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Influence of specimen thickness on the fatigue behavior of notched steel plates subjected to laser shock peening

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ABSTRACT

The influence of specimen thickness on the fatigue crack initiation of 2205 duplex stainless steel notched specimens subjected to laser shock peening (LSP) was investigated. The purpose was to examine the effectiveness of LSP on flat components with different thicknesses. For the LSP treatment a Nd:YAG pulsed laser operating at 10 Hz with 1064 nm of wavelength was used; pulse density was 2500 pulses/cm^2. The LSP setup was the waterjet arrangement without sample coating. Residual stress distribution as a function of depth was determined by the hole drilling method. Notched specimens 2, 3 and 4 mm thick were LSP treated on both faces and then fatigue loading was applied with $R = 0.1$. Experimental fatigue lives were compared with life predictions from finite element simulation. A good comparison of the predicted and experimental fatigue lives was observed. LSP finite element simulation helps in explaining the influence of thickness on fatigue lives in terms of equivalent plastic strain distribution variations associated with the change in thickness. It is demonstrated that specimen size effect is an important issue in applying LSP on real components. Reducing the specimen thickness, the fatigue life improvement induced by LSP is significantly increased. Fatigue life extension up to 300% is observed on thin specimens with LSP.

1. Introduction

Laser Shock Peening (LSP) is an effective surface treatment technique to improve fatigue properties of a number of metals and alloys. Potential applications are directed to aerospace and automotive industries. Peyre [1] provides deep revision of LSP trends related to the physics, the mechanics and the applications involved. Static, cyclic, fretting fatigue and stress corrosion performance are some properties that have been improved by LSP for different materials. The fatigue behavior improvements on samples were attributed to a combination of increased dislocation density and compressive residual stress induced by the laser shock waves according to results reported in [2]. Rubio-Gonzalez et al. [3] demonstrated that LSP reduces fatigue crack growth and increases fracture toughness in an aluminum alloy and in a duplex stainless steel [4] while wear rate decreases by using LSP as shown in [5]. For steels and nickel-based alloys, beneficial effects provided by LSP have been reported. Tsay et al. [6] evaluated the fatigue crack growth behavior of laser-processed 304 stainless steel in air and gaseous hydrogen; on both cases, a lower fatigue crack growth was observed. LSP has also been applied to superferritic stainless steel [7] where an interesting effect of intergranular corrosion was observed that deteriorates low cycle fatigue properties of this steel.

Numerical simulations of the LSP have been demonstrated to be useful in order to evaluate the effect of changing process parameters and analyze the response on different materials. Ocaña et al. [8] developed a FE model to estimate residual stresses and surface deformation induced by LSP using different process parameters. In [9] a 3D FEA was used to determine the response of aluminum alloy thin plates including the effect of wave reflections from the plate back side. A FE simulation of multiple LSP impacts was presented in [10] to estimate the magnitude and distribution of residual stresses on steel samples. A fully 3D finite element model was used in [11] to predict the residual stresses and optimize the LSP in order to increase the fatigue life of materials.

It is known that the residual stress field due to LSP is extremely sensitive to geometric features [12] and it is well understood that geometric details, such as notches or holes, are typical fatigue crack initiation points because they act as stress concentrators. In addition, specimen thickness affects significantly fracture

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toughness and therefore fatigue and fracture behavior of components; the critical stress intensity factor increases when specimen thickness is reduced due to the growth of the plastic zone size around the crack tip [13,14]; and consequently, it would be expected that the effect of LSP on fatigue performance of components is also influenced by the specimen thickness.

Only few references are available in the open literature where the effect of geometric characteristics on the behavior of LSP has been analyzed [15–17]. In addition, no previous work has been reported evaluating the effect of thickness on the fatigue life of notched components subjected to LSP.

The aim of this paper is to investigate the effect of sample thickness on the fatigue behavior of 2205 duplex stainless steel (DSS) components subjected to LSP. This investigation follows two paths, experimental study and numerical simulation of the LSP process. In the experimental part, notched specimens with different thicknesses and processed by LSP were subjected to fatigue loading and fatigue life was recorded. The size effect on fatigue life is demonstrated. On the simulation part, a finite element simulation of the LSP process on notched samples followed by a fatigue analysis employing multiaxial fatigue criteria to predict fatigue life was performed. Predicted lives are compared with experimental results in order to assess different fatigue criteria. The LSP simulation was performed using the commercial code ABAQUS and the fatigue analysis was made employing the code FE-Safe using as input the residual stresses obtained in the previous LSP simulation. Simulation results are employed to explain the influence of thickness on fatigue life by means the analysis of the plastic strain distribution through specimen thickness. In addition, failure mechanisms are analyzed using electronic microscopy and the effect of LSP on striation spacing on the fracture surface is also discussed.

2. Experimental procedure

2.1. Material

The specimens were obtained from a plate of 2205 DSS with 9.5 mm thickness. The chemical composition of 2205 DSS analyzed by spark emission spectrometer was: 0.021 wt% C, 0.42 wt% Si, 1.22 wt% Mn, 0.028 wt% P, 22.13 wt% Cr, 3.08 wt% Mo, 5.56 wt% Ni, 0.188 wt% N, 0.19 wt% Cu. The mechanical properties of the samples were determined by tensile tests using dog-bone type specimens. The offset tensile yield stress was 520 MPa, ultimate tensile strength was 710 MPa and elastic modulus was 190 GPa.

The specimens for fatigue tests were cut with a waterjet machine at high pressure to minimize the thermal damage and roughness along the cut surface, then the thickness was reduced by a CNC and the machining marks were erased by surface grinding, leaving a finish surface of 0.1 μm in the sample longitudinal axis direction (rolling direction and loading axis). The dimensions of the specimens are shown in Fig. 1(a).

Fig. 1(b) also illustrates pulse swept direction which is perpendicular to the specimen longitudinal axis. In order to investigate the size effect; three specimen thicknesses values were used on fatigue tests: 2, 3 and 4 mm. The specimens used for residual stress measurement were blocks of $50 \times 50 \times 4$ mm with LSP on both sides.

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, the FWHM of the pulses was 6 ns. A convergent lens was used to deliver 0.85 J/pulse. Spot diameter was 1.3 mm, this corresponds to a power density of 10.6Nd:GW/cm^2. Pulse density was 2500 pul/cm^2. A special device to produce a controlled water jet was implemented to form a thin water layer on the sample to be treated. Fig. 2 shows the experimental set-up used in this study. The treatment was performed without protective coating [18]. Specimen treated area was 25×25 mm on both sides of the notched specimen. A 2D motion system was used to control specimen position and generate the pulse swept as illustrated in Fig. 1(c). Controlling the velocity of the system, the desired pulse density was obtained. No protective coating was used during LSP. Fig. 1(b) shows a photograph of a notched specimen with LSP.

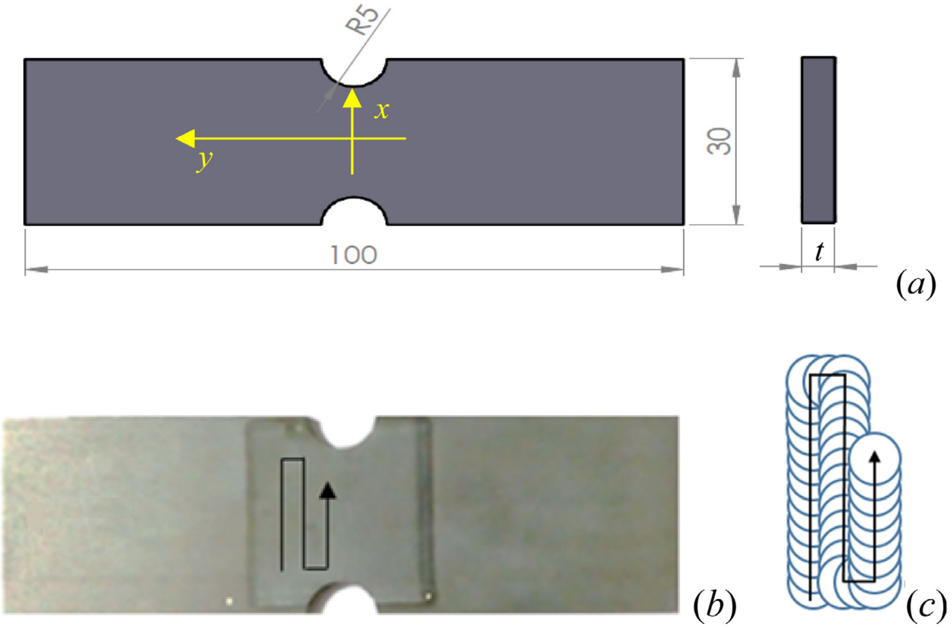

Fig. 1. (a) Dimension of samples for fatigue tests (mm), (b) photograph of the specimen used in fatigue tests showing the LSP treatment, (c) schematic illustration of the LSP swept direction.