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Microstructure and properties of V–5Cr–5Ti alloy after hot forging

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ABSTRACT

In this work, the microstructure of V–5Cr–5Ti alloy after hot forging was analyzed by X–ray diffraction, optical microscopy, scanning electron microscopy, and transmission electron microscopy. After hot forging, the microstructure of V–5Cr–5Ti alloy was broken. An axial grain was formed through recrystallization, and the average grain size was approximately 80 μm. With increasing annealing temperature, the grain size increased from 80 μm to 150 μm. The precipitates elongated to form band structures. During annealing, the band structure changed into several small grains enriched in the precipitates. Some short strip–like precipitates were distributed near the grain boundary irregularly. The two types of precipitates in the V–5Cr–5Ti alloy after hot forging were as follows: a) short–strip precipitate $(VTi)_2(CON)$ with FCC structure and lattice parameter of 0.4220–0.4259 nm and b) elliptical–shaped precipitate $(VTi)_2(CON)$ with FCC structure and lattice parameter of 0.4252–0.4347 nm. The two precipitate types during annealing were as follows. The first type was a rectangular precipitate $(VTi)_2(CO)$ with FCC structure and lattice parameter of 0.4186–0.4270 nm. The second type was an elliptical–shaped precipitate $(VTi)_5(CO)$ with FCC structure and lattice parameter of 0.4246–0.4344 nm.

1. Introduction

V–Cr–Ti alloy is an ideal candidate structural material for fusion reactors because of its high–temperature strength [1–3], resistance to neutron radiation damage [4–6], and corrosion resistance to liquid metal [7,8]. As early as the 1960s, domestic and foreign research work on vanadium alloys were began. In the 1990s, with the intensive research on structural materials for fusion reactors, the United States, Russia, and the European Union conducted a large number of systematic studies on vanadium–based alloys [9–15]. By the end of the 1990s, Japan and China became involved in research on fusion vanadium alloys.

V-Cr-Ti alloy ingot is usually prepared by electron beam + vacuum arc remelting [16], vacuum arc remelting [17–19], vacuum magnetic levitation melting [20–22] or mechanical alloying process [23]. The alloy ingot is processed into various profiles (bar, pipe, plate, and foil) by hot or cold working (forging and drawing or rolling). However, the cogging process is different. The General Atomic (GA) Company commissioned in Wah Chang, Albany and the OR corporation produced the industrial–grade 1200 kg alloy ingot US832864. The ingot is hot extruded at an extrusion temperature of 1413 K extrusion pressure of 49 MN, and extrusion ratio of 3 [24]. After extrusion, the ingot is transformed into various profiles by cold working (rolling, forging, and drawing). V–4Cr–4Ti alloy ingot (50 kg) from Russia is prepared by M.M. Potapenko. The ingot was hot extruded at 1373 K with an extrusion ratio of 2–3 [25,26]. T. Muroga prepared 160 kg of V–4Cr–4Ti alloy ingot named as NIFS–HEATb–2; the ingot was hot forged at 1423 K [27]. In the 1990s, the Southwestern Institute of Physics began to prepare experimental vanadium alloy by vacuum magnetic levitation melting. Such alloys included V–4Cr–4Ti, V–4Ti, and V–3Ti–Al–Si alloys. Then, the ingots were deformed to various samples by hot forging and cold working [28–31]. From the beginning of the 21 st century, the General Research Institute for nonferrous metals carried out research on the vanadium alloy. Specifically, 200 kg V–4Cr–4Ti alloy ingots and various profiles were prepared.

This work aims to achieve the grain refinement and plastic improvement of V–5Cr–5Ti alloy ingots by hot forging. The microstructure, precipitate features, tensile properties, and precipitation evolution behavior of V–5Cr–5Ti alloy after hot forging and annealing were examined.

2. Experimental

2.1. Materials

V–5Cr–5Ti alloy was prepared by vacuum melting process. To prevent the oxidation of vanadium alloys and avoid environmental

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Table 1
Chemical composition of the V–5Cr–Ti alloy, including main elements and impurities (wt.%).

Elements	Cr	Ti	C	O	N	Al	Fe
wt.%	5.22	5.22	0.010	0.018	0.0042	0.0038	0.0058

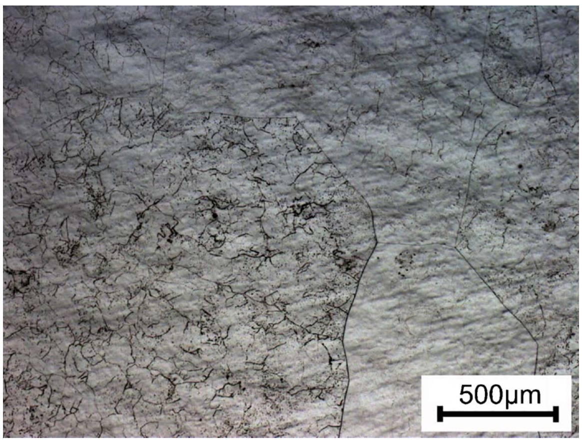

Fig. 1. As-cast microstructure of V-5Cr-5Ti alloy.

pollution during the hot working process, vanadium alloys must be protected under a vacuum better than $\leq 2 \times 10^{-2}$ Pa. The vacuum canning material comprised 3 mm thick 1Cr18Ni9Ti stainless steel. The canning billet was heated in a furnace for 100 min at 1473 K and then die forged in forging hydraulic machine until ~50% plastic stain of height. Subsequent annealing was then carried out in the furnace under a vacuum better than $\leq 2 \times 10^{-2}$ Pa at the following conditions: 993 K, 1093 K, 1193 K, 1293 K, 1343 K and 1393 K for 1 h. Table 1 lists the chemical components of the studied alloy. Fig. 1 is the microstructure of as-cast V-5Cr-5Ti alloy

2.2. Methods

After hot forging and annealing, the samples were sectioned along the direction perpendicular to the press direction. The microstructure was observed by optical microscopy, scanning electron microscopy (SEM), and transmission electron microscopy (TEM). For optical microscopy and SEM, all specimens were prepared by electrolytic corrosion with 10 vol.% HF + 90 vol.% H_2O. For TEM, specimens 3 mm in diameter were prepared by twin–jet electro–-polishing thinning method with 5 vol.% H_2SO_4 + 95 vol.% CH_3OH. Alloy phase was determined by X–ray diffraction (XRD) analysis using Cu K_α radiation.

All specimens were tested at room temperature. At the beginning of testing, a strain rate of 0.5 mm/min was applied until plastic deformation occurred, and then the rate was increased to 2 mm/min until final fracture. The fracture of the specimens were observed by SEM after tensile testing.

3. Results and discussion

3.1. Hot forging

Fig. 2 shows the canning and forging blank of the V–5Cr–5Ti alloy after hot forging. Under hot–forging temperature, the strength of 1Cr18Ni9Ti stainless steel was low, and the package set was drum shaped (Fig. 2a).This result was mainly explained by the large deformation of the middle portion of the alloy and the relatively high deformation heat. After hot forging, the alloy became drum shaped (Fig. 2b).

Fig. 3 shows the microstructure of V–5Cr–5Ti alloy after hot forging. During the hot–forging process, due to the deformation strain and the dynamic recrystallization, the coarse columnar grain of the as–cast V–5Cr–5Ti alloy disappeared. The alloy exhibited slightly equiaxed grains (~80 μm).

3.2. Heat treatment

Fig. 4 shows the microstructure of V–5Cr–5Ti alloy at different annealing temperatures after hot forging. With increasing annealing temperature, the nucleation and growth proceeded, and the new equiaxed grain size increased from 80 μm to 150 μm. The microstructure of the V–5Cr–5Ti alloy exhibited small new grains after 993 K × 1 h, showing that the alloy began recrystallization (Fig. 4a). The recrystallization become evident after 1093 K × 1 h annealing, the grains changed to equiaxed grains, and the size significantly enlarged (~80 μm) (Fig. 4b). Under 1193 K × 1 h annealing, the recrystallization was basically completed, and the size of the equiaxed grains was ~100 μm (Fig. 4c). When the temperature was higher than 1293 K, the recrystallization of V–5Cr–5Ti alloy was completed. The equiaxed grain size became uniform and gradually increased (~120 μm to 150 μm) (Figs. 4d–f). In the range of 1293 K to 1393 K, the microstructure was relatively stable.

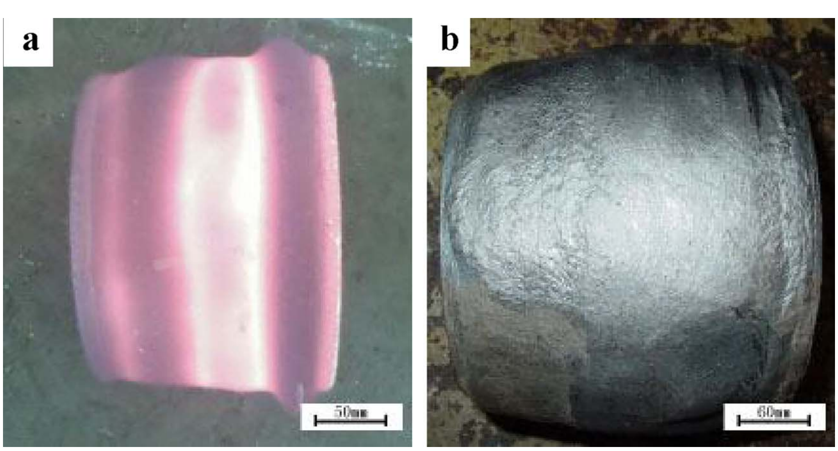

Fig. 2. Canning and forging blanks of V–5Cr–5Ti alloy after hot forging: (a) canning; (b) forging blank.