Engineering Failure Analysis 83 (2018) 1–8

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Pitting behavior of thermally aged Z3CN20.09M cast stainless steel for primary coolant pipe of nuclear power plant

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ARTICLE INFO

Keywords:
Primary coolant pipe
Duplex stainless steel
Thermal aging
Pitting

ABSTRACT

The effect of thermal aging at 400 °C for various times on the pitting corrosion behavior of Z3CN20.09M duplex stainless steel was investigated using comprehensive study of potentiodynamic polarization and electrochemical impedance spectroscopy (EIS). It is revealed that the pitting resistance of this steel has a negative relationship with increasing the aging time. It is indicating that the property of the specimens aged and then annealed at 550 °C for 1 h can be recovered to that of the un-aged. We found by making use of TEM that through the annealing processes the Cr-rich α′ phase is dissolved in the ferrite phase, while G phase still exists in the ferrite phase at the same time, suggesting that the α′ phase is the major reason for the deterioration in pitting corrosion resistance of the thermally aged Z3CN20.09M steel.

1. Introduction

Among duplex stainless steels (DSSs), austenitic-ferritic stainless steel Z3CN20.09M containing 12–20 vol% ferrite phase has been extensively used to produce the primary coolant pipes of pressurized water reactors (PWR) [1–7]. However, this steel undergoes thermal aging embrittlement during the operating service (290–310 °C, ~16 MPa) by a spinodal decomposition in the ferrite phase, leading to a notable decrease in its fracture toughness [8–10]. Recently, we found that the thermal aging carried out in this steel was detrimental not only to the fracture toughness, but also to the pitting corrosion resistance in distilled water [11]. It is noteworthy that the thermal aging embrittlement and pitting corrosion of this steel may affect each other, accelerating definitely the failure of the primary coolant pipes. However, pioneering studies usually focused on the mechanical properties of thermally aged duplex stainless steel [12–14]. Little work has focused on the pitting corrosion resistance of the steel after thermal aging [15–17].

Pitting resistance equivalent number (PREN) was widely used to evaluate the correlation between alloy elements and pitting resistance of well annealed duplex stainless steels without any unexpected precipitation phases. While the PREN is unsuitable for evaluating the thermally aged Z3CN20.09M steel due to the Cr-rich, Fe-rich and G phases formed during spinodal decomposition for all thermally aged specimens [18–21]. Pitting corrosion behavior of this thermally aged steel is hard to be investigated by means of traditional Cr-depleted zone theory due to form a lot of nano Cr-rich α′ as well as Fe, Si-rich G phases in the ferrite phase [9]. By means of in-situ high temperature projection electron microscope, Chung et al. [3,10,22] observed that the α′ phase disappeared quickly after annealing treatment at 510–520 °C, and G phase did not decomposed until the annealing temperature up to 620–650 °C. On the other hand, according to Fe-Cr phase diagram, no $M_{23}C_6$ and σ phases could be precipitated at 550 °C for several time [23].

Thus present study focuses on the effect of thermal aging on the pitting potential and stability of passive films of Z3CN20.09M

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http://dx.doi.org/10.1016/j.engfailanal.2017.09.005
Received 12 May 2017; Received in revised form 16 September 2017; Accepted 17 September 2017
Available online 19 September 2017

Table 1
Chemical composition of Z3CN20.09M stainless steel (wt%).

C	Cr	Si	Mn	P	S	Ni	Cu	Co	Mo	N	Fe
0.024	20.16	1.09	1.11	0.023	0.0039	9.06	0.031	0.026	0.26	0.033	bal.

stainless steel. By annealing at 550 °C for 1 h, we can distinguish whether α′ or G phase is the major reason for the degradation in the pitting corrosion resistance of the steel after thermal aging.

2. Experimental

The chemical composition of the Z3CN20.09M cast stainless steel obtained from Manoir Company, China for the present study is shown in Table 1. First, the steel was made by argon oxygen decarburization (AOD) + vacuum oxygen decarburization (VOD) duplex smelting process, which was aimed to eliminate the shrinkage pore before casting. Second, the steel was used to produce primary coolant pipe by means of centrifugal casting. Then, a solution treatment was performed at 1180 °C for 8 h, and subsequently water quenched.

The pitting corrosion resistance of the steel was investigated after thermally aging at 400 °C for 2000, 3000, 5000, 7000 and 10,000 h. After the thermal aging, part of the specimens were aged at 550 °C for 1 h in order to distinguish whether α′ or G phase is the key reason for the depravation in the pitting corrosion resistance of the Z3CN20.09M stainless steel.

First, the samples were abraded successively to 2000 # grit using silicon carbide abrasive paper, polished with diamond paste to 1.5 μm and swashed with distilled water and dried in a hot air flow. Second, the specimens for microstructure characterization were electrochemically etched for 10 s with direct voltage 3 V in a 20 wt% NaOH distilled water solution in order to distinguish ferrite and austenite. The size of the specimens used for electrochemical test is 10 × 10 × 3 mm^3. All the electrochemical test specimens were embedded in epoxy resin with exposed area of 10 × 10 mm^2, and rinsed by deionized water, dried by hot air.

Electrochemical tests were carried out on an electrochemical workstation of three electrode system, using a platinum foil as counter electrode and a saturated calomel electrode (SCE) as reference electrodes. All potentials quoted in this paper refer to SCE. The tests were performed at 30 °C without deaeration in 0.5 $mol \cdot L^{-1}$ NaCl solution, prepared from analytical grade reagent and distilled water. The pitting potential of the specimen was tested by the potentiodynamic polarization curve method. Potential scanning started from 200 mV below the open circuit potential (OCP) and ended when the current density was 100 $\mu A \cdot cm^{-2}$, the corresponding potential was definition as pitting potential E_{pit}, at a sweep rate of 20 $mV \cdot min^{-1}$ [24]. In addition, OCP was measured for 0.5 h to approximate the steady state condition potential before applying potential in each experiment. The passive film properties of the specimens were detected by electrochemical impedance spectroscopy (EIS) after 1 h of immersion in the naturally aerated 0.5 $mol \cdot L^{-1}$ NaCl. The measurement was carried on the OCP, running from 100 kHz to 10 mHz, and the amplitude of the disturbance is 10 mV. The test data were fitted with ZView 3.01 software. To confirm data reproducibility, the electrochemical tests were performed at least three times.

3. Results and discussion

3.1. Microstructure of Z3CN20.09M specimens after thermal aging

Measured by a ferrite scope (Feritscope MP30, Fischer, Germany), the mean ferrite content of the as-cast steel was 14.6 vol%.

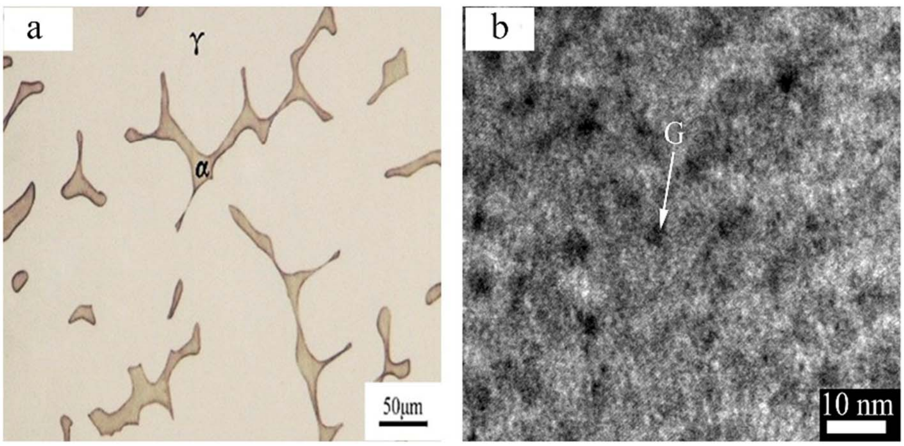

Fig. 1. Optical microstructure of the as-cast Z3CN20.09M specimen (a); TEM micrographs of the ferrite after thermal aging at 400 °C for 10,000 h (b).