Low-temperature carburised AISI 316L austenitic stainless steel: Wear and corrosion behaviour

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ABSTRACT

Low temperature carburising (LTC) is a thermochemical treatment designed so as to achieve a good combination of wear and corrosion resistance in stainless and duplex steels. In this work, the influence of LTC on both corrosion and dry sliding behaviour of AISI 316L was investigated. LTC significantly enhanced surface hardness, due to the formation of the carbon-supersaturated S-phase. Consequently, the wear behaviour (evaluated against different countermaterials) improved, due to increased resistance to plastic deformation, as well as to decreased tendency towards adhesion. In order to evaluate the corrosion behaviour, electrochemical measurements were performed both in conventional environments and in reference conditions for the food industry. The results showed a significantly improved corrosion resistance in chloride environments, where the formation of a C-rich surface layer ennobles the treated steel, even though pitting corrosion was observed at very high anodic potentials. Conversely, the treated steel showed comparable (in acetic acid) or worse (in a sanitising solution) behaviour than the untreated one. In sulphuric acid the treated steel did not passivate, but it corroded at a limiting current density much lower that the critical current density for AISI 316L passivation.

1. Introduction

Austenitic stainless steels are widely used in chemical, food and automotive processing industries, medical instruments and pharmaceutical equipments, owing to their excellent corrosion resistance, high toughness and good workability. A major limitation placed on austenitic stainless steels is, however, the low hardness and consequently poor wear resistance in sliding conditions. In fact, stainless steels are prone to galling, scoring and seizure [1,2], but they are often required for a given application because of their good corrosion resistance. In the field of surface engineering, many attempts have been made to improve the wear resistance of austenitic stainless steels, without deteriorating the corrosion resistance [3–8]. Among these, low temperature carburising (LTC) [9] seems to be a promising surface modification technique, improving surface hardness and tribological behaviour of austenitic stainless steels without decreasing the corrosion resistance (due to the formation of a surface layer of S-phase, a single austenite phase supersaturated with carbon [3,5,10,11], without the precipitation of undesired Cr carbides).

In order to test the achievement of a good combination of both wear and corrosion resistance, the effect of LTC on both the corrosion and the dry sliding behaviour of AISI 316L were investigated and discussed in this study. In particular, tribological tests in dry sliding conditions were carried out against both LTC-treated and untreated AISI 316L, in order to characterise the behaviour in self-mating conditions, which take place in components such as valve seats, pumps and bearings.

As regards the corrosion behaviour of low-temperature carburised AISI 316L stainless steel, most papers focus on conventional environments such as NaCl [11–16] in order to evaluate the tendency towards localised corrosion, or H_2SO_4 [12,16]) so as to test the passivity behaviour.

In the present work, since LTC-treated AISI 316L is applied in the food industry for components such as lobe pumps, also other environments were taken into account, namely acetic acid (recommended for testing of metal articles in contact with acetic foodstuffs [17]) and a sanitizing solution used for cleaning procedures in the food industry (Oxonia Active®, consisting of hydrogen peroxide (15–30%), peracetic acid (<5%) and acetic acid (5–15%)), in order to extend the characterisation of the corrosion behaviour to a wider range of aggressive environments.

2. Experimental details

2.1. Materials and characterisation methods

The material under investigation was AISI 316L austenitic stainless steel, with the following nominal chemical composition (wt.%): C: 0.03, Cr: 17, Fe: 65, Mn: 2, Mo: 2.5, Ni: 12, P: 0.045, S:

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0.03, Si: 1 [18]. The alloy was supplied as an extruded bar, which underwent a standard solution treatment. Before the carburising process, the specimens were ground, using silicon carbide papers up to 320 grit, to achieve a surface roughness R_a of 0.4 μm.

The specimens were then subjected to LTC, which involves diffusion of large amounts of C atoms into the material, at a diffusion temperature below 500 °C, in order to prevent the formation of chromium carbides. Due to the low treatment temperature, LTC requires a long diffusion time for achieving an effective hardening depth up to 33 μm. The microstructural characterisation was carried out by means of optical and scanning electron microscopy (OM, SEM), on specimens prepared using conventional metallographic techniques (chemical etching by $FeCl_3$/HCl or by Beraha II [19], followed by observation in reflected polarised light). The phase constitution of the treated steel was determined by X-ray diffraction (XRD), performing θ–2θ scans from 35° to 100° with steps of 0.02° 2θ and counting times from 1 to 10 s/step using a Cu Kα radiation source.

Carbon content and distribution through the cross section of the LTC-treated samples was estimated by glow discharge optical emission spectrometry (GDOES).

Surface microhardness and microhardness profiles were measured by a Vickers hardness tester in the cross sections of LTC-treated samples (indentation load: 50 g; indentation time: 15 s).

2.2. Tribological tests

The tribological behaviour in unlubricated sliding conditions of both untreated and LTC-treated AISI 316L was investigated by a slider-on-cylinder tribometer (block-on-ring contact geometry, Fig. 1), described with more details in Ref. [20]. The stationary sliders consisted of AISI 316L (in the form of prismatic blocks, $5 \times 5 \times 70$ mm³), whilst two different countermaterials were used for the rotating cylinder (40 mm in diameter): untreated and LTC-treated (in the same conditions as the sliders) AISI 316L. Dry sliding tests were carried out under normal loads ranging from 5 to 25 N, at a sliding speed of 0.3 m/s, over a distance of 2000 m. Hertzian maximum contact pressures for the block-on-ring contact geometry, were calculated according to Eq. (1) [21]:

$$P_{max} = (PE^*/\pi R)^{0.5} \tag{1}$$

where P is the normal load, R the radius of the cylinder (20 mm) and E^* is the contact modulus defined by following equation:

$$\frac{1}{E^*} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \tag{2}$$
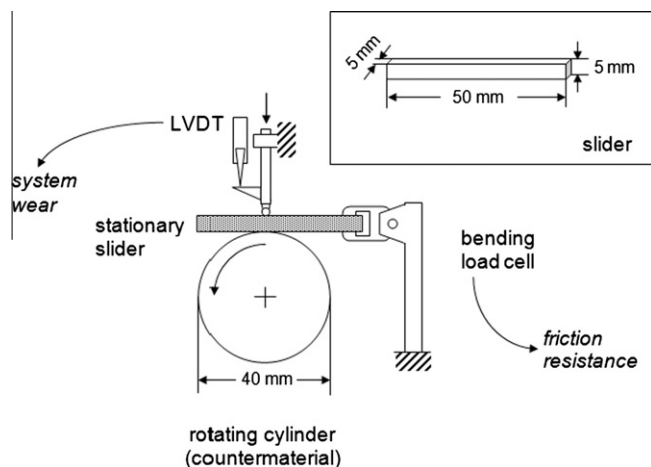

Fig. 1. Schematic drawing of the slider-on-cylinder (block-on-ring) tribometer.

which combines the Poisson's ratio and elastic modulus of the cylinder and the slider. For these evaluations, a Poisson's ration v of 0.3 for both untreated and treated AISI 316L was used, whilst the elastic modulus values were derived from Ref. [22] (179.3 ± 0.6 for the untreated steel and 199.9 ± 4.8 GPa for the LTC-treated steel). The maximum pressures estimated by Eq. (1) ranged from about 40 to 90 MPa. The maximum wear scar depth and width was measured at the end of each test by stylus profilometry (pickup curvature radius: 5 μm). Wear volumes were calculated on the basis of profilometric data according to the ASTM G77-05 standard [23].

2.3. Corrosion tests

In order to test the corrosion behaviour of the treated surface, electrochemical tests were performed in a 2 L cell equipped with a three electrode system (reference electrode: Ag/AgCl) connected to a Solartron SI 1280B potentiostat. Specifically for the corrosion tests, disks of 30 mm in diameter and 5 mm in thickness were machined from the extruded bar. The selected corroding media were: aqueous solutions of NaCl 3.5 wt.%, HCl 2.5 vol.%, H_2SO_4 0.5 M, CH_3COOH 3 vol.% and Oxonia 2.5 vol.%.

Before immersion into the electrolytes, the treated and untreated specimens were ultrasonically cleaned in acetone. Further details on the experimental procedure are reported in [24]. After 1 h immersion time, parameters such as open-circuit potential, E_{corr}, and polarisation resistance, R_p, were measured; afterwards, the specimens were submitted to a potentiodynamic scan, at a 0.1667 mV s⁻¹ scan rate, from −0.1 up to +1.0 V with respect to the free corrosion potential. After the tests, the corroded surfaces were observed by OM in order to identify the corrosion morphology.

3. Results and discussion

3.1. LTC-treated samples characterisation

Representative micrographs of the cross section of LTC-treated AISI 316L are shown in Fig. 1a. The chemical etchant highlights the austenitic microstructure of the steel, with typical twinned grains (Fig. 2a), whilst the C-rich layer (about 30 μm thick) on the treated surface maintains a whitish (in reflected polarised light, Fig. 1a) or featureless (in the SEM image of Fig. 2b) appearance because of its lower reactivity towards the etchant, as already observed by Sun and Bell [25].

The phase composition of LTC-treated samples was checked by X-ray diffraction (XRD) measurements (Fig. 3), indicating that the reflections of the austenite phase were shifted towards lower diffraction angles than in the untreated steel, due to the expansion of the lattice induced by C atoms. The comparison of lattice parameters of treated and untreated samples, corrected according to the Nelson–Riley extrapolation method [26], showed a lattice expansion of about 2%. This indicates an average carbon concentration of about 2 wt.% (7 at.%) in the investigated thickness, on the basis of the linear correlation described in Ref. [27].

The XRD patterns in Fig. 3 also show the presence of the Hägg or "χ" carbide (Fe_5C_2) in the LTC-treated steel. TEM observations reported in Ref. [22] demonstrated that the χ carbide is structurally coherent with austenite and therefore forms as the first carbide phase in highly supersaturated austenite. However, due to the presence of significant amounts of alloying elements such as Cr and Ni in the AISI 316L steel, the carbide phase detected in the LTC samples is isostructural with the χ carbide but probably contains other alloying elements in addition to Fe.