Wear 297 (2013) 998–1005

Contents lists available at SciVerse ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Improvement of cavitation erosion resistance of a duplex stainless steel through friction stir processing (FSP)

J.D. Escobar [a], E. Velásquez [a], T.F.A. Santos [b,c], A.J. Ramirez [b,c], D. López [a,*]

[a] Universidad Nacional de Colombia—Medellín, Departamento de Ingeniería Mecánica—Grupo de Tribología y Superficies, Cra 80 65-223, Medellín, Colombia
[b] Brazilian Nanotechnology National Laboratory (LNNano), PO Box 6192, Campinas 13083-970, Sao Paulo, Brazil
[c] School of Mechanical Engineering, University of Campinas (Unicamp), Campinas 13083-860, Sao Paulo, Brazil

ARTICLE INFO

Article history:
Received 27 February 2012
Received in revised form
8 August 2012
Accepted 15 October 2012
Available online 2 November 2012

Keywords:
Cavitation erosion
Duplex stainless steel
Friction stir processing
Incubation period
Roughness parameters

ABSTRACT

The cavitation erosion (CE) resistance of an UNS S32205 duplex stainless steel (DSS) was improved through microstructural modification using friction stir processing (FSP). As-received material was processed using 200 rpm and 100 mm/min spindle and travel speeds, respectively. The cavitation erosion tests were performed in a vibratory apparatus according to ASTM G32 standard. The incubation period, the maximum erosion rate and the variation of surface roughness during the tests are reported and the results are compared with those obtained for the base metal samples (BMS). The worn surfaces were characterized using roughness measurements and scanning electron microscopy (SEM). After a CE testing time of 10 h, FSP samples showed a 70% diminution of the mass loss when compared to the BMS. Moreover, a 200% enhancement of incubation time and 100% reduction in the erosion rate were achieved after FPS. The improvement of CE performance is related to the recrystallized and refined microstructure, as well as to the modification of the elongated α/γ interfaces.

1. Introduction

Duplex austenitic–ferritic stainless steels combine desirable properties of the austenitic and ferritic phases and have been characterized as materials with good performance under high mechanical loads and corrosion, especially under chloride stress corrosion cracking conditions [1]. These properties make them good candidates for applications in mining, boilers, food, paper, chemical, petrochemical and offshore industries [2]. In addition, the high price of Nickel during last years has motivated the use of this kind of low Ni alloys, starting to become competitive and spreading its use to new applications.

Cavitation erosion resistance is a desirable characteristic for many systems in the industries mentioned before, however there are few reports regarding the performance of duplex stainless steels (DSS) under this condition. Former studies have addressed the DSS performance under cavitation erosion tests, reporting both crack propagation mechanisms and grain size influence. Some have reported a considerable lower cavitation erosion resistance than other stainless steels, due to the presence of ferrite and the α/γ interfaces [3–6].

In this study, friction stir processing (FSP) is used to modify the microstructure of an UNS S32205 duplex stainless steel to improve its cavitation erosion resistance. FSP is a solid-state thermomechanical process derived from friction stir welding (FSW). It subjects the material to a severe and localized plastic deformation at intermediate temperatures, resulting a refined microstructure composed by recrystallized grains [7–10]. Therefore, it is a promising technology to locally modify the tribological properties of metals.

During FSP a rotating tool is plunged into the piece to be processed and after a short dwell time it starts to travel along the surface that is being processed. The tool generates heat by friction and deformation, which softens the material, allowing it to be mechanically deformed around the tool. The simultaneous rotational and translation motion of the tool during FSP generates an asymmetric processed zone with respect to the traveling direction. The side of the zone on which the rotational motion of the tool coincides with the travel direction is called “advancing side (AS).” The opposite one is the “retreating side (RS)” [11].

In the present investigation, plates of UNS S32205 DSS were modified by FSP in order to produce a refined and recrystallized structure. Cavitation erosion tests were performed both in the as-received and FSP conditions to compare incubation period and erosion rate. A complementary study of roughness evolution of the wear process was performed to characterize the wear mechanisms acting for both samples.

2. Experimental procedure

2.1. Materials and microstructural modification

The chemical composition of the UNS 32205 DSS used in this work is shown in Table 1 and it was provided by the supplier.

---

[*] Corresponding author. Tel.: +574 4255231; fax: +574 4255000.
E-mail address: dmlopez3@unal.edu.co (D. López).

0043-1648/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.wear.2012.10.005

Table 1
Chemical composition (wt-%) of a UNS S32205 duplex stainless steel.

C	Mn	Si	Cr	Ni	Mo	P	S	N
0.023	1.80	0.30	22.5	5.4	2.8	0.03	0.01	0.16

Plates of 350 × 150 × 6 mm were used for the sample preparation. The processing was performed normal to the rolling direction, using a dedicated TTI FSW system, which allows position and force control. Downward forces of 37 kN (force controlled process) were necessary to produce good quality surfaces, using an un-tilted PCBN-40%W-Re tool with threaded conical shape, 6 mm long pin and convex threaded shoulder. Process speeds were limited to keep the forces in the travel direction at or below 15 kN in order to extend the tool life. The parameters used were 200 rpm and 100 mm/min. An Argon atmosphere was introduced through a gas cup around the tool at a flow rate of 1.68 m^3/h to protect the tool from chemical degradation.

2.2. Microstructural characterization

Friction stir and base material samples, from this point on named FSP and BMS, respectively, were prepared for optical microscopy. The metallographic preparation consisted on sanding and polishing up to 1 μm grain diamond paste; final polishing was performed in a Vibromet® vibratory polisher with a 0.06 μm colloidal silica solution. Electrolytical etching was used in order to reveal the microstructure. The etching solution consisted of 40% vol. HNO_3 in distilled water. Voltage and etching time were 1.50 V and 75 s, respectively.

An Olympus microscope with a PAXCam digital camera attached to it was used for the optical microscopy performed in this study. PAX-it!® software was used to record and analyze the images. The scanning electron microscope (SEM) analyses were carried out using a JEOL JSM 5900 LV and a Zeiss Supra-55VP. Vickers microhardness map was performed through LECO® microindentation hardness testers using a load of 1.96 N ($HV_{0.2/15}$).

Volumetric fractions of ferrite and austenite were determined by digital image analysis using the free software *Image J* and PAX-it. The ferrite grain size was measured by manual-intercept counting with a superimposed circle of known perimeter, following ASTM E-112 [12]. A confidence interval of 95% was used for the grain-size and volumetric-fraction measurements.

2.3. Cavitation erosion tests

Cavitation erosion tests were carried out in a Telsonic DG-2000-2 ultrasonic equipment according to ASTM G32 standard [13]. Test samples were held stationary below a vibrating horn at a distance of 0.50 ± 0.02 mm (indirect method). The frequency of vibration of the horn was 20 ± 0.5 kHz, and the test liquid was distilled water maintained at 25 ± 0.5 °C (Fig. 1).

Prior to the tests and according to the ASTM G32 standard [13], all the samples were ground polished on emery papers ASTM 80, 240, 320, 400 and 600, in order to obtain surfaces with mean squared roughness (R_q) lower than 1 μm. Cavitation erosion tests were developed on BMS during 10 h and during 16 h for the FSP samples. Since the erosion resistance of the FSP samples is higher, their testing time had to be increased from 10 to 16 h. The mass losses and roughness changes were monitored every hour to obtain curves plotted as a function of time. Mass losses were measured in a Sartorius CP225D scale, with an accuracy of 0.01 mg. After the third hour, the worn surfaces were examined in order to identify the main wear mechanisms using secondary electrons imaging in the SEM. The cavitation erosion resistance is discussed in terms of the measured mass losses and the topographical features of the worn surfaces.

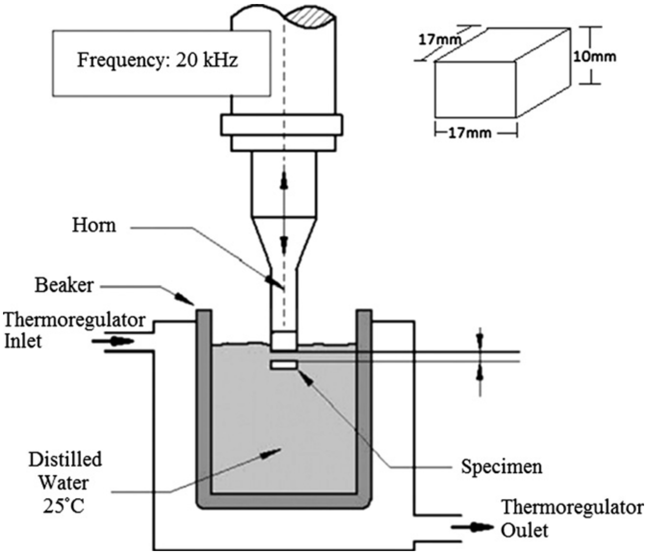

Fig. 1. Ultrasonic equipment for cavitation erosion tests.

2.4. Surface topography measurements

The changes in surface topography of the samples during the tests were monitored with a Mitutoyo surftest sv3000 profilometer with tip radius of 1 μm and resolving power of 0.01 μm. A cut-off length of $L=0.8$ mm was selected for all the measurements according to ISO 4288 standard [14]. A Gaussian filter was used for all measurements. Roughness parameters R_a, R_q, R_p, R_v, R_{sm}, R_k, R_{sk} following ISO 4287 standard, were used to characterize the surfaces [15].

R_a is the mean height of the roughness profile, R_q is the root mean square of the roughness profile heights, R_{sk} (Skewness) is the third central moment of profile amplitude probability density function, measured over the assessment length used to measure the symmetry of the profile about the mean line, R_{ku} (Kurtosis) is the fourth central moment of profile amplitude probability function, measured over the assessment length and describes the sharpness or flatness of the probability density of the profile, R_{sm} is the mean spacing between profile peaks at the mean line and R_p and R_v are the maximum and the minimum heights of the profile above and below the mean line, respectively [16]. Roughness values were measured at the beginning and after each hour of cavitation erosion tests. The values correspond to the average of 10 measurements performed on different directions on randomly selected areas of each sample.

3. Results

3.1. Microstructural characterization and hardness

The microstructure of the processed zone in FSP samples can be classified into four different regions including the base metal zone (BMZ), which is unaffected by the process; the thermomechanically affected zone (TMAZ); the heat affected zone (HAZ) and the stir zone (SZ). Additionally, these regions can show distinct characteristics on the advancing side (AS) and the retreating side (RS) since the FSW/FSP produces an asymmetrical distribution of friction and deformation in the welded joint [11]. The HAZ has