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Influence of heat treatment on mechanical properties, microstructure, and fracture surface morphology of V-5Cr-5Ti alloy

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ABSTRACT

Nuclear fusion reactors are becoming an efficient source of energy in next generation energy. The development of structural materials is a foremost step towards building the environmentally friendly reactors. The structural components require superior mechanical and thermal properties to sustain under extreme heat, and radiation fluxes. V-5Cr-5Ti alloy is considered as promising structural material for vessel first wall components and blanket applications in fusion reactors due to its high melting point and superior mechanical and thermal properties. In this study, the influence of heat treatment on mechanical properties, microstructural changes, and fracture surface morphology of V-5Cr-5Ti alloy were investigated. The result showed that the tensile residual strength was increased by 40% but the elongation dropped significantly by 67% after the heat treatment at 650 °C due to dynamic strain aging (DSA) after significant plastic deformation and work hardening. At the higher temperature window from 400 °C to 700 °C, the diffusion of chromium and titanium possibly facilitate the DSA phenomenon, which enhances the strength at elevated temperatures. The microstructure of the V-5Cr-5Ti alloy showed that grain sizes were reduced to 20-60 µm after the heat treatment at 650 °C from the grain sizes of 50-100 µm at room temperature. The fracture surface at room temperature displayed ductile tearing ridges and pulled-up features. After the heat treatment to 650 °C, the sample showed brittle fracture features with inter-granular cracks and cleavage facets. The morphological features can be correlated with the mechanical properties to analyze the microstructural origin of strength and toughness of the materials.

KEY WORDS: Mechanical properties, Heat treatment, Microstructure, Fracture surface, Morphology, V-5Cr-5Ti alloy

1. INTRODUCTION

The materials in nuclear fusion reactors need to withstand extreme temperatures, pressures, neutron doses, radiation fluxes etc. The structural components include first wall, blanket, vacuum chamber, diverter, pressure vessel, condenser, superconducting coils, solenoid, piping, and valves etc., which can be fabricated with different materials. Most common materials used in reactors consist of ferritic/martensitic steels, titanium alloys, austenitic stainless steels, vanadium alloys, tungsten, tantalum alloys, molybdenum alloys, nickel-base super alloys, engineering composites, advanced ceramics, etc. [1, 2, 5]. Among them, vanadium-based alloys (such as V–Cr–Ti alloy) are considered as promising structural material for fusion reactors for first wall vessel and blanket applications and they can endure high temperature, high pressure, and radiation fluxes. The V–Cr–Ti alloy alloys exhibit better mechanical, physical, and nuclear properties compared to ferritic steel alloys for the fusion environment. These alloys have an excellent thermal conductivity, high strength, good chemical inertness, excellent resistant to radiation, high melting temperature, and low thermal stresses [3, 4, 5]. The nuclear properties assure high neutron wall loading capability and high operating temperature (melting point 1890 °C). The V-5Cr-5Ti alloy is considered an optimized alloy that exhibits superior creep and fatigue properties. Alloying element titanium improves irradiation-induced swelling and embrittlement resistance with better fabricability, and chromium improves oxidation and creep resistance, neutronic properties, thermal stability, and high heat flux [3, 5, 6]. The effect of temperature on mechanical

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and fracture properties of V-Cr-Ti based alloys have been extensively studied and most cases, it is reported that the mechanical and fracture properties are increased, and elongation is decreased due to hardening phenomenon at temperatures below 700 ^{o}C. The mechanical strength of the vanadium alloy at elevated temperatures is also increased by increasing chromium content by reducing interstitial impurities. However, the key concerns for these proposed structural materials that will subject to long term extreme thermomechanical stresses that may cause stress corrosion cracking, high temperature embrittlement, radiation induced defects, and swelling [5, 6, 7]. The rationale behind selecting experimental environmental temperature, 650 ^{o}C, was based on actual operating temperatures of first wall and blanket materials in the fusion reactor system, which ranges from 450 ^{o}C to as high as 700 ^{o}C [6]. The upper and lower operating temperature of V-5Cr-5Ti alloy are also similar to the actual operating temperature in the fusion reactor and the limits are based on high temperature strength and irradiation embrittlement [5].This work aims to simulate the extreme environment conditions and examine the heat treatment effect on tensile properties, microstructure, and fracture surface morphology of as-received cast and hot forged V-5Cr-5Ti alloy.

2. MATERIALS AND EXPERIMENTAL

In this study, the specimens of 2.3 mm thickness were cut from the V–5Cr–5Ti alloy by following sample geometry (Fig. 1). The annealed metal thick sheets were manufactured by Wah Chang Company, Albany, OR. The specimens were exposed to elevated temperature environment before the mechanical testing in order to determine the differences in strength and fracture toughness of the alloys at different environmental conditions. Thus, the base materials were heated in a vacuum oven (Thermo Scientific™ Lindberg/Blue M™) at a heating rate of 5 ^{o}C/min to the temperature of 650 ^{o}C with dwell time of 2 hours, and subsequent cooled down to ambient environment at a rate of 1 ^{o}C /min. The static tensile experiments were performed using a servo hydraulic MTS 810 material testing system. The instrument was facilitated with a load cell of 100 kN and managed with MTS TestStar II software at a controlled displacement of 0.02 mm/s. Using a computer, force and displacement data were obtained in the real time with the TestStar IIs software. The stress-strain relationship was then developed, from where the yield strength, the ultimate strengths, and the strain to failure were obtained. Static tensile test results of the unnotched specimens were used to calculate the ultimate tensile and yield strength. The test results based on the notched specimens were used to determine the residual strength and the plain stress fracture toughness as outlined in ASTM E399.

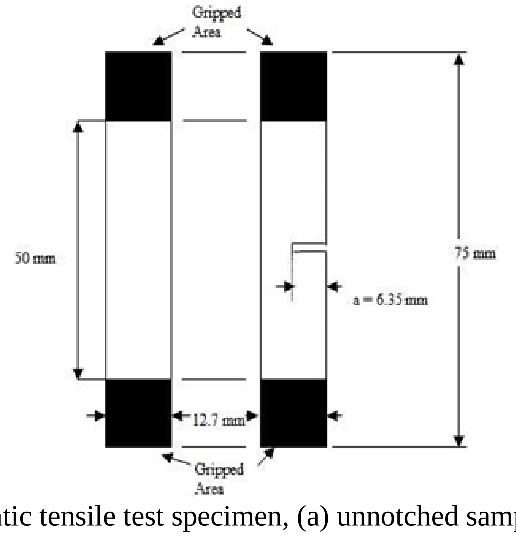

Fig. 1 Specimen geometry for static tensile test specimen, (a) unnotched sample, (b) notched sample.

For optical microstructure studies, the sample from each group was polished and then metallographic etchant (Keller's reagent 95% DI water, 5% HNO_3, 1.5% HCl, and 1% HF) was used to reveal the microstructures. The optical micrographs were captured with a Paxit digital camera and corresponding software. Scanning electron microscopy (SEM) analyses were performed in order to observe the fracture surface morphology. Specimens were examined after failure under static loadings with a Hitachi S-3400N SEM operated at 15 kV acceleration voltage.

3. RESULTS AND DISCUSSION

***Static Tensile Stress-Strain Behavior*:** The static tensile tests were also performed for both unnotched and single edge notched V-5Cr-5Ti specimens to determine the average ultimate strength, yield strength, and strain to failure at different environmental temperatures of 25 ºC and 650 ºC. The tensile stress-strain curve of the alloy for the unnotched specimens as a function of temperature is shown in Fig 1.

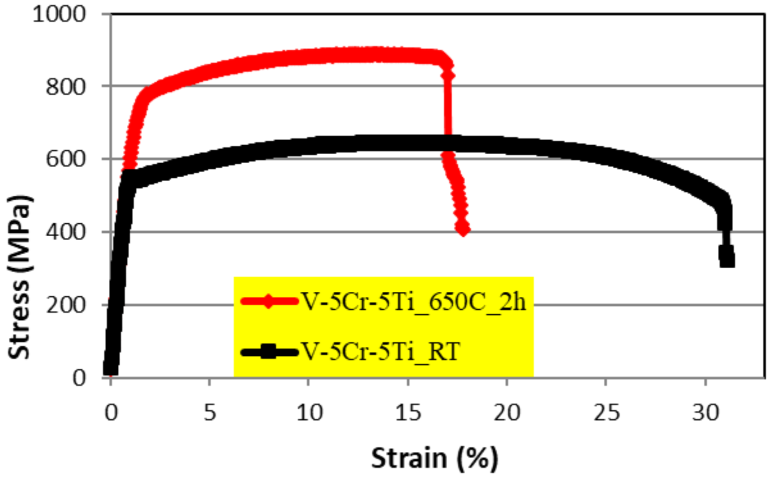

Fig. 1 Tensile strength-strain relationships of V-5Cr-5Ti for unnotched specimens at room temperature and after exposure (2 hours) to elevated environmental temperature at 650 ºC.

For the unnotched tensile specimens, at room temperature, the average maximum strength of 655 MPa, yield strength of 550 MPa, and elongation of 29% was achieved. After 650 °C exposure for 2 hours, the tensile strength and yield strength increased to 869 MPa and 745 MPa, with a 33%, and 36% change, respectively. The elongation decreased significantly by a percentage of approximately 45% (Fig 1). The reason behind the increasing high temperature strength is dynamic strain aging (DSA). At the lower temperature window from room temperature to 400 ºC, the diffusion of oxygen and carbon are assumed to be liable for DSA, while at the higher temperature window from 400 ºC to 700 ºC, the diffusion of chromium and titanium possibly facilitate to DSA, which enhances the strength at elevated temperatures. This phenomenon has been reported by Kurtz and Takeshi et al. [7, 8].

Fracture Resistance Behavior: The fracture resistance of the specimens was calculated using the maximum stress acquired from the tested notched specimen and is given by following fracture toughness formula as outlined in ASTM E399 [9]. For the single edge notched specimens, the average residual strength of the room temperature and 650°C specimens were 320 MPa and 450 MPa, respectively (Fig. 2). The tensile residual strength increased by 40% but the elongation dropped significantly by 67%. The reason for lower elongation value is due to the brittle behavior of the V-5Cr-5Ti alloy at elevated temperatures, which can be observed from the fracture surface morphology by using scanning electron microscopy. The average fracture toughness (K_I) value obtained for the room temperature specimens was 39.2 MPa√m, while the average K_I value of the 650 ºC specimens was about 51.96 MPa√m. There is a 32% increase from their room temperature values. The calculated value for K_I represents plane stress conditions. The detailed data of all tested specimens are given in Table 1.

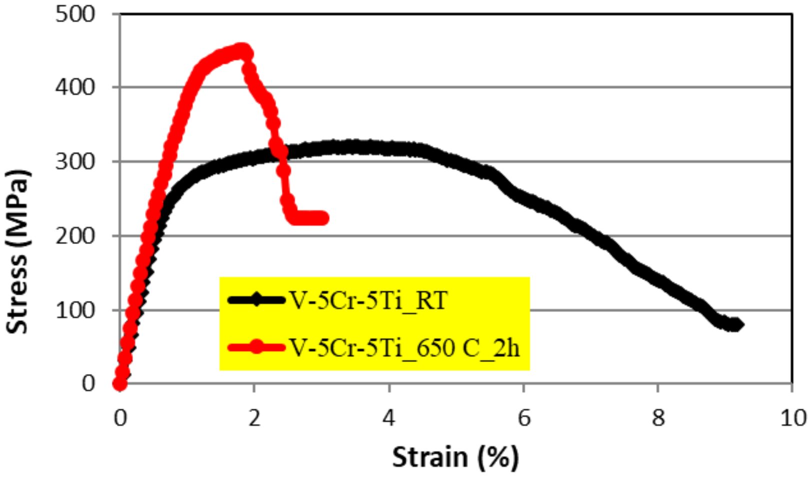

Fig. 2 Residual strength-strain relationships of V-5Cr-5Ti for single edge notched specimens at room temperature and after exposure (2 hours) to elevated environmental temperature at 650 °C.

Table 1 Average fracture resistance data of V-5Cr-5Ti alloy for notched samples at room temperature and 650 °C samples.

Specimen	W (mm)	B (mm)	a (mm)	a/W	F(a/W)	P_m (kN)	K_I (MPa√m)	Residual Strength (MPa)	ε (%)
S-25°C	12.8	2.3	6.42	0.50	2.841	9.446	39.23	320.86	9.17
S-650°C	12.7	2.3	6.14	0.48	2.680	12.924	51.96	450.28	3.00

Where, W = width of specimen; B = thickness; a = total crack length; ε = failure strain; K_I = fracture toughness.

Microstructure and fracture surface morphology: The micrograph of the V-4Ti-5Cr alloy at room temperature (Fig. 3a) shows a coarse crystal shape structure with a grain size of 50-100 µm and visible distinct grain boundaries. After 650 °C exposure for 2 hours (Fig. 3b), the grain size becomes smaller compared to the room temperature grain. Some micro grains are also visible after heat treatment. The average grain size reduced to 20-60 µm after heat treatment, which may be related to the improved the strength and toughness because of finer grains.

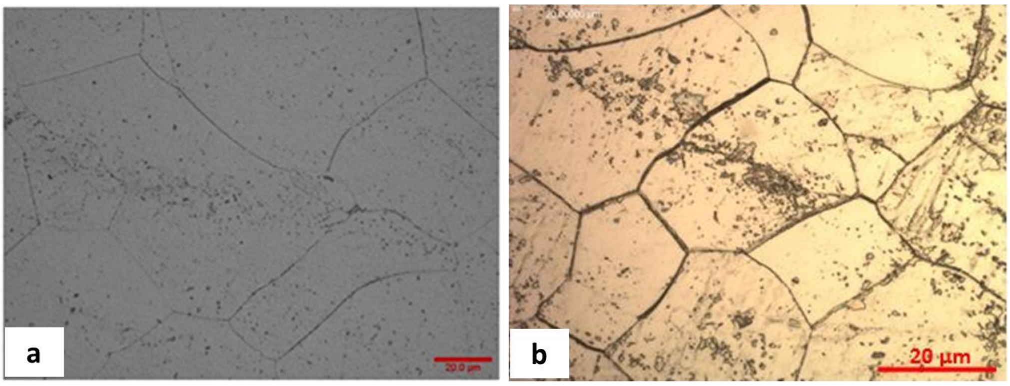

Fig. 3 Microstructural analysis of V-5Cr-5Ti at (a) room temperature and (b) 650 °C at 50 X magnification.

The fracture surface morphology at room temperature and after 650 °C exposure for 2 hours is shown in Figures 4a and 4b, respectively. It is clearly seen that the fracture surface exhibits ductile pulling features with ripping ridges and ripped out strips and demonstrates the plastic deformation. However, the specimen after 650 ºC exposure for 2 hours exhibits some cleavage facets with minor crevices. Thus, the material after the heat treatment at 650 ºC demonstrates more brittle fracture characteristics due to the enhancement of inter-granular fracture by grain boundary precipitates.

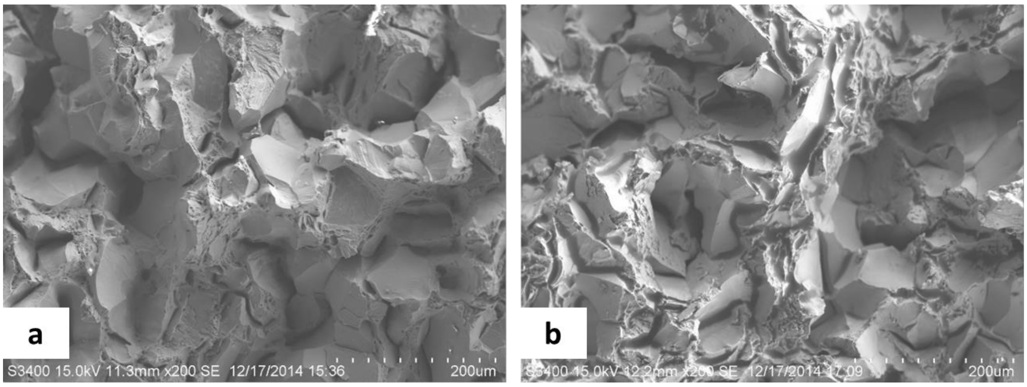

Fig. 4 SEM micrographs of V-5Cr-5Ti fracture surface at (a) room temperature and (b) 650 ºC at 200 X magnification.

4. CONCLUSIONS

In summary, our study demonstrated that the tensile and fracture properties of V- 5Cr-5Ti alloy at elevated temperature increased up to 700 ºC due to significant plastic deformations create heavily stained microstructure and considerable work hardening discloses excellent thermal stability. The diffusion of chromium and titanium may also facilitate the dynamic strain aging (DSA) phenomenon at higher temperatures window from 400 ºC to 700 ºC, thus enhancing its strength at high temperatures.

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