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Effect of sigma phase on the wear behavior of a super duplex stainless steel

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ABSTRACT

The effect of sigma phase on the sliding wear behavior of a commercial super duplex stainless steel (sDSS) was investigated. The material was heat treated at temperatures from 875 to 975 °C in order to promote the formation of sigma phase. Wear tests were carried out using ball on disc technique at constant velocity and different sliding conditions. Results show that the volume fraction of sigma phase increases the wear resistance under both dry and corrosive media although its detrimental consequences on corrosion resistance. The analysis of wear rate demonstrated that hardness introduced by sigma phase particles reduces significantly the plowing wear mechanism, typical of ductile abrasive wear, and plastic deformation in the subsurface leading to lower fatigue wear.

1. Introduction

Super duplex stainless steels (sDSS) are defined as the subset of duplex stainless steels which show a pitting resistance equivalent number (PRE_N) greater than 40, where PRE_N=% Cr+3.3% Mo+16% N. They are characterized by a two phase microstructure consisting of approximately equal amounts of austenite (γ) and ferrite (α) which offers significant advantages over the more frequently used stainless steels [1–3]. Their attractive combination of mechanical strength and corrosion resistance in aggressive environments has led to an increasing number of applications, mainly in chemical and offshore industries [4–6].

However, a number of undesirable phases such as carbides, nitrides and intermetallic compounds may appear in the ferrite matrix and at austenite/ferrite interfaces if the processing conditions are not carefully controlled. Among the phases listed above, sigma phase with fast formation kinetics has been particularly studied. It can be formed in the temperature interval from 600 to 1000 °C by passing through the temperature range of the thermodynamical stability ("C" curve of the sigma phase), either by both slow heating or cooling. Numerous investigations have been performed to show the effect of sigma phase on mechanical properties [7–11] and corrosion resistance [12–16]. It was demonstrated that small percentage of sigma phase originates a dramatic deterioration of toughness and ductility. Moreover, the precipitation of sigma phase induces a pronounced change in partitioning of Cr, Mo and Ni between ferrite and austenite which reduces the resistance to corrosion, specially the pitting and crevice corrosion resistance in chloride solutions.

Although some research on wear behavior of duplex stainless steels has been performed [17–19], little information exists about the influence of sigma phase on this property [20–22]. Furthermore, none of these studies has focused on the relationship between microstructure and sliding wear. For this reason, the present work analyses the kinetics and the mechanisms of wear that develop in sDSS's with different amounts of sigma phase and their correlation to microstructural characteristics.

2. Experimental procedure

Experiments were performed on an EN 1.4410 sDSS, also known as 2507, supplied by Sandvik AB (Sweden). Its chemical composition is (wt%): 25.2 Cr, 7.10 Ni, 5.10 Mo, 2.10 Mn, 1.10 Si, 0.28 N and 0.03 C. The geometry of material is a bar of 20 mm diameter which was cut into discs of 10 mm thickness. The as-received condition of the bar corresponds to the final stage in the industrial production solution where the material is subjected to a solution heat treatment at 1050 °C with water quench in order to produce recrystallization of both phases. To induce different percentages of sigma phase the material was heat treated at specific temperatures and times as shown in Table 1. Heat treatments conditions were selected based on previous studies performed by the authors and published elsewhere [12]. Precipitates formed after heat treatments were identified by X-ray diffraction (XRD) technique.

The microstructures were examined by optical microscopy (OM). Quantitative metallographic measurements were carried out using image analysis software. As received sDSS material

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Table 1
Conditions and designations of the studied heat treatments.

Temperature (°C)	Time (min)	Designation
875	20	HT875-20
875	180	HT875-180
975	20	HT975-20

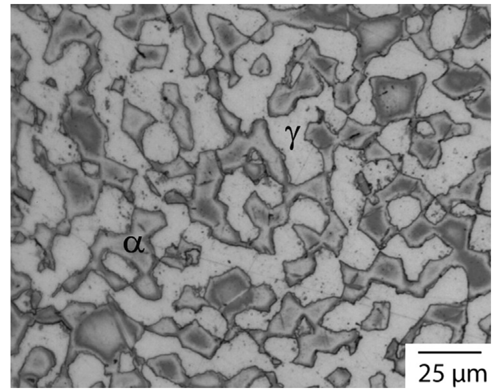

Fig. 1. Transversal section microstructure of the AR SDSS.

(AR) was electrolytic etched in 10 N KOH solution. Sigma phase originated after heat treatments was clearly identified by a solution of 1 g $K_2S_2O_5$, 15 mL HCl and 85 mL H_2O. Vickers hardness was measured for each condition applying a load of 98.07 N.

For wear tests, specimens were polished up to roughness values lower than R_a=0.7 μm following the guidelines of ASTM G99 standard [23]. Sliding wear tests were performed using ball on disc technique in a tribometer TRM-1000 of Wazau GmbH. The ball used was of tungsten carbide of 10 mm diameter and a hardness of 1600 HV10. Dry sliding wear tests were carried out at a constant load of 20 N and a mean linear velocity of 0.048 m/s for all sliding distances: 100, 250, 450, 500, 600, 700, 800 and 1000 m. Before and after each wear test, balls and specimens were ultrasonically cleaned, dried and weighted by an electronic balance having a resolution of ±0.1 mg. The wear volume was determined using weight loss measurements and wear track profile method. In the latter case, wear volume was determined by measuring the cross-section area of the material displaced at the edges at eight equidistant positions along the wear track.

After dry sliding test, the higher wear resistance condition was selected in order to study its behavior on corrosive media and compared it with untreated specimens. In this case, wear tests were performed in 3.5% NaCl and 1 M HCl aqueous solutions in order to evaluate the effect of chloride in neutral and acid media. For all experiments, the sliding distance and mean linear velocity were fixed on 800 m and 0,0048 m/s respectively, while different loads were applied: 20, 40, 60 and 80 N. The same two methods were used to determine wear rate. Wear tracks and the induced damage on the surfaces were examined by OM, confocal laser scanning microscopy (CLSM), scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX).

3. Results and discussion

3.1. Microstructural characterization

Microstructure of transversal section AR-sDSS material is shown in Fig. 1. Homogeneous and equiaxial distribution of austenitic and ferritic phases were observed. The austenite grains were embedded in the gray etched ferrite matrix without the presence of other precipitates. The volume fractions of the two-phase microstructure are approximately 40 vol% of austenite and 60 vol% of ferrite.

Microstructure of heat treated specimens showed that the rate of sigma phase precipitation decreased by raising treatment temperatures. The decomposition of ferrite after 20 min at 875 °C, referred as HT875-20, induces the formation of 24±4% of sigma phase (Fig. 2a) while at 975 °C, referred as HT975-20, this percentage was reduced to 6±2% (Fig. 2b). Some authors [24–27] have described this phenomenon due to the highest diffusivity of solute atoms at increasing temperatures. The homogenization of promoting sigma phase elements, Cr and Mo, between autenite/ferrite causes a reduction of driving force for sigma formation. The highest amounts of sigma phase, 40±2% were achieved after 3 h at 875 °C, referred as HT875-180 (Fig. 2c). This holding temperature enhanced the eutectoid decomposition of ferrite into lamellar mixture structure formed by sigma phase and secondary austenite (γ_2) as shown in Fig. 3. It is known that the formation of this new phase is enhanced by the depletion of ferrite stabilizers, Cr and Mo [28,29].

XRD analysis of specimens heat treated at 875 and 975 °C showed the presence of the peaks corresponding to austenite, ferrite and sigma phase. Other typical secondary phases at these temperatures, e.g. chi phase, were no detected. This result was in agreement with previous studies [30,31] which showed that chi phase appears at short times and starts to dissolve from the moment that sigma phase starts to form.

As it can be observed in Table 2, sigma phase has a significant influence on the steel hardness. The increase in hardness is an indicator of the increasing content of sigma phase. Heat treatments also induce changes on ferrite/austenite volume fractions, internal stresses, dislocations substructures and crystallographic textures which could influence the mechanical response of the steel [32,33].

3.2. Dry sliding wear

The wear maps, i.e. the wear volumes as a function of the sliding distance, are shown in Fig. 4. All studied conditions presented a progressive increase in wear volume with sliding distance. However, depending on the amount of sigma phase the wear volume became significantly lower compared with two-phase austenite/ferrite microstructure. This trend was especially relevant for sliding distances longer than 500 m. Wear resistance was improved by the presence of high volume fractions of sigma phase, HT875-180, while low amounts, HT975-20, seemed to have no effect and showed similar values as untreated specimens.

Subsurface microstructure was analyzed at the end of tests. Plastic deformation due to friction of the ball on the surface was clearly observed for AR specimens at different sliding distances as shown in Fig. 5. In this case, austenite/ferrite phases appeared strongly shifted in the sliding direction. Grains are drawn out and oriented parallel to surface at 10–12 μm from the track surface. The presence of hard particles of sigma phase reduced plastic deformation according to its volume fraction, therefore, HT975-20 specimens showed similar subsurface microstructure as AR, while HT875-180 specimens displayed slightly banded microstructure of 3–5 μm thick (Fig. 6). It is important to note that after 500–600 m sliding distance, HT875-20 and HT 875-180 specimens presented the accumulation of sigma particles in the deformed areas almost without presence of the softer austenite/ferrite matrix which was removed from the surface after repeated loading and unloading cycles (Fig. 7).

The observation of the cross-sections areas for AR specimens showed the presence of plowing wear mechanism which