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Chi Phase after Short-term Aging and Corrosion Behavior in 2205 Duplex Stainless Steel

Qi SUN[1,2], Jian WANG[1,2], Hua-bing LI[3], Yue LI[1,2], Ya-di HU[1,2], Jin-gang BAI[4], Pei-de HAN[1,2]

(1. College of Materials Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, Shanxi, China; 2. Key Laboratory of Interface Science and Engineering in Advanced Materials, Taiyuan University of Technology, Taiyuan 030024, Shanxi, China; 3. School of Metallurgy, Northeastern University, Shenyang 110819, Liaoning, China; 4. Technology Center of Taiyuan Iron and Steel (Group) Co., Ltd., Taiyuan 030003, Shanxi, China)

Abstract: Correlation between pitting corrosion behavior and chi (χ) phase formed after a short-term aging (5, 10 and 15 min) at 850 ℃ of 2205 duplex stainless steel (DSS) was investigated using potentiodynamic polarization tests, optical microscopy, and scanning electron microscopy equipped with energy-dispersive spectrum system. Results showed that after aging for 5 min, the χ phase initially precipitated at ferrite grain boundaries, developed and then became linked with prolonging aging time. The χ phase was rich in Cr and Mo, resulting in formation of depleted zones nearby. The χ phase could reduce corrosion resistance of DSS and slightly influence its stability, but the specimens still displayed the capacity for repassivation. Some lines of evidence showed that stable pitting corrosion initiated at the boundaries of precipitates. The χ phase was selectively corroded during the first stage of corrosion and then the depleted zones nearby were attacked. In addition, the grain size and volume of precipitates also affected pit nucleation and progress, and suitable size and distribution of χ phase could aggravate pit initiation at precipitate boundaries. The χ phase with considerably low volume fraction and small size was not sensitive position for pit initiation.

Key words: duplex stainless steel; short-term aging; χ phase; pitting corrosion; selective corrosion; grain size

A 2205 duplex stainless steel (DSS) contains a two-phase microstructure with approximately equal amount of ferrite and austenite, showing attractive mechanical properties and corrosion resistance[1-4]. However, some undesirable phases are prone to form in ferrite matrix and at ferrite-austenite boundaries if manufacturing processes are not carefully controlled, severely reducing the corrosion resistance of DSS[5,6]. Undesirable secondary phases, such as nitrides, carbides, chi (χ) phase and sigma (σ) phase, mainly form and are clearly separated from each other when the temperature interval is between 550 and 1000 ℃[1,7-9], and some of these phases can even form when DSS is welded or heat treated for a short period according to the time-temperature-precipitation diagram of 2205 DSS[10].

χ phase occurs only in ternary Fe-Cr-Mo, quaternary Fe-Cr-Ni-Mo and Fe-Cr-Ni-Ti systems compared with σ phase, which can also precipitate in binary Fe-Cr system[10-12]. χ phase can precipitate in a small amount in DSS prior to σ phase; owing to its meta-stable properties, χ phase will transform into σ phase after prolonged aging[13,14]. The presence of σ and χ phases will lead to Cr- and Mo-depleted zones nearby, thereby considerably reducing the corrosion resistance[15].

Among the precipitate phases mentioned above, the correlation between σ phase precipitation and

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Biography: Qi SUN, Master; **E-mail**: imsunqi@163.com; **Received Date**: March 23, 2016

Corresponding Author: Pei-de HAN, Doctor, Professor; **E-mail**: hanpeide@126.com

corrosion resistance of DSS has been widely studied owing to its high volume fraction after erroneous heat treatment. Some scholars have also reported that the reduction in corrosion resistance results from the precipitates that formed after short-term aging. Domínguez-Aguilar and Newman[16] have found that chloride pitting favors χ phase sites in 25Cr DSS, and χ phase does not remarkably influence corrosion resistance. Santos et al.[17] have reported that σ phase that formed after 1, 5 and 10 min of aging treatment scarcely influences the pitting potential of 2205 duplex stainless steel, and selective corrosion takes place mainly on sigma-ferrite interfaces. However, because the amount of χ phase is less than that of σ phase, less attention has been devoted on the relationship between different volumes of χ phase and corrosion behavior; moreover, χ phase is possibly neglected intentionally at times[18]. In fact, the presence and volume of χ phase influence the complex pitting corrosion behavior, and the electrochemical properties of χ phase differ from those of σ phase, resulting in the discrepancy in their corrosion behavior. Furthermore, most studies generally defined the type of corrosion in neutral Cl^- solutions as pitting corrosion, but selective corrosion would actually occur between intermetallic χ phase and matrix phase because of the differences in electrochemical properties among phases. Besides that, few articles have contrasted the microstructures of the same area before and after electrochemical tests to distinguish which phases have been exactly corroded at different corrosion stages. Thus, this work detailed the correlation between pitting corrosion behavior and precipitates that formed at 850 ℃ after a short-term isothermal aging of 2205 DSS. Furthermore, the order of corrosion of different phases and the relationship between the size of χ phase and position of pit initiation were investigated.

1 Experimental

1.1 Material preparation

A hot-rolled 4 mm-thick 2205 DSS sheet (Taiyuan Iron & Steel (Group) Co., Ltd.) was chosen as the experimental material, and its chemical composition is shown in Table 1. The as-received steel sheet was cut into 14 mm × 14 mm specimens. All of these specimens were homogenized by solution treatment at 1050 ℃ for 60 min followed by water quenching[19,20]. The so-called solution-treated specimens were subsequently aged at 850 ℃ for 5, 10, and 15 min, respectively. An additional specimen aged for 4 h was also prepared to compare the precipitates and corrosion resistance of specimen aged for short and long periods. Each sample was ground to 1200 grit SiC abrasive paper and then polished. Afterwards, they were etched by modified Behara reagent consisting of 1 g $K_2S_2O_5$, 20 mL HCl, and 80 mL distilled water for metallographic observation. Optical microscopy (OM) and scanning electron microscopy (SEM) equipped with energy-dispersive spectrum (EDS) system were employed to characterize the microstructures of specimens and to analyze their chemical composition. The same microstructures were compared before and after the tests to determine the exact location of the pitting corrosion.

Table 1 Typical chemical composition of 2205 steel mass%

Cr	Ni	Mo	Mn	Si	N	P	S	C	Fe
22.75	5.04	3.19	1.46	0.56	0.19	0.024	<0.001	0.019	Balance

1.2 Polarization test

To assess the pitting corrosion resistance of 2205 DSS containing different amounts of precipitates, potentiodynamic polarization tests were performed on CS350 electrochemical workstation. A conventional three-electrode cell was used in the tests. Exactly 1 cm^2 of the polished specimens, which served as working electrode, was exposed to 3.5 mass% NaCl aqueous solution (pH=7); Pt foil served as counter electrode and saturated calomel electrode (SCE) as reference electrode at room temperature (approximately 25 ℃). Prior to polarization measurements, the specimens were immersed in electrolyte for 30 min to stabilize the open circuit potential (OCP). Then, the potentiodynamic scan started at cathode region of −200 mV below the OCP, with electrode potential continuously rising at a scan rate of 0.5 mV/s and ending at a current density of approximately 10 $mA \cdot cm^{-2}$ when visible pitting corrosion occurred. The pitting potential corresponding to the rapid and stable increase in anodic current density was measured[21]. Each electrochemical test was repeated five times.