets were intermediately annealed at 580℃ in a vacuum furnace for 2 hr and the final cold-rolled sheets were also annealed at 510℃ in a vacuum furnace for 8 hr to obtain a fully recrystallized structure.

Creep specimens were machined from the sheet along the RD direction with a gauge length and width of 25 mm and 5 mm, respectively. Creep tests were carried out under a constant load condition in the temperature range of 280-330℃ and a stress range from 100 to 140MPa. The axial creep strains were monitered by using an LVDT (Liner Variable Differential Transformer) estensometer. Creep samples were tested at given temperature for 70 hours to reduce the creep exposure time. TEM observation was performed on the after creep test specimens.

3. Results and discussion

3.1 Effect of and alloying element on the creep behavior

The creep behavior was affected by certain parameters such as the chemical composition, microstructuctural characteristics of the grain size, dislocation density and the precipitates. It was impossible to study the solute range effect of both elements in this study due to the very low solubility of copper and iron in zirconium at a low temperature. The creep behavior in this work would be affected by the solid solution as well as the precipitates and determined by the type of alloying elements and the amount of alloying elements.

Fig. 1 shows the creep strain of the tested binary and ternary alloys for 70 hr. Zr-based alloys with different applied stresses and the creep strain of the (a) and (b) as a function of the creep strain and the temperature at 280℃. Creep strain of the binary alloys was increased by increasing the applied stress at 280℃ and the creep strain of the Zr-0.3Cu alloy was higher than that of the Zr-0.3Fe alloy.

Fig 1 (c) and (d) show the creep strain at 330℃. The creep strain behavior of the ternary Zr-based alloy was similar to that of the binary Zr-based and the creep strength of the copper containing ternary alloy was lower than that of the iron containing ternary alloy. However, the total creep strain of the ternary alloys at the same tested time was much lower than that of the binary alloys, even though the test temperature of the ternary alloys was higher than of the binary alloys.

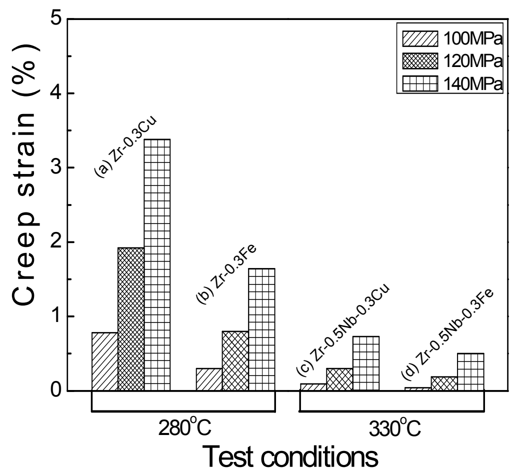

Fig. 1 Thermal creep strain after the creep test of the zirconium alloys with a different applied stress range from 100 to 140 MPa and a different test temperature at 280 and 330℃.

3.2 Stress exponent and microstructural characteristics

The stress exponent and the total creep strain of the binary and ternary alloy are summarized in Table1. The stress exponent and value of the binary and ternary alloys was about 5.5 in the stress range of 100 to 140 MPa. This range of the stress exponent n corresponds to region Ш which was clearly indicated by a control of the dislocation glide and climb as the rate-controlling mechanisms.

Fig. 2 shows the bright field TEM micrographs of the sample after the creep test of the binary ternary zirconium alloys. From the results of the stress exponent values and the dislocation characteristics in this study, it is thought that the creep behavior of the binary and ternary zirconium alloys containing copper, iron and niobium are controlled by a dislocation glide creep. Because the dislocation glide creep is related to the diffusion of the atoms, the diffusivity of the alloying element in zirconium is one of the main factor to determine the creep strength at the temperature range 280-330℃.

Table 1 Stress exponent and the total creep strain of the binary and ternary zirconium alloys.

Factor / Alloys	Stress exponent, n	Total strain, %		
		100MPa	120MPa	140MPa
Zr-0.3Cu	5.0	0.78	1.92	3.38
Zr-0.3Fe	5.4	0.30	0.80	1.64
Zr-0.5Nb-0.3Cu	5.7	0.09	0.30	0.73
Zr-0.5Nb-0.3Fe	5.8	0.04	0.19	0.50

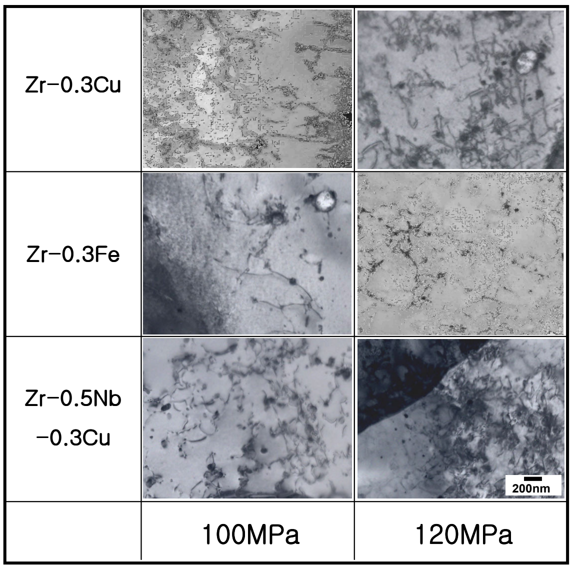

Fig. 2 TEM micrographs of the after creep test samples of the binary zirconium alloys tested at 280℃ and ternary zirconium alloy tested at 330℃

3. Conclusion

The creep characteristics of binary and ternary zirconium-based alloys containing copper, iron and niobium were evaluated at the stress range of 100 to 140 MPa and at a temperature of 280 and 330℃. From the creep strength results of the zirconium alloys, niobium showed the strongest effect on the creep resistance among the alloying element and iron was more effective then copper as an alloying element from the viewpoint of a creep resistance of the zirconium alloy. The creep mechanism of the binary and ternary zirconium alloys containing copper, iron and niobium was controlled by a dislocation glide creep from the results of the stress exponent values and the dislocation characteristics.

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