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Role of γ′ characteristic on the hydrogen embrittlement susceptibility of Fe–Ni–Cr alloys

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ABSTRACT

The effect of γ′ characteristic on the hydrogen embrittlement (HE) susceptibility was investigated in Fe–Ni–Cr alloys with respect to γ′ amount and antiphase boundary (APB) energy. Tensile results revealed that HE susceptibility would increase with an increase in the γ′ amount or APB energy. Fractographic analysis showed that an increase in γ′ amount enhances the frequency of intergranular cracking while the fracture mode changed from intergranular fracture to transgranular fracture with increasing APB energy. The hydrogen–induced cracking mechanism is attributed to that APB energy has a greater effect on the degree of planar slip than the γ′ amount.

1. Introduction

The exposure to hydrogen environment has been known to be detrimental to the mechanical properties of metals and alloys, and this phenomenon is known as hydrogen embrittlement (HE). Among materials in hydrogen environment, austenitic alloys are highly resistant to HE because of their high activation enthalpy for migration of hydrogen atoms [1], and are usually considered as hydrogen-resistant engineering materials [2–10]. Nowadays, the usage of high strength steels in the hydrogen environment is becoming increasing important, which in turn demands high strength austenitic steels.

Therefore, an austenitic matrix strengthened by ordered precipitates of γ' phase is proposed to obtain higher strength. Investigations have demonstrated that a combination of high strength, high ductility and good fracture toughness was obtained in the γ' phase strengthened Fe–Ni–Cr alloys [11–15]. However, these alloys would lose half of the ductility after hydrogen charging, showing more pronounced HE susceptibilities than the single γ-austenitic steels. The characteristic precipitates in the γ' phase strengthened Fe–Ni–Cr alloys mainly include: γ' phase, η phase and TiC. The HE susceptibility is closely related to their microstructures, thus understanding the interaction of hydrogen with each phase is critical to clarify the HE mechanism of the γ' phase strengthened Fe–Ni–Cr alloys.

The effect of η phase on the HE susceptibility has been studied by several researchers. Thompson et al. [16] found that cellular η phase would precipitate at the grain boundaries during aging treatment in A-286, and the degree of intergranular fracture after hydrogen charging was related to the amount of η phase. The presence of η phase could increase the HE susceptibility because the incoherent interface between η phase and matrix was thought to be an irreversible hydrogen trap. Recent studies showed that appropriate addition of boron in the Fe–Ni–Cr alloys could suppress the precipitation of η phase so as to reduce the degree of intergranular fracture after hydrogen charging [17]. In addition, Ti-rich MC carbides were usually observed in the matrix of Fe–Ni–Cr alloys. The irreversible trapping constant in A-286 using potentiostatic pulse technique showed that MC carbides were not the principal hydrogen traps compared with γ' phase and η phase [18].

Correlation between γ' phase and HE susceptibility is one of hot topics in the Fe–Ni–Cr alloys. It was found that the γ–γ′ coherent interface was not the trap for hydrogen by the embedded atom method (EAM) [19] and first-principle study [20]. However, hydrogen permeation studies revealed that γ′ precipitates were the irreversible hydrogen trap sites by comparing the effective hydrogen diffusion coefficients of solutionized and precipitation–hardened Inconel 718 alloys [21]. Thompson et al. [11,16] suggested that the loss of γ–γ′ coherency during deformation allowed hydrogen to accumulate at these incoherent

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Table 1
Chemical composition (wt.%) of experimental alloys.

Alloy	Ti	Al	Ni	Cr	Mo	V	Si	B	C	Fe
A1	1.88	0.36	30.8	14.9	1.31	0.24	0.19	0.0008	0.003	Bal
A2	3.13	0.60	30.9	14.8	1.32	0.24	0.19	0.0008	0.004	Bal
A3	2.01	0.99	30.8	14.8	1.32	0.24	0.19	0.0008	0.003	Bal
A4	2.73	0.22	30.9	14.9	1.33	0.24	0.20	0.0006	0.004	Bal

interfaces, and then led to hydrogen-assisted fracture, which was supported by the observations of smaller dimple size on the fracture surfaces of hydrogen-charged samples. Meanwhile, Turnbull et al. [22] calculated the binding energy associated with hydrogen trap at γ–γ′ interface using diffusion-trapping model, and considered that segregation of hydrogen atoms to the γ–γ′ interface might be responsible for the cracking behaviors. Recently, Guo et al. [23] found that hydrogen would not segregate at the γ–γ′ interface after hydrogen charging using atom probe tomography (APT), and the coherency of γ–γ′ interface maintained during the deformation even to fracture by the high-resolution transmission electron microscopy (TEM) observation. Our previous studies have found that hydrogen–dislocation–γ' phase interactions were mainly responsible for the fracture behaviors of Fe–Ni–Cr alloys after hydrogen charging [13,24]. Planar slip would happen after dislocations sheared the ordered γ' phase, which was demonstrated by the observation on deformation characteristic in the fractured specimens. What is more, the presence of hydrogen further enhanced the slip planarity according to the hydrogen enhanced localized plasticity (HELP) mechanism [25]. In the work of Hicks and Altstetter [26], the hydrogen-induced cracking behaviors were different in several γ' phase strengthened alloys even though the primary fracture mechanisms were identified as the HELP mechanisms. Therefore, understanding of how γ′ characteristic affects HE susceptibility is inadequate until now, which hampers the microstructural design of γ' phase strengthened Fe–Ni–Cr alloys. In this study, the role of γ′ characteristic on hydrogen-induced cracking behaviors is assessed so as to further clarify the hydrogen embrittlement mechanism of γ' phase strengthened alloys. This work also hopes to be helpful for the optimum design of γ' phase strengthened alloys in the hydrogen environment.

2. Experimental

Two sets of Fe–Ni–Cr alloys were produced by vacuum induction melting technique and chemical compositions were given in Table 1. A1 and A2 alloys were designed to examine the effect of (Ti + Al) content by maintaining the same Ti/Al ratio. A3 and A4 alloys were used to examine the effect of Ti/Al ratio by maintaining the same (Ti + Al) content. The ingots were homogenized at 1433 K for 20 h, then forged and rolled into 15 mm diameter bars. The above processing parameters were determined on the pieces cut from each ingot. Specimens were solution treated at 1303 K for 1 h and water quenched, then aging-treated at 1013 K for 8 h followed by air cooling, which was determined by our previous work [27].

Specimens for optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and tensile test were spark machined from the bars. The specimens for OM and SEM observations were mechanically polished, followed by electro-etching in a solution of 10% chromic acid. Thin foils for TEM analysis were prepared by double-jet polishing at 253 K in 10% perchloric acid ethanol solution, and TEM examinations were conducted on FEI Tecnai G220 TEM. The tensile specimens were machined with the gauge sections of 5.0 mm in diameter and 25 mm in length. The tensile tests were carried out immediately at

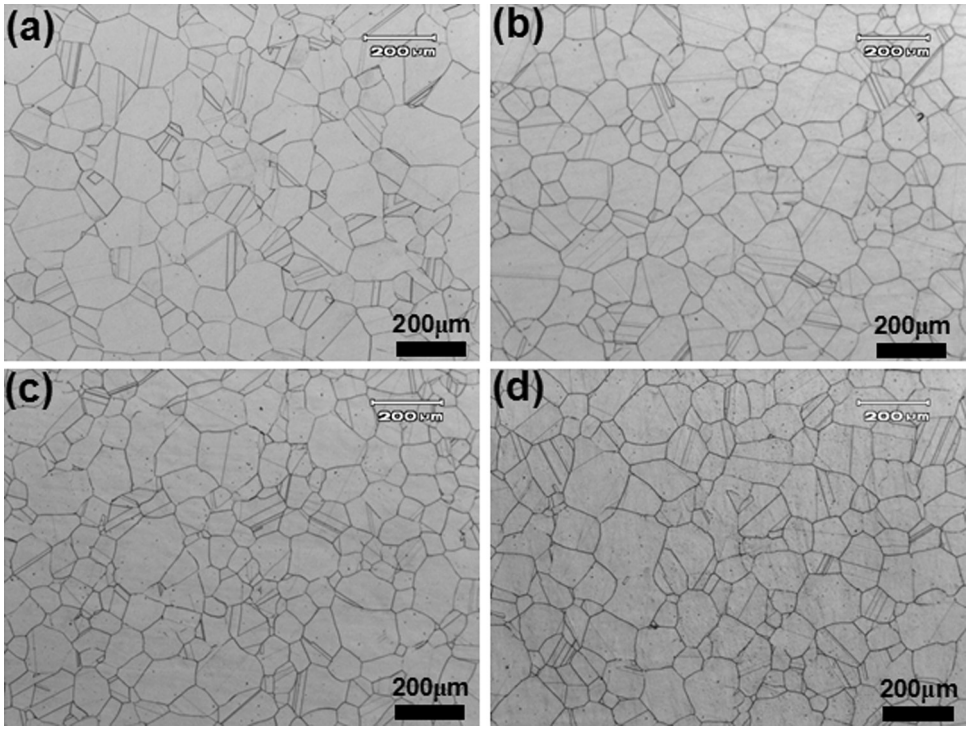

Fig. 1. Optical microstructure alloys after aging treatment: (a) A1, (b) A2, (c) A3 and (d) A4.