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Effect of stress and strain on corrosion resistance of duplex stainless steel

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A B S T R A C T

The interplay of the mechanical and electrochemical phenomena has been a subject of active research. In this paper, corrosion resistance studies about SAF2205 and SAF2507 duplex stainless steel were carried out under elastic stress applied (100 MPa, 300 MPa, 500 MPa) and pre-strain (5%, 10%, 15%) in 3.5% NaCl and 2 mol/L HCl solution. Potentiodynamic anodic polarization study revealed that corrosion resistance of SAF2205 duplex stainless steel decreases slightly with increasing of elastic stress level and noticeably with increasing of pre-strained level. Scanning electron microscopy investigation on surface of the electrochemical tested SAF2205 duplex stainless steel samples indicated that pitting is always located in austenite grains when pre-strain level is below 5% (including different elastic stress level) and located on intersection of ferrite and austenite grain when pre-strain level is above 5%. For SAF2507 duplex stainless steel, elastic stress and pre-strain have no effect on general corrosion and pitting corrosion. Based on deformation mechanism of duplex structure and the relationship of mechanical load and corrosion potential, Pitting corrosion behavior of duplex stainless steel is explained and discussed.

1. Introduction

Almost metal components operate under mechanical and corrosive environments, stress or strain caused by welding, machining, cold working and operation pressure is inevitable. So, the interplay of the mechanical and electrochemical phenomena has been a subject of active research [1,2]. Lots of studies have shown that stress or strain plays a key role in corrosive behavior of stainless steel. In addition to stress corrosion cracking and corrosion fatigue which have been comprehensively studied as the classic representatives of the interplay of the mechanical and electrochemical phenomena, uniform corrosion resistance and pitting corrosion resistance of stainless steel will take on evident change under the action of elastic stress or in cold worked conditions [3–7]. The practical effect of stress and strain on uniform corrosion resistance and pitting corrosion resistance of stainless steel depends on the positive or negative, and the magnitude of stress, the cold worked degree, and the specific corrosive environmental.

Duplex stainless steels are widely used in chemical and petrochemical industries due to high strength and corrosion resistance [8]. Especially, they have prominent pitting corrosion resistance and stress corrosion cracking resistance under the solution annealed conditions, which makes them usually replace 304 and 316 austenitic stainless steels to be used in very aggressive environment containing high chloride concentration [9].

However, exposure of duplex stainless steel welds to elevated temperatures, as encountered in service, leads to a series of metallurgical transformations. Very rapid cooling after welding leads to the formation of chromium nitrides that decreases the resistance to pitting corrosion. Moreover, more ferrite phase will be maintained in welding microstructure, which breaks the balance of the two-phase ratio and increases the brittleness of weld joints. When the heat energy input per unit length is high and the cooling rate is low, the most detrimental development is the precipitation of the σ-phase in the HAZ and the weld metal that makes the resistance to pitting corrosion and uniform corrosion decrease. Welding thermal cycle can lead to the precipitation of fine secondary austenite inside the stable ferrite grains that degrades corrosion resistance of duplex stainless steel due to depletion in chromium and molybdenum. The above problems may be avoided by sound welding process. However, residual stress, strain and non-uniform microstructure will occur during welding, which are the most important factors causing premature failure of duplex stainless steel components. Several studies pay more attention to effect of elastic stress and cold working on corrosion behavior of duplex stainless steel [10–13], which show that elastic stress decreases the

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Table 1
Chemical compositions of SAF2205 and SAF2507 duplex stainless steels (wt%).

	C	Si	Mn	P	S	Ni	Cr	Mo	N
SAF2205	0.017	0.60	1.10	0.027	0.001	5.49	22.37	3.07	0.157
SAF2507	0.030	0.80	1.20	0.035	0.020	5.0	25.54	3.18	0.250

resistance of pitting corrosion and effect of plastic deformation of pitting corrosion depends on the magnitude of cold working.

In the literature, there is a lack of overall knowledge concerning effect of elastic stress and plastic deformation on the resistance of uniform corrosion and pitting corrosion about duplex stainless steel. In this paper, the objective is to investigate how elastic stress and strain affects corrosion behavior of duplex stainless steel in 3.5% NaCl and 2 mol/L HCl solution by Potentiodynamic anodic polarization technique.

2. Experimental

Two types duplex stainless steel were considered and the corresponding chemical compositions are shown in Table 1. The samples for potentiodynamic anodic polarization testing were cut out from hot rolled plates (11 mm thickness) which were solution annealed at 1050 ± 50 °C for 15 min and water quenched (Metallographic microstructure is shown in Fig. 1). Direction of the specimen sampling is along the rolling direction of the plate and the dimensions of the sample are shown in Fig. 2.

The potentiodynamic anodic polarization testing was carried out by a conventional three-electrode cell with a Pt-foil as the auxiliary electrode, and a saturated calomel electrode (SCE) as the reference one. The sample is embedded in epoxy resin and the exposed area is about 1.6 cm^2 (the length of working area is about 1 cm). A constant elastic stress is applied using INSTRON 8800 Servo Hydraulic Universal Testing Machine. In this investigation, three stress levels of 100 MPa, 300 MPa (nearly 50% of Yield strength) and 500 MPa (90% of Yield strength) are carried out. The pre-strained samples with 5%, 10% and 15% of total strain are gained through tensile testing using INSTRON 8800 machine, in which strain is controlled through strain gauge extensometer.

The potentiodynamic anodic polarization testing was carried out in deaerated 3.5% NaCl and 2 mol/L HCl acid solution by pure nitrogen before the test starts and sustained during the test. A potential sweep rate is applied in the anodic direction at 10 mV/min and the potential sweep is from −0.8v to 1.2v after steady-state open circuit potential (EOC) has developed (about 30 min). Prior to the test, the working electrodes were ground and polished with alumina paste 0.1 μm, degreased with alcohol and cleaned in deionized water. Full care and protection during installation are

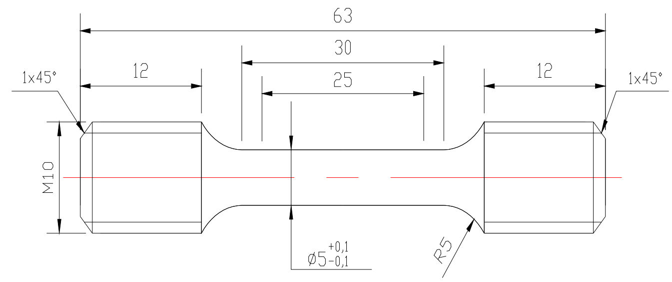

Fig. 2. Dimensions of the sample for anodic polarization test.

taken to avoid crevice corrosion. The corrosion behavior was evaluated by the absolute value of the pitting potential (Epit) and the passivity current density. Tests were carried out at 25 °C. The specimens were tested more than three times under each condition for obtaining the repeatable results and the corresponding value was presented in the results.

3. Test results

Figs. 3 and 4 show the anodic polarization curves obtained at different elastic stress levels for specimens of SAF2205 and SAF2507 duplex stainless steel, respectively, both in 3.5% NaCl and 2 mol/L HCl solution. For SAF2205 duplex stainless steel, the pitting

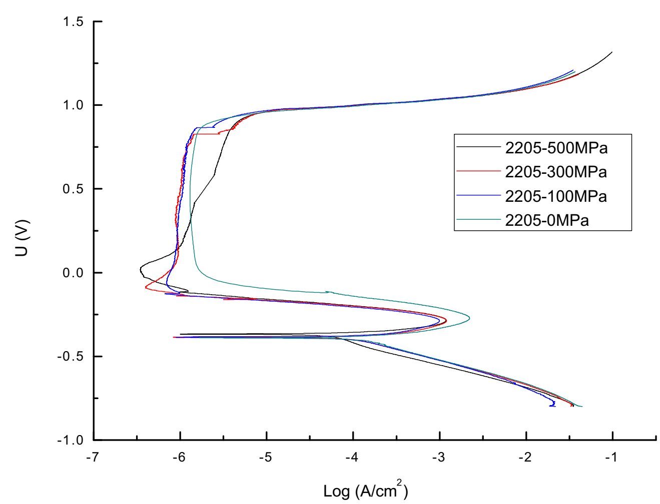

Fig. 3. Anodic polarization curves for SAF2205 in 3.5% NaCl and 2 mol/L HCl solution with potential scan rate 10 mV/min at different elastic stress levels.

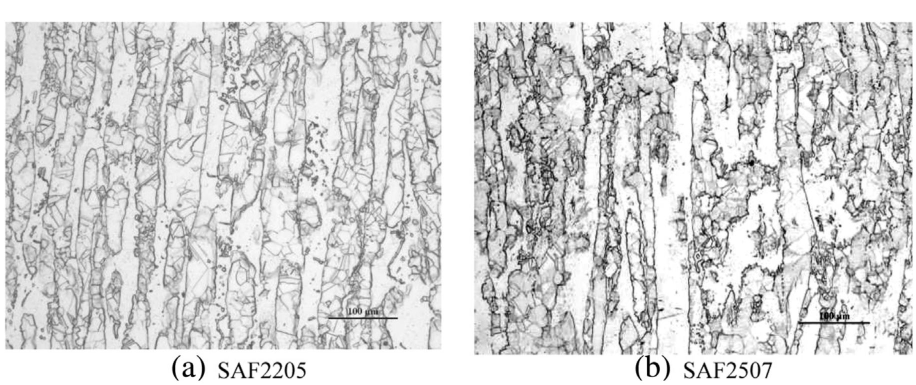

Fig. 1. Metallographic microstructure SAF2205 and SAF2507 along the rolling direction.

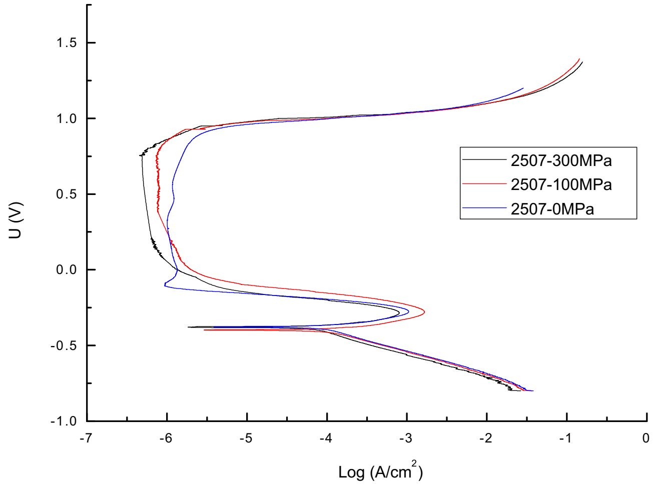

Fig. 4. Anodic polarization curves for SAF2507 in 3.5% NaCl and 2 mol/L HCl solution with potential scan rate 10 mV/min at different elastic stress levels.

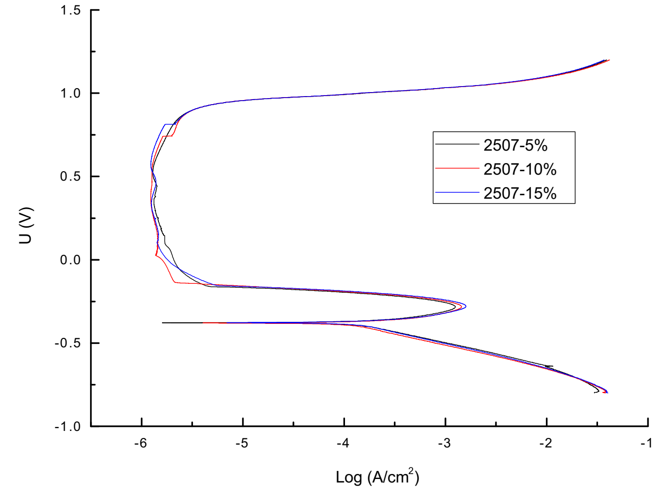

Fig. 6. Anodic polarization curves for SAF2507 in 3.5% NaCl and 2 mol/L HCl solution with potential scan rate 10 mV/min at different pre-strain levels.

potential has a little change, although the corrosion current density increases slightly with the elastic stress increasing, which shows that the nominal elastic stress has no noticeable effect on the pitting corrosion resistance and uniform corrosion assistance of SAF2205 duplex stainless steel. For SAF2507 duplex stainless steel, the pitting potential decrease lightly with the elastic stress increasing, and passive current density showed the opposite trend. In fact, the corrosion resistance of SAF2507 duplex stainless steel is more excellent than SAF2205 because SAF2507 duplex stainless steel has a higher content of alloying elements and forms more stable passive film on its surface.

Figs. 5 and 6 show the anodic polarization curves obtained at different pre-strain levels for specimens of SAF2205 and SAF2507 duplex stainless steel, respectively, both in 3.5% NaCl and 2 mol/L HCl solution. For SAF2205 duplex stainless steel, the corrosion current density of the 5% pre-strained sample higher than that of the solution treated sample is almost one order of magnitude. The corrosion current density increases with increasing the pre-strained level. Especially, the corrosion current density no longer remains the same at the range of passivation and with increases as the potential is shifted to the positive direction in the case of pre-strain. However, the pitting potential keeps the same value for different pre-strain levels. For SAF2507 duplex stainless steel, the pitting potential and the corrosion current density varied little at different pre-strained levels. So, strain level has a strong affection on the corrosion resistance of SAF2205 duplex stainless steel and no sound effect on corrosion resistance of SAF2507 duplex stainless steel under the same conditions.

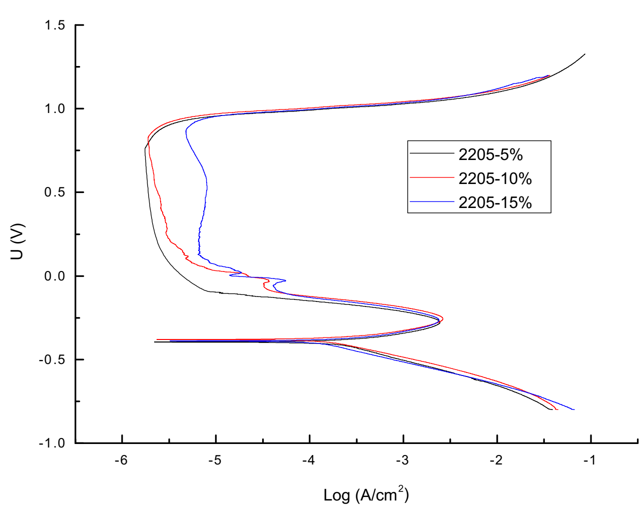

Fig. 5. Anodic polarization curves for SAF2205 in 3.5% NaCl and 2 mol/L HCl solution with potential scan rate 10 mV/min at different pre-strain levels.

Fig. 7(a–c) shows the microstructure of the electrochemical tested specimen surface at different pre-strain levels, respectively. The results indicated that pitting of SAF2205 duplex stainless steel is always located in austenite grains when pre-strain level is below 5% (containing different elastic stress level) and located on intersection of ferrite grain and austenite grain when pre-strain level is above 5%. But, for SAF2507 duplex stainless steel, some pits of pitting corrosion are found at different elastic stress levels and pitting sites are seldom found on corroded surface and only slight uniform corrosion takes place at different pre-strain levels. The above observation shows that the elastic stress and plastic deformation has an noticeable effect on the formation and development of the pitting corrosion for SAF2205 duplex stainless steel and plastic deformation can improve the resistance of pitting corrosion for SAF2507.

4. Discussion

Mechanical stress can induce some changes including structure and distribution of dislocations near the surface, properties of the passive film and so on, which influences electrochemical behavior of stainless steels. It has been demonstrated, by using Auger electron spectroscopy, that the composition of passive films was formed on type 302 and 316 steels [14,15] depends on the nature (compression or tension) and level of stresses. The passive film was formed in a tensile stress field, it is richer in oxygen and poorer in molybdenum in the outer part and thicker than unstrained sample. On the other hand, the beneficial effect of a compressive stress was both attributed to the increased chromium enrichment and the decreased thickness passive film. Similar results (the extent of electrochemical reactivity being significantly enhanced when subjecting the sample to tensile as opposed to compressive stress) about nickel and alloyed aluminum were gained by atomic force microscopy imaging studies [16]. Generally, elastic tensile stress decreases corrosion resistance of stainless steel due to changes of the nature of passive film.

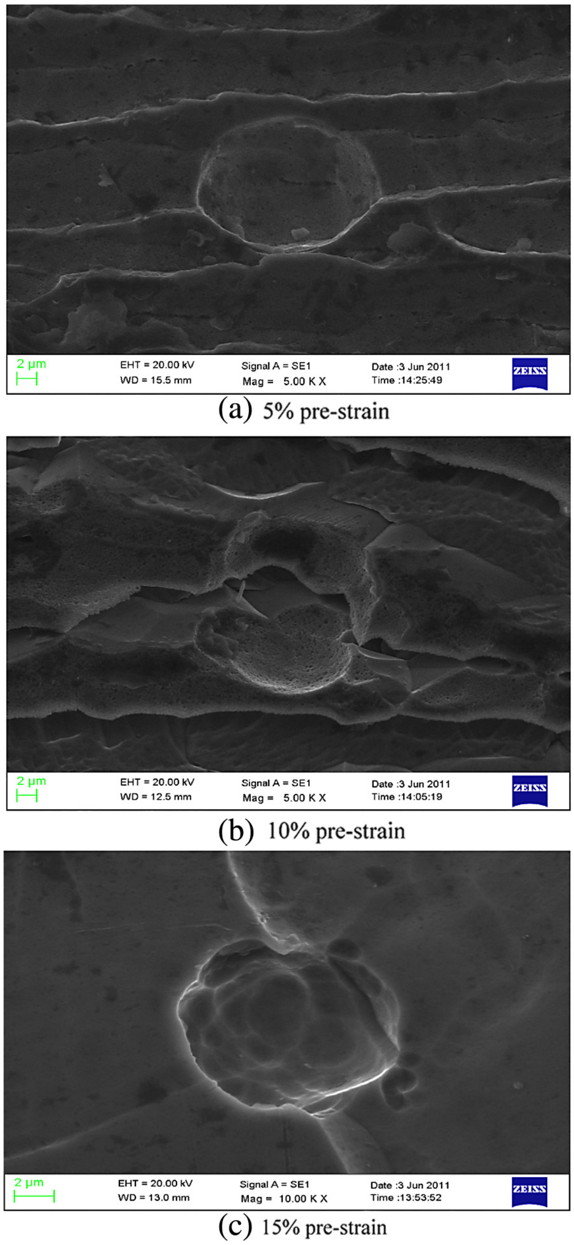

Fig. 7. Pitting sites of SAF2205 duplex stainless steel observed after the electric-chemical test.

In this study, electrochemical behavior of SAF2205 in elastic stress conditions can be explained reasonably according to the above studies. However, it appears that electrochemical behavior of SAF2507 in elastic stress conditions does not agree with the above law. This should be attributed to higher content of alloying elements in SAF2507 than SAF2205. Though elastic tensile stress can change the properties of the passive film in SAF2507, the stability of the passive film does not loss.

Effect of elastic stress on the development of pitting corrosion showed that the initial tensile stress plays a key role in accelerating formation of pitting corrosion locating in austenitic phase [13]. Initial stress state and content must be considered for duplex stainless steel. Residual stress in duplex stainless steel appears during solution treatment because of different thermal expansion coefficient between austenite and ferrite [17,18]. Compressive residual microstresses are found in the ferritic phase and the balancing tensile microstresses in the austenitic phase. Yield phenomenon takes place preferentially in austenitic phase although there is controversy about which phase is the harder phase [18,19]. At lower elastic stress conditions or lower strain level (not higher than 5%), austenitic phase is tensile stress state, which can explain that why the pitting corrosion sites is always located in the austenitic phase. Accumulation of dislocation close to grain boundaries area results high stress concentration, which makes pitting corrosion happen on intersection of ferrite grain and austenite grain. Unlike the electrochemical behavior of SAF2205 being very susceptible to plastic deformation, SAF2507 keeps stable under straining conditions, which can be attributed to higher content of alloying elements and special dislocation structure during plastic deformation [20].

Higher residual stress may exist in microstructure of SAF2507 because of higher content of alloying elements and higher solution annealed temperature than SAF2205. So, yielding behavior happens in austenitic phase at low elastic stress, which makes electrochemical behavior of SAF2507 duplex stainless steel under elastic stress similar to that of SAF2507 under straining conditions. However, the exact stress state in microstructure of solution treated SAF2507 needs to be investigated further. On the other hand, the pitting potential only characterizes some aspects of electrochemical behavior. The development of corrosion pits under elastic stress and plastic deformation conditions is very important and needs to be studied thoroughly.

5. Conclusion

The present study has confirmed that the effects of stress and strain on corrosion behavior of duplex stainless steels are fairly complex, which may depend on initial stress state, stability of passive film, structure and distribution of dislocation and chemical compositions. Nevertheless, it has made it possible to isolate the various results of stress/strain, which depend on the type of duplex stainless steel:

(i) For SAF2205 duplex stainless steel, the nominal elastic stress has no effect on the pitting corrosion resistance, but can decrease uniform corrosion resistance and strain decreases the stability of passive film and accelerates the dissolution of passive film.
(ii) For SAF2507 duplex stainless steel, elastic stress and strain have no effect on general corrosion and pitting corrosion.

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