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Microstructural and ultrasonic characterization of 2101 lean duplex stainless steel welded joint

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ABSTRACT

In this paper, welded joint of a 2101 lean duplex stainless steel (DSS) was studied using ultrasonic attenuation measurements. Two plates were welded using gas metal arc welding (GMAW) process. Attenuation measurements were performed by the immersion ultrasonic pulse-echo technique using a high precision x, y, z scanner in order to generate *c-scan* images of the welded sample. Experimental measurements show that the longitudinal ultrasonic wave amplitude is significantly affected by the recrystallization of the microstructure caused by multi-pass welding.

An increase in the attenuation coefficient of the ultrasonic wave was measured and related to coarser ferrite grains with bigger mean free ferrite distance while recrystallized zones with finer grains of intergranular austenite produce a substantial reduction in the attenuation coefficient. Similarly, it was found from Vickers microhardness maps, that finer microstructure show higher microhardness values while coarser grains present the lower values. The experimental evidence indicates that attenuation measurements can be used as nondestructive evaluation method to assess the microstructure of this type of welds.

1. Introduction

With the appearance of new materials, engineers are facing the need of joining in order to optimize performance by exploiting the characteristics in engineering design of structures or components. A number of studies have been performed to study the mechanical response, microstructural characteristics, residual stress effect and corrosion resistance of fusion welds. The results indicate that depending on the welding procedure, weld joint geometry, parent and consumable materials a weld joint exhibits several regions with substantially different microstructures and thereby different properties. 2101 Lean duplex stainless steels is a low Ni and Mo alloy content that was commercially introduced at the beginning of the 21 century by Outokumpu Company [1]. This type of duplex stainless steel has higher mechanical properties and better resistance to pitting and stress corrosion cracking in comparison to the AISI 300 alloys [2].

Duplex stainless steels (DSS) have been extensively used in the fabrication of different components for many industrial applications such as pressure vessels, pipelines, and heat exchangers in the food, oil and nuclear industries. Its use is due to their high strength and toughness properties as well as their high corrosion resistance in very aggressive environments [3–6]. In recent years, due to economic reasons duplex stainless steel with lower nickel and molybdenum content, have been designed and it is expected to be used extensively in different structural components. It is known that nickel affects the toughness of the ferrite phase and promotes the formation of austenite; consequently, this effect needs to be considered at the time of fusion welding DSS. Also, all the elements that promote austenite formation need to be considered [7–10]. It has been reported that high contents of ferrite diminish the corrosion resistance and affect the mechanical response of the weld [11,12].

In the industry, ultrasonic techniques (UT) are extensively used because of their capabilities to detect and size potential in-depth flaws. Austenitic stainless steel welds present inspection difficulties because during the solidification process of the weld pool the mechanism of crystalline growth produces a microstructure comprised of numerous grains with elongated shape that exhibit a locally preferential orientation that creates areas with strong anisotropy [13,14] i.e., grains with crystallographic axis orientations differing from one grain to another [15–18]. Ultrasonic attenuation in polycrystalline metals is primarily caused by a loss in the amplitude of the ultrasonic signal, this loss takes place at boundaries of grains that have different crystallographic orientations where the

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propagating wave is scattered due to impedance mismatch [19]. Measurement of attenuation due to scattering presents real difficulties, especially in anisotropic materials [16,20]. Using numerical calculations on randomly oriented aluminum grains and aligned stainless steel, Ahmed et al. concluded that the attenuation is controlled by grain volume [19]. Welded metal also produced complex microstructural regions with different acoustic properties that could complicate residual stress assessment [21].

Saiie et al. [22] used an statistical model to investigate the effect of the microstructure of materials. They measured the backscattered signal that consists of multiple interfering echoes with random amplitudes and phase, finding that the attenuation coefficient is position dependent.

Typically, in pulse-echo configuration, the frequency dependent attenuation coefficient ($\alpha(\omega)$) from scattering is calculated from the Fourier transform of the frontwall ($F(\omega)$) and backwall ($B(\omega)$) signals using the expression [23]:

$$\alpha(\omega) = \frac{20}{d} \log \left[\frac{F(\omega)}{B(\omega)} \frac{D_1}{D_0} R^2 \right] \tag{1}$$

were d is the two times propagation distance, D_0 and D_1 are the diffraction correction terms and R is the reflection coefficient.

In the literature, it is possible to find several papers that used this approach to investigate microstructural characteristics of different materials [23–26]. Several models have been proposed to study the scattering-induced attenuation of the ultrasonic wave using perturbation theory based on the Keller approximation among them [27] or using the Dyson equation [28].

Vargas-Arista et al. [29] used ultrasonic spectral analysis to characterize artificial aging of welded joints of an API 5L X52 steel pipeline. The experimental results showed that the attenuation coefficient of the longitudinal waves is sensitive to gradual microstructural changes produced by the aging treatments. Ruiz et al. [30], reported the aging of 2205 stainless steel at 700 and 900 °C for different time intervals; their findings indicate that the ultrasonic attenuation coefficient is sensitive to the transformation of ferrite into sigma phase and secondary austenite. Ultrasonic characterization has been applied to establish grain size [31], since grain size has an important influence in most mechanical properties and therefore it is very important in quantitative materials characterization. Kang et al. proposed degradation indexes of attenuation to characterize fatigue damage of Al6061-T6 using c-scan imaging [32].

Due to the importance associated with microstructural characterization of welded joints, this study undertakes an interdisciplinary research to evaluate the changes of microstructure and hardness in a welded joint of 2101 lean duplex stainless steel and to establish a relationship with ultrasonic parameters. The ultrasonic attenuation coefficient was used to correlate the variation in the microstructure caused by multi-pass welding.

2. Methods

2.1. Materials preparation

Two plates of 2101 lean duplex stainless steel ($12.7 \times 70 \times 150$ mm^3) were welded using gas metal arc welding (GMAW) process with a mixture of Ar + 3% N_2 as shielding gas flowing at 14.5 L/min with three welding passes. The chemical compositions of base metal and filler wire (ER-2209 with 1.2 mm in diameter) are given in Table 1.

The filler metal has higher nickel content in order to promote the formation of austenite in the weld bead. The plates were milled to form a single V groove butt joint forming an angle of 60° between plates and root face of 2 mm. The plates were separated 3 mm at the root. The welding torch was displaced at 3.6 mm/s with a stick out of 10 mm. Direct current and reverse polarity were employed. The welding parameters for each pass are given in Table 2.

After welding, quasi-static tension test was performed according to ASTM E-8M Standard. The tensile test was conducted with an electromechanical tensile machine equipped with a 100 kN load cell. The strain was measured by an extensometer. For this, two specimens were obtained from the welded plates as shown in Fig. 1(a), the tension test specimens were machined to the dimensions shown in Fig. 1(b).

Optical microscopy and scanning electron microscopy (SEM) imaging were performed in order to characterize the microstructural features of the welded joints and fracture surfaces following standard metallographic techniques.

A computer controlled microhardness tester was used to measure the Vickers microhardness in transverse profiles of the welds. The microhardness tester is equipped with manual *xy* stage unit with digital micrometer head and 1 μm resolution. Microhardness was measured using a load of 300 g in an area 4 mm high and 24 mm long as illustrated in Fig. 2; the area is composed of 21 horizontal microhardness lines each one containing 121 indentations. In this way, the area contains 2541 indentations separated every 200 μm. The measured area covers the non-heat affected base metals, heat affected zones and weld metal.

2.2. Ultrasonic measurements

Ultrasonic pulse-echo measurements were performed on welded samples in order to assess the effect of microstructure on the attenuation of the ultrasonic wave. Fig. 3 shows the schematic representation of the attenuation measurements, for this, the measured total loss is calculated from two consecutive backwall echoes namely E_1 and E_2 respectively using:

$$L_{total} = 20\log_{10}\left(\frac{E_1}{E_2}\right) \tag{2}$$

Here E_i is the voltage amplitude of two consecutive backwall echoes. In order to measure the attenuation coefficient with high accuracy, it is necessary correcting the raw attenuation. The measured total loss is the sum of four components from experimental factors that affect the measurement and corrections need to be performed before the attenuation coefficient could be evaluated from grain scattering. Among these experimental factors, it is required to account for impedance mismatch loss, additional surface roughness induced loss and diffraction losses due to beam spreading. In order to minimize the effect of surface roughness, the specimens were carefully ground with 2000-grade emery paper.

Impedance mismatch loss (L_{imp}) is associated to the reflection coefficient (R) which at normal incidence can be calculated from the acoustic properties of the two media using $R = (Z_2 - Z_1)/(Z_2 + Z_1)$. Where Z_1 and Z_2 are the acoustic impedances of water and LDSS respectively and in the case of first and second backwall echoes it can be calculated by:

$$L_{imp} = 20\log_{10}\left(\frac{1}{R^2}\right) \tag{3}$$

Diffraction losses are associated with the spreading of the ultrasonic beam and is function of the transducer-sample propagation distance (z), the frequency (f), radii (a), and near field (N) of the transducer. As the ultrasonic wave transmit from water to steel the difference in sound velocities of the media produces a