destruction and weakly strength of the grain boundary[4], respectively, although direct observations are hardly reported. In present experiment, we at least supplied a powerful evidence to particle emission of coatings.

C/C composite: like the coating materials, two kinds of erosion products were found, one came from the evaporation of C/C composite, and the other displayed the structure of carbon fibers which should result from brittle destruction of carbon materials, it located on the edge of deposition zone too.

According to the weight increment of Si plate, it can be estimated that the average thickness of deposition zone is 1~2 μm, the maximum thickness is about 3~4 μm and the thickness reduced with increasing of particle emission angle.

REFERENCES

1 Linke J, Bolt H, Duwe R, et al. High Heat Flux Simulation Experiments with Improved Electron Beam Diagnostics. J. Nucl. Mater., 2000, 283 ~ 287: 1152

2 LIU Xiang, CHEN Jiming, ZHANG Fu, et al. High Heat Flux Testing of B_4C/Cu and SiC/Cu Functionally Graded Materials Simulated by Laser and Electron Beam. Plasma Science & Technology, 2002, 4 (1): 1171

3 Linke J, Akiba M, Duwe R, et al. Material Degradation and Particle Formation under Transient Thermal Loads. J. Nucl. Mater., 2001, 290~293: 1102

4 Scaffidi-Argentina F, Safronov V, Arkhipov I, et al. Erosion Mechanisms and Products in Graphite Targets under Simulated Disruption Conditions. J. Nucl. Mater., 2000, 283~287: 1111

2. 6 The Brittle Fracture Mechanism of Vanadium Alloy with High Level of Oxygen and Hydrogen

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Key words: Vanadium alloy, Hydrogen embrittlement, Oxygen effect

Hydrogen embrittlement is one of the key issues for the vanadium alloys for fusion application[1]. Previous study has shown that V4Ti alloy had better properties against the embrittlement than V4Cr4Ti and V4Ti3A1 alloys[2]. It was thought that the better property was benefited from the small ratio of its yield strength over its ultimate tensile strength. However, the different alloying elements and the high oxygen concentration in the alloy could also affect their hydrogen embrittlement behavior and led to different fracture mode. J. R. DiStefano et al. reported[3] that oxygen could seriously enhance the hydrogen embrittlement of a V4Cr4Ti alloy and stressed the importance of the synergetic effect of oxygen and hydrogen on the fracture behavior. But so far there is no report on the synergetic fracture mechanism. Some theories on strength and ductility were used in this paper to analyze the hydrogen embrittlement fracture mechanism and the effects of the alloy strength and the oxygen concentration.

1 Alloy strength and its relation with the fracture mode

The major alloy elements in the vanadium alloy for fusion application was Cr, Ti, A1 and Si. They mainly played the role of solution hardening since the amount of the alloy elements was not high (3%~4% in mass), but the ductility of the alloy didn't change much[4]. On the other hand, the vanadium alloys took in oxygen from the atmosphere during the forging and hot-rolling process. It also makes the alloy stronger, causing the reduction of its ductility and changing the hydrogen embrittlement behavior. According to the result reported by J. R. DiStefano[3], the oxygen was most likely distributed along the grain boundaries. It weakened the grain boundary and led the alloy to a higher danger of intergranular fracture. When hydrogen was taken in, the grain boundary of the alloys would be further weakened while the strength of the grain would increase since hydrogen could inhibit dislocation movement. Thus the strength of the grain boundary may become lower than the strength of the grain at a critical hydrogen concentration over which intergranular fracture might occur, resulting in great loss in ductility.

Fig. 1 (a) schematically shows the changes of the grain boundary strength (σ_{GB}) and the grain strength (σ_{G}) with hydrogen for V4Ti and the alloys with addition of A1 or Cr element in different oxygen concentration. In comparison with other alloys with A1 or Cr. V4Ti alloy should have much lower tensile strength. Besides, V4Ti should also have lower grain strength but similar grain boundary strength because the A1 or Cr was substitutional atom in other alloys. It could be clearly seen from the figure that oxygen caused the critical hydrogen concentration shift to lower level and the concentration was higher for V4Ti alloy than that for the alloy with A1 or Cr element. Therefore, the hydrogen embrittlement sensitivity of a vanadium alloy is affected by the combination of oxygen concentration and mechanical strength of the alloy. The increase in the grain strength by oxygen was not considered in the figure. If the effect was considered, the critical hydrogen concentration would be decreased further. Eventually, if the oxygen concentration were very low, intergranular fracture would not occur because the applied stress first exceeds the grain strength for transgranular cleavage fracture prior to the grain boundary strength.

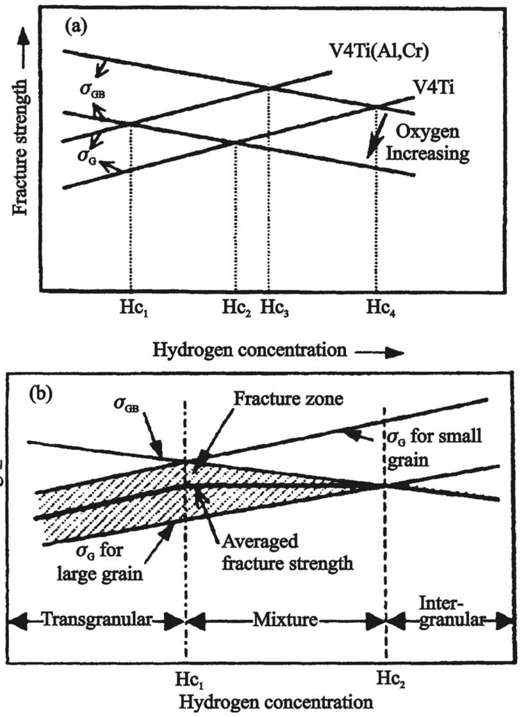

Fig. 1 Schematic representation of the grain strength and the grain boundary strength of the alloy with the change of hydrogen and oxygen concentration

$H_{c1,2,3,4}$——critical hydrogen concentration.

Grain size could also affect the grain strength. According to the Hall-Petch relationship between the yield strength and the grain size, small grain has higher yield strength than coarse grain. Thus the ultimate tensile strength must be also high because of the high dislocation moving resistance in the small grain. In practice, the grains in an alloy must be in different size, resulting in different grain strength for different grain even in one alloy. This difference will influence the micro-fracture mechanism of the alloy and cause the changes in macro-tensile properties of the alloy. Fig. 1 (b) schematically showed these effects. When hydrogen concentration is lower than C_{1H}, the alloy will take transgranular fracture since the grain strength is lower than the grain boundary strength. The ultimate tensile strength (the averaged fracture strength shown in the figure) will increase with the increasing hydrogen concentration. When the hydrogen concentration is more than C_{2H}, entire intergranular fracture will occur and the ductility of the alloy will be lost. The strength will decrease with the increasing hydrogen. However, when hydrogen concentration is between C_{1H} and C_{2H}, a mixed fracture will occur. The ratio of intergranular fracture will increase with the increasing hydrogen. The ultimate tensile strength will hardly change with hydrogen in this case but the ductility of the alloy will decrease drastically with the increasing hydrogen concentration.

2 The hydrogen embrittlement fracture of several vanadium alloys

Fig. 2 shows the fractographies of the V4Cr4Ti, V4Ti3A1, V3TiA1Si, V4Ti and

V4TiSi alloy tensile specimens with 50 mg • kg^{-1} hydrogen. The alloys had high oxygen concentration ranging from 700 to 1 100 mg • kg^{-1}. The detailed tensile test procedure was reported elsewhere[2]. The hydrogen embrittlement fracture surfaces were observed by a scanning electron microscope and the results showed that the fracture was mainly transgranular cleavage. However some intergranular fractures were found for the V4Ti3A1, V3TiA1Si and V4Cr4Ti alloys [see Fig. 2 (a) ~ (d)]. The fractures seem to be associated with the fine grains since fine grain has higher strength than coarse grain. Many fine precipitates in diameter lower than 1 μm was found on the surface of the grain of V4Ti3A1 alloy [Fig. 2 (d)], which may weaken the grain boundary of the alloy. V4Ti and V4TiSi alloys were found to have very small cleavage plane and many secondary cracks [see Fig. 2(e), (f)], indicative of more energy was exhausted during the fracture process. Therefore, the critical hydrogen concentration for V4Ti and V4TiSi alloys must exceed 50 mg • kg^{-1} while that for other alloys must be less than 50 mg • kg^{-1} according to the fracture modes. The observation also showed that there was no intergranular fracture for V4Ti and V4TiSi alloys even at 113 mg • kg^{-1}. Their critical hydrogen concentration should be more than 113 mg • kg^{-1}. Therefore, they are in the transgranular region while others are in the mixture region in Fig. 1 (b).

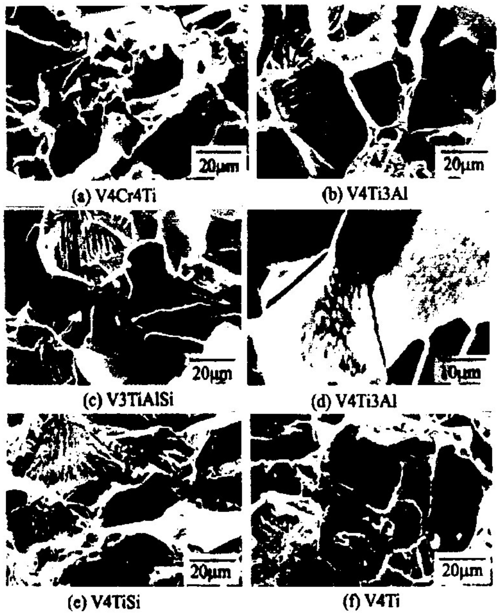

Fig. 2 SEM photos showing the tensile fracture features of the alloys with 50 mg • kg^{-1} H

It could be obtained from Fig. l(b) that the ultimate tensile strength of V4Ti and V4TiSi alloys must increase with the increasing hydrogen but nearly unchanged for other alloys. It was confirmed in the experiment. Fig. 3 showed the hydrogen dependence of the ultimate strength for the alloys. The decrease in ultimate strength for V4TiSi alloy at 113 mg •kg^{-1} was caused by the occurrence of two-phase fracture in the tensile test.

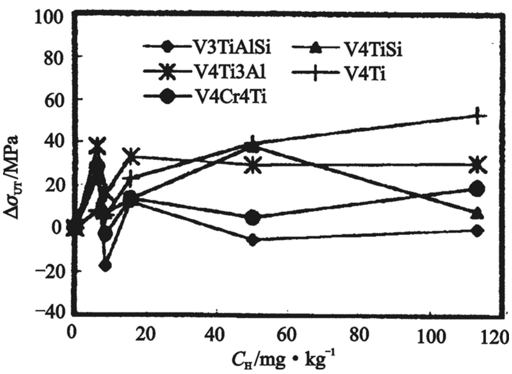

Fig. 3 Hydrogen dependence of the increment in ultimate tensile strength ($\Delta\sigma_{UT}$)

3 Conclusions

The hydrogen embrittlement mechanism has been studied. It could be concluded that intergranular fracture is the main reason to cause the hydrogen brittle fracture for the alloys with high oxygen concentration. The critical hydrogen concentration required to embrittle the alloy is dependent of the combination effects of the hydrogen and the oxygen on the grain and grain boundary strength. The alloys with lower strength have higher critical hydrogen concentration because of its lower grain strength. Oxygen causes the alloy more sensitive to hydrogen embrittlement.

The hydrogen embrittlement fracture contains both transgranular cleavage fracture and intergranular fracture because the grains in an alloy are not uniform in size and small grains are easily fractured in intergranular mode.

REFERENCES

1 Kurtz R J, Abe K, Chernov V M, et al. Critical Issues and Current Status of Vanadium Alloys for Fusion Energy Applications. J. Nucl. Mater., 2000, 283~287: 70

2 CHEN Jiming, XU Zengyu. The Hydrogen Embrittlement of Vanadium Alloy. Annual Report, SWIP, 2000

3 DiStefano J R, Pint B A, DeVan J H, et al. Effects of Oxygen and Hydrogen at Low Pressure on the Mechanical Properties of V-Cr-Ti Alloys. J. Nucl. Mater., 2000. 283 ~287: 841

4 CHEN Jiming, YANG Lin. The Development of V-Based Alloys. Annual Report, SWIP, 2000

2. 7 Experimental Study on the Resistance to Hydrogen Embrittlement of NIFS-V4Cr4Ti Alloy

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Key words: Vanadium alloy, Hydrogen embrittlement

There are more and more countries to make an effort to the studies of vanadium alloy for fusion application. NIFS in Japan has recently developed an 80 kg heat

1) Japan National Institute of Fusion Science.