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Effect of laser shock processing on fatigue crack growth of duplex stainless steel

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ABSTRACT

Duplex stainless steels have wide application in different fields like the ship, petrochemical and chemical industries that is due to their high strength and excellent toughness properties as well as their high corrosion resistance. In this work an investigation is performed to evaluate the effect of laser shock processing on some mechanical properties of 2205 duplex stainless steel. Laser shock processing (LSP) or laser shock peening is a new technique for strengthening metals. This process induces a compressive residual stress field which increases fatigue crack initiation life and reduces fatigue crack growth rate. A convergent lens is used to deliver 2.5 J, 8 ns laser pulses by a Q-switched Nd:YAG laser, operating at 10 Hz with infrared (1064 nm) radiation. The pulses are focused to a diameter of 1.5 mm. Effect of pulse density in the residual stress field is evaluated. Residual stress distribution as a function of depth is determined by the contour method. It is observed that the higher the pulse density the greater the compressive residual stress. Pulse densities of 900, 1600 and 2500 pul/cm^2 are used. Pre-cracked compact tension specimens were subjected to LSP process and then tested under cyclic loading with $R = 0.1$. Fatigue crack growth rate is determined and the effect of LSP process parameters is evaluated. In addition fracture toughness is determined in specimens with and without LSP treatment. It is observed that LSP reduces fatigue crack growth and increases fracture toughness if this steel.

1. Introduction

Laser shock processing (LSP) is a relatively new surface treatment technique and has been shown to be effective in improving the fatigue properties of a number of metals and alloys. Potential applications are directed to aerospace and automotive industries. The beneficial effects of LSP on static, cyclic, fretting fatigue and stress corrosion performance of aluminum alloys, steels and nickel-based alloys have been demonstrated [1–9]. Since laser beams can be easily directed to fatigue-critical areas without masking, LSP technology is expected to be widely applicable for improving the fatigue properties of metals and alloys, particularly those that show a positive response to shot peening.

Duplex stainless steels have wide applications in different fields like the ship, petrochemical and chemical in industries. The main applications of these steels are related to their high strength and excellent toughness properties as well as their high corrosion resistance. The outstanding mechanical properties of these steels are due to its duplex microstructure with approximately equal amounts of austenite γ and ferrite δ. However, when the steel is subjected to high temperature its susceptibility for sigma (σ) phase formation raises due to extended exposure to temperatures ranging from 600 °C to 900 °C [10]. Sigma phase is a very hard and brittle intermetallic compound that affects impact properties of duplex stainless steel.

There has been interest to evaluate the effect of shot peening on the fatigue behavior of 2205 duplex stainless steel [11]; and the effect of burnishing on stress corrosion cracking susceptibility of that steel [12]. However, few works are available that investigate the effect of laser peening on the fatigue behavior of duplex stainless steel. The changes in surface hardness, wear resistance, and corrosion resistance with and without laser peening has been reported in [13].

The objective of this work is to examine the effect of laser shock processing on the fatigue behavior and of 2205 duplex stainless steel specimens. Process parameters such as pulse density are varied. The effect of LSP on fatigue crack growth rate, fracture toughness, micro-hardness, and residual stresses are investigated. A microscopic evaluation of fracture surfaces and microstructure is presented as well.

In the laser shock processing of metals, the sample is either completely immersed in water or in air. A water jet may be used also to produce a water wall with constant thickness on the sample. The laser pulse is then focused onto the sample. The schematic of how the process works in water is shown in Fig. 1. When the laser beam is directed onto the surface to be treated, it passes through the trans-

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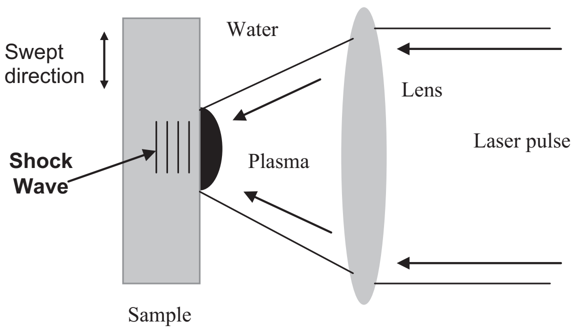

Fig. 1. Principle of laser shock processing.

parent overlay and strikes the sample. It immediately vaporizes a thin surface layer of the overlay. High pressure against the surface of the sample causes a shock wave to propagate into the material. The plastic deformation caused by the shock wave produces the compressive residual stresses at the surface of the sample. Laser pulse may come directly from the laser apparatus or may be delivered using an optical fiber [14].

2. Experimental procedure

2.1. Material

Plates of 2205 duplex stainless steel with thickness of 9.5 mm were machined to obtain the specimens. Its chemical composition (wt%) was: 0.023 C, 0.55 Si, 1.40 Mn, 0.02 P, 0.001 S, 22.19 Cr, 3.21 Mo, 5.78 Ni, balance Fe. Chemical composition was determined using a spark emission spectrometer. The mechanical properties were determined using dog-bone type specimens. Results are shown in Fig. 2. The offset tensile yield stress is 532 MPa, ultimate tensile strength is 750 MPa and elastic modulus is 190 GPa.

The specimens used for residual stress measurement were blocks of 50 mm × 50 mm × 5 mm with LSP on only one side. The specimen used for fatigue crack growth tests were compact tension specimens as illustrated in Fig. 3. All fatigue crack growth tests specimens were machined with the loading axis parallel to the rolling direction (L). Fig. 3(a) also illustrates pulse swept direction. The thickness of all specimens was reduced from 9.3 mm to 5 mm (or 6.3 mm for compact tension specimens) by machining the specimen faces to eliminate the manufacturing effect of the original plates.

2.2. Laser shock processing

The LSP experiments were performed using a Q switched Nd:YAG laser operating at 10 Hz with a wave length of 1064 nm

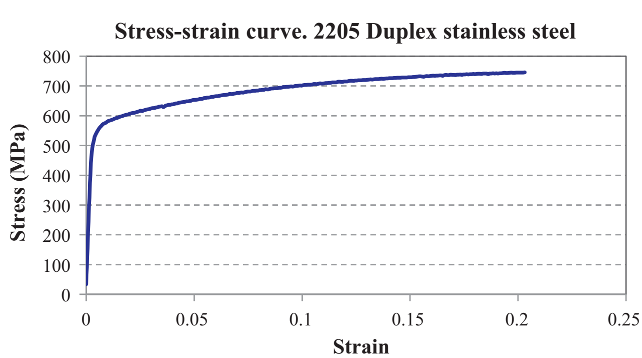

Fig. 2. Stress–strain curve of 2205 duplex stainless steel under tensile loading conditions.

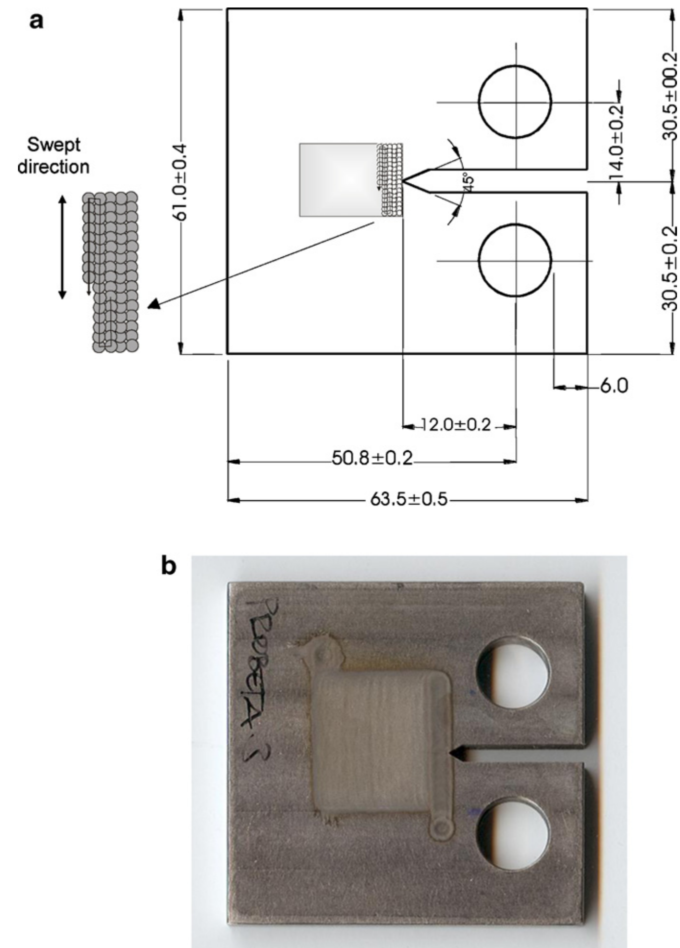

Fig. 3. Compact tension test specimens used in the fatigue crack growth tests. (a) Specimen illustration with dimensions in mm. Specimen thickness is 6.3 mm. (b) Real specimens.

and the FWHM of the pulses was 8 ns. A convergent lens is used to deliver 2.5 J. Spot diameter was 1.5 mm. Three pulse densities were used: 900, 1600 and 2500 pul/cm^2. A special device to produce a controlled water jet has been implemented to form a thin water layer on the sample to be treated. Specimen treated area was 20 mm × 20 mm on both sides of the compact tension specimen. A 2D motion system was used to control specimen position and generate the pulse swept as shown in Fig. 3. Controlling the velocity of the system, the desired pulse density was obtained. No protective coating was used during LSP [9]. Fig. 3(b) shows a photograph of a compact tension specimen with LSP applied after the pre-crack was induced.

2.3. Characterization of the effects induced by LSP

Micro-hardness measurement was made with 200 g load and 11 s hold time. Roughness measurement on the different specimens was performed using a roughness meter “Mitutoyo Surftest”. A summary of arithmetic mean roughness measurements, R_a, with different pulse densities is given in Table 1. The overall trend is that the higher the pulse density the higher the roughness of the specimen surface. Note that roughness does not increase considerably increasing the pulse density as observed in other materials, for instance 6061-T6 aluminum alloy [8]. In aluminum treated with 900 pul/cm^2, roughness increased by a factor of 2.5 with respect to the untreated surface [8]. To observe microstructural changes, samples were prepared by conventional metallographic polishing