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Effect of thermal treatments on the wear behaviour of duplex stainless steels

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Abstract. Duplex stainless steel (DSS) is a family of steels characterized by two-phase microstructure with similar percentages of ferrite (α) and austenite (γ).Their attractive combination of mechanical properties and corrosion resistance has increased its use in last decades in the marine and petrochemical industries. Nevertheless, an inappropriate heat treatment can induce the precipitation of secondary phases which affect directly their mechanical properties and corrosion resistance. There are few works dealing with the influence of heat treatments on wear behaviour of these steels in the literature. For instances, this paper aims to determine wear kinetic and sliding wear volume developed as a function of heat treatment conditions. Therefore, the samples were heat treated from 850 ° C to 975 º C before sliding wear tests. These wear tests were carried out using ball on disk technique at constant sliding velocity and different sliding distances. Two methodologies were used to calculate the wear volume: weight loss and area measurement using a simplified contact model. Microstructural observations showed the presence of sigma phase for all studied conditions. The formation kinetics of this phase is faster at 875 ºC and decrease at higher temperatures. Results related to wear showed that the hardness introduced due to the presence of sigma phase plays an important role on wear behaviour for this steel. It was observed also that wear rates decreased when increasing the percentage of sigma phase on the microstructure.

1. Introduction

The increased use of duplex stainless steels (DSSs) is a result of their attractive combination of mechanical strength and corrosion resistance in various types of environments [1]. Their alloy compositions are always carefully balanced in order to obtain a suitable mixture of ferrite and austenite in the final structure. The specific amounts of the phases can differ between different steel grades, but most of them show an austenite content from 20 to 60% and the rest ferrite. DSSs presents typically higher chromium content than corrosion resistant austenitic stainless steel, maximum molybdenum content from 4 to 5% whereas only half nickel content [1,2]. The combination of higher chromium and molybdenum content is a cost efficient way of achieving good resistance to chloride induced pitting and crevice corrosion. Therefore, they are usually selected where localized corrosion is a potential problem, such as marine structures, gauges, fasteners, ships, valves, petrochemical plants and oil and gas production systems.

The balance of alloying elements can be disturbed inadvertently by the formation of precipitates. These can be formed in the temperature range from 600ºC to 1000 ºC during solidification, subsequent heat treatment or aging during service [3-5]. In DSSs, the most common precipitates are: Cr_2N [6] and intermetallic precipitates such as the sigma phase [7], chi phase [8], pi phase [9], R phase [10] and G phase [11]. The formation of these compounds has a detrimental effect on workability, strength, corrosion resistance, and impact strength [1,12-14]. Among these, sigma phase is the most important due to its fast formation kinetics and drastic effect on the toughness and corrosion resistance, even just for the presence of little amounts [15-21].

In the literature, many authors have studied the influence of heat treatments of DSSs on mechanical properties and corrosion resistance. However, there are few investigations related to wear behaviour for this kind of steels. Therefore, in the present work wear tests were carried out after heat treatments from 850 to 975 ºC in order to determine the effect of precipitates on wear behavior.

2. Experimental procedure

The material studied was a duplex stainless steel EN 1.4410, also designed as AISI 2507. It was supplied as industrially manufactured bars of 20 mm in diameter. Its chemical composition is given in table 1.

Table 1. Chemical composition of 2507 duplex stainless steel (%w).

C	Cr	Ni	Mn	N	Si	Mo
0.03	25.2	7.10	2.10	0.28	1.10	5.10

Discs of 10 mm of thickness were cut from the bars. After cutting, different heat treatments were made on the samples in order to induce the formation of different percentages of sigma phase, as shown in table 2. Temperatures and isothermal time-keeping were selected taking into account a previous study performed by the authors on the same type of steel [21]. After the isothermal maintaining, samples were water quenched. To calculate the percentage of ferrite and austenite present in the untreated material (ST), an electrochemical etching was used. Aqueous solution of 400 g of sodium and potassium hydroxide with a voltage of 4.2 V for 10 seconds was applied. The quantification of the percentage of sigma phase present for each condition was carried out using image analysis by optical microscopy. The electrochemical attack used in this case is a sodium hydroxide 10 M solution. The applied voltage was 4 V for 4-8 seconds. Also Vickers hardness was measured for each condition using a load of 10 kg and the results are included in Table 2.

Table 2. Heat treatments conditions studied.

Temperature (ºC)	-	875	875	975
Time (minutes)	-	20	180	20
Sigma phase (%)	0	24	41	6
HV Hardness	241	332	374	274
Designation	ST	875-20	875-180	975-20

Previous to wear testing, the samples were polished up to roughness values lower than 0.7 µm, as recommended in the standard ASTM G99 [22]. Sliding wear tests were performed using ball on disc technique at ambient conditions in a tribometer TRM-1000 of Wazau GmbH. The ball used was of tungsten carbide with 10 mm of diameter and a hardness of 1600 HV10. Tests were done at a constant load of 20 N and a mean linear velocity of 0.048 m/s. Different distances were considered: 100, 250, 500, 700 and 1000 m.

Wear volumes were determined using two methodology techniques: weight loss and area measurement. In the case of weight loss, a high-precision balance with a resolution of 10^{-4} g was used. For the case of area measurement, the amount of wear volume was determined assuming a simplified contact model in which the wear track area is measured using linear profilometry and the sliding track using optical microscopy.

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3. Results and discussion

The microstructure of the studied EN 1.4410 duplex stainless steel is shown in figure 1. After etching, ferrite is coloured while austenite remains unaltered. Volume fractions of the two phases are approximately: 60 vol% α and 40 vol% γ.

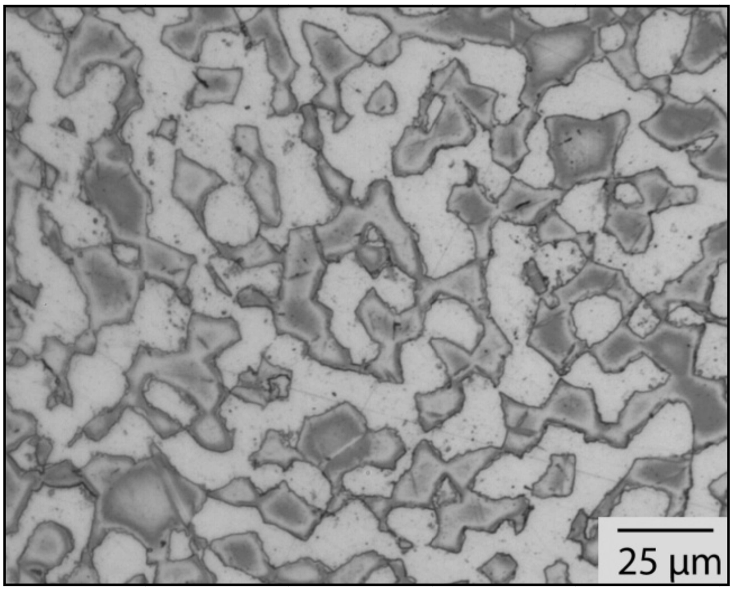

Figure 1. Microstructure of the studied duplex stainless steel

The analysis of the heat treated samples by X-ray diffraction revealed only the presence of sigma phase in all the studied conditions, as can be observed in figure 2.

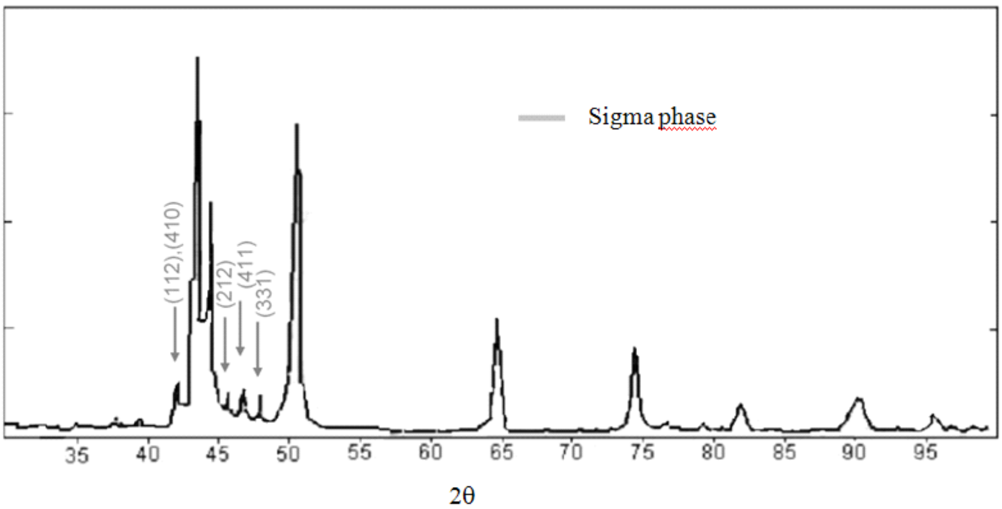

Figure 2. X-ray diffraction pattern of the sample heat treated at 875 ºC during 20 minutes.

Figure 3 shows that sigma phase nucleates at the ferrite-austenite interfaces and grows into the adjacent ferritic grains, developing an eutectoid structure consisting of sigma phase (white colour in the image) and secondary austenite (dark colour).

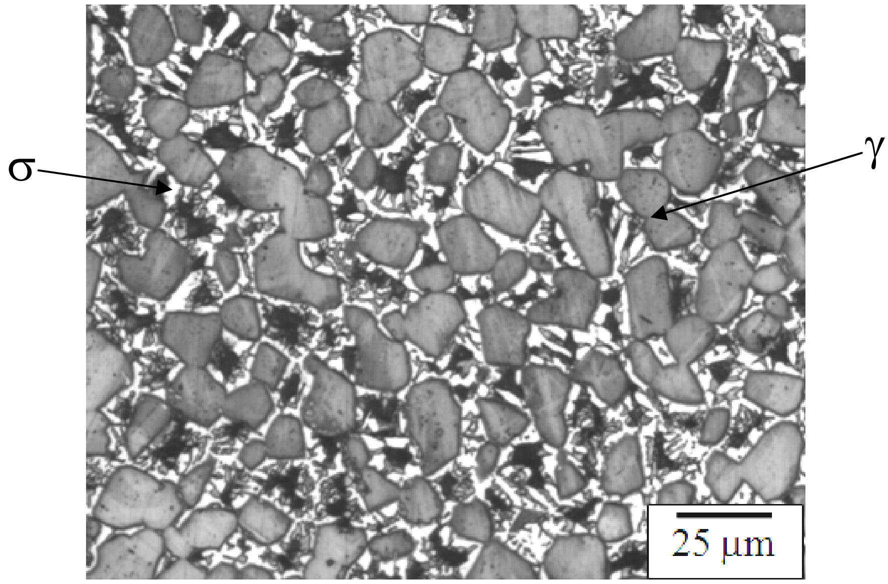

Figure 3. Microstructure after heat treatment at 875 ºC during 180 minutes.

Figure 4 presents the results of the wear tests for 500 m of sliding distance. As it can be observed, only the presence of high percentages of sigma phase, i.e. sample 875-180, produces an increase on the wear resistance, as compare with the untreated sample (ST).

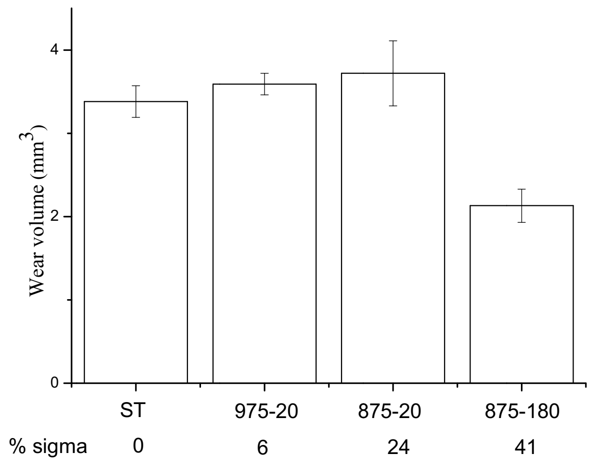

Figure 4. Wear volumes after tests at 500 m of sliding distance.

Wear kinetics was studied at the same load value and applying different sliding distances for the two conditions that offered dissimilar behaviour at 500 m, i.e. ST and 875-180). Figure 5 illustrates wear volume as a function of sliding distance using weight loss technique. It was observed that the existence of large amounts of sigma phase in the microstructure led to a better wear behavior. This phenomenon can be explained considering the hardness introduced by sigma phase, which strengthens the surface and contributes to improve the resistance against stresses originated due to the action of the ball on the surface. In this way, hardened steel is less sensible to the repeated action of shear stresses that induce microcracks and consequently loss of material.

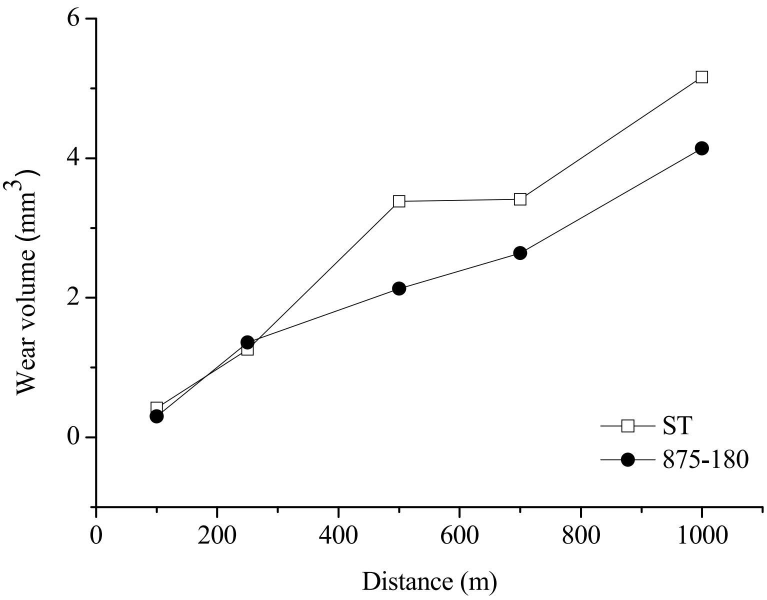

Figure 5. Wear volume for ST and 875-180 samples at studied sliding distances.

Table 4 compares the results of wear volumes using weight loss method with those obtained following the area measurement methodology. As shown, the values obtained by both methods are in agreement, despite the trend to higher values in the case of area measurements. This can be explained because area measurement method considers track primary profile taking into account the area of material ploughed in the surface whereas the weight loss method not.

Table 4. Wear volume calculated using two methodologies: weight loss and area measurement using a simplified contact model.

	Weigth loss (mm^3)		Area measurement(mm^3)	
Distance (m)	ST	875-180	ST	875-180
100	0.42	0.30	0.43	0.31
250	1.26	1.36	1.46	1.78
500	3.38	2.13	3.31	2.45
700	3.41	2.64	3.68	2.88
1000	5.16	4.14	5.40	4.48

4. Conclusions

In the present work the effect of thermal treatments on wear behaviour of duplex stainless steel EN 1.4410 was studied. Samples were heat treated at 875 and 975 ºC before wear tests. Those tests were carried out using ball on disc technique at ambient conditions. The main conclusions are summarized as follows:

Analysis of the heat treated samples revealed only the presence of sigma phase in all studied conditions. The presence of high percentages of this phase increases the wear resistance as compare with the untreated sample for all sliding distances studied. Hardness introduced by sigma phase improves the resistance against stresses originated due to the action of the ball on the surface.

Values obtained following area measurement method were slightly higher comparing with weight loss method. The difference observed between two methods is related to the material ploughed in the surface.

5. Acknowlegments

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