were clearly observed at some area on the fracture section. It is a very dangerous fracture mode because component failed in this mode would have no omen.

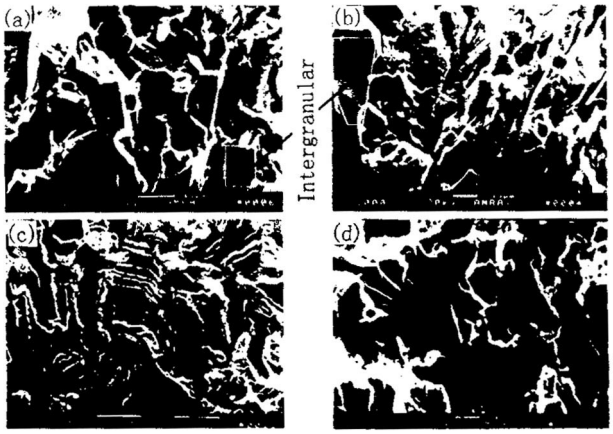

Fig. 2 SEM fractographes of the tensile specimen of NIFS-V4Cr4Ti alloy with 310 mg • kg^{-1} H

3 Conclusion

NIFS-V4Cr4Ti alloy showed different properties against hydrogen embrittlement in static tension and impact load. The critical hydrogen concentration required to embrittle the alloy was about 215~310 mg • kg^{-1} on static tension load, but less than 130 mg •kg^{-1} on impact loading. The different behavior should be taken into consideration in the engineering design of the alloy for fusion application.

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2. 8 Hydrogen and Neutron Irradiation Induced Hardening in Vanadium Alloys

CHEN Jiming

Key words: Vanadium alloy, Hardening, Hydrogen and neutron irradiation

It is well known that vanadium alloy will face to strong neutron irradiation and hydrogen environments as a structural material in a fusion reactor. Some researches have reported that vanadium alloy took strongly hardening after an exposure to hydrogen environment and irradiation by neutron at a temperature lower than 400 ℃[1 ~3]. The ductility of the alloy was lost largely, even entirely brittle fracture occurred sometimes in tension loading of the alloy. Therefore, it's to get the knowledge of the hardening mechanism and the fracture mechanical for the purpose to improve the performances of the alloy under the circumstances.

It will determine the ductility and the strain hardening capability of an alloy whether its ultimate tensile strength could follow the speed of the increasing yield strength during the irradiation or the hydrogen exposure. If the difference between the two strengths gets small or becomes zero, the alloy will take low ductility or entirely brittle fracture on a tension load. This is very dangerous in engineering applications.

The hardening caused by hydrogen solution, neutron irradiation and plastic deformation is schematically shown in Fig. 1. The critical stress (σ_c) causing the brittle fracture for any metal materials is dependent on the fracture toughness (K_{IC}) and the crack length (a) in a component. Their relationship could be expressed as:

$$K_{IC} = Y\sigma_c\sqrt{a} \tag{1}$$

where Y is a constant for a fixed component and a is related to the sizes of the defects and microstructure in an alloy.

The basic theories and some explanations about Fig. 1 are listed as follows:

(1) K_{IC} of a material will generally decrease after absorbing hydrogen and/or neutron irradiation. It decreased more quickly with the increasing yield strength to higher level. So the fracture stress σ_c decreased with the yield strength according to Eq. (1).

(2) Strain hardening in a tension test couldn't change the ultimate strength of a vanadium alloy.

(3) T_c could be approximately taken as the critical temperature below which the strain hardening capability of a post-irradiated vanadium alloy lost drastically.

(4) Effect of hydrogen: σ_y will increase with the increasing hydrogen in a vanadium alloy since hydrogen induced hardening is a kind of solution hardening. It has a relation with σ_{UT} as:

$$\sigma_{UT} = \sigma_y + k\delta^n \quad (2)$$

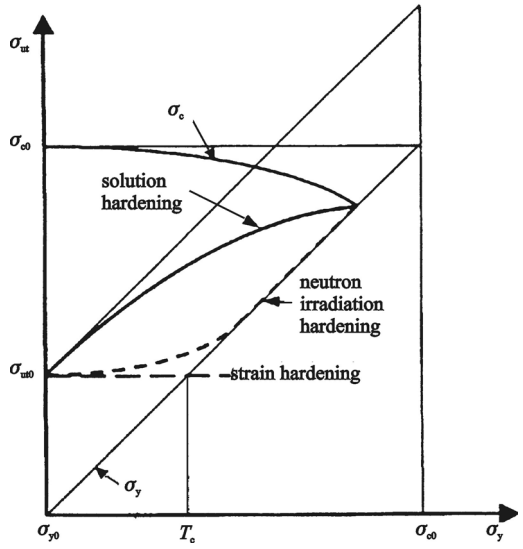

Fig. 1 Schematic representation of the relations between the yield strength and the ultimate strength

σ_y——yield strength, σ_{UT}——ultimate tensile strength.

where σ_{UT} is the ultimate strength of the alloy, n is the strain-hardening exponent, δ is the uniform elongation and k is a proportional number, n will slightly increase with the increasing σ_y in solution hardening condition. Thus,

$$\frac{d\sigma_{ut}}{d\sigma_y} = 1 + kn\delta^{n-1}\frac{d\delta}{d\sigma_y} + k\exp(\delta)\delta^n\frac{dn}{d\sigma_y} \quad (3)$$

The second term on the right side of Eq. (3) is negative since δ will decrease with the hydrogen and the decreasing rate get larger when the yield strength get adjacent to the σ_c where brittle fracture will occur. The third term in the equation would be much smaller since d n/dσ_y is very small. So dσ_{UT} /σ_y must be less than 1 and will decrease with the increasing yield strength.

(5) Neutron irradiation: Microstructure changes caused by neutron irradiation may lead to big changes in material properties. The changes in microstructure varied with the irradiation temperature for V-Cr-Ti alloys[4]. Neutron irradiation produced coarse Ti_5Si_3 at temperature over 400 ℃ and high number density Ti_x(O, N, CP) precipitates in diameter smaller than 4 nm in the temperature range from 300 ℃ to 400 ℃. At even lower temperature the irradiation led to high number density of dislocations in the alloy. The coarse Ti_5Si_3 precipitates will not harden the alloy

much because of its large size. However other changes in the lower temperature regime could strongly harden the alloy and reduce the ductility because of their high resistance to dislocation movement. As the dislocation density is so high that the intersecting slide of the dislocation could easily occur, the strain hardening exponent *n* would drop to lower level. No mater how to divide the temperature regime according to the microstructure changes, the dislocation density should increase gradually with the decreasing irradiation temperature. The process is just like the change of the dislocation density in a tension test of an alloy. Although the yield strength will increase if the alloy is unloaded in the process, the ultimate strength will not change. This is the reason that the ultimate strength of a post-irradiated alloy nearly follows the strain-hardening curve initially at relatively higher irradiation temperature when the dislocation density is not so high. However, as the neutron irradiated vanadium alloy does not the formation of dimples in it but the alloy with large plastic deformation will do, its ultimate strength will be larger than the strain-hardening alloy when the dislocation density gets high. The difference gets higher and higher with the increasing dislocation density and the increasing yield strength. The yield strength of the neutron irradiated alloy gets more and more adjacent to the ultimate strength and the uniform elongation of the alloy losses more. At last it increases to the same value as the ultimate strength.

Fig. 2 shows the experimental results of the tensile test of the V4Cr4Ti alloy with 0~ 550 mg • kg^{-1} H and after neutron irradiation to doses from 0. 1 to 18 dPa. The alloy was produced in U. S. in 500 kg large heat. It showed the relations between the yield strength and the ultimate tensile strength. The curves went just like that in Fig. 1, indicating that it is reasonable to use Fig. 1 to explain and to foresee the mechanical properties of a vanadium alloy after neutron irradiation or the hydrogen embitterment behavior of the alloy. The temperature for the occurrence of high-density dislocation for a neutron irradiated vanadium alloy mainly depends on the dynamic recovery temperature of the alloy. So it seems hard to change this temperature. However, it could be deduced from Fig. 1 that low strength alloys could have better properties against hydrogen embrittlement and the neutron irradiation induced ductility loss for a vanadium alloy, which has been confirmed in some experiments[5, 6].

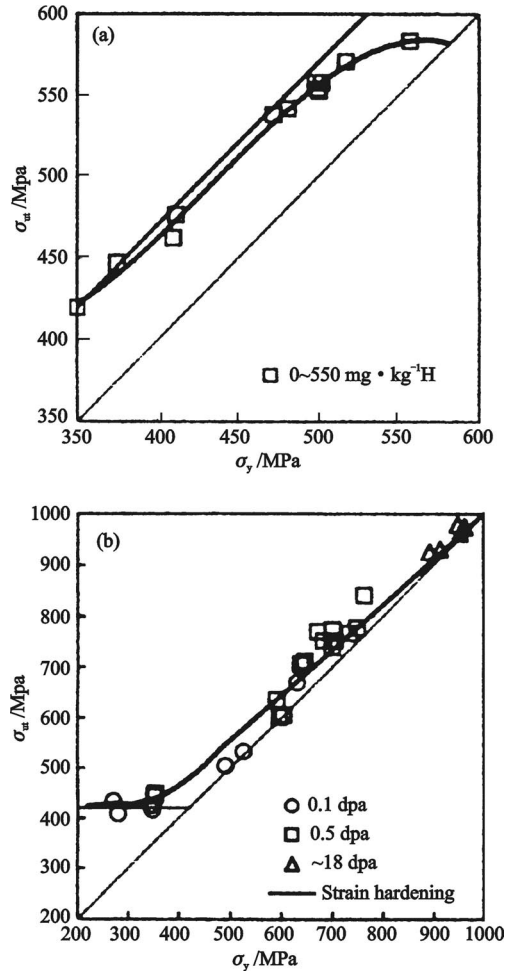

Fig. 2 The relations between the yield strength and the ultimate strength of a V4Cr4Ti alloy with hydrogen (a) and after neutron irradiation (b) Data was from Refs. [7] and [8]

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2. 9 The Oxidation Behavior of Vanadium Alloys in Air at Elevated Temperature

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Key words: Vanadium alloy, High temperature oxidation

Vanadium alloy is one of the most important candidate structural materials for a fusion reactor. Its main advantages over other candidates are its low activity feature and feasible properties at high temperature[1~4]. However, vanadium is easily oxidized at high temperature to form a non-protective surface film of V_2O_5. Oxygen concentration would thus get high and the properties get worse in not only the loss of the ductility[5] but also the enhanced hydrogen embrittlement by the oxidation[6]. Therefore, measures must be taken to improve its high temperature properties against oxygen contamination and oxidation, such as the effective way of adding Al, Si and Y into the alloy.

1 Experimental procedure

The specimens used in the oxidation experiment were fabricated from V4Cr4Ti, V4Ti3A1 and V4Ti alloys, which were developed in SWIP. The chemical compositions and the alloying processes were introduced in Refs. [7, 8]. Specimens in size of 12 mm×12 mm×1 mm were cut from the annealing alloy plate, cleaned