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Effect of advancing direction on fatigue life of 316L stainless steel specimens treated by double-sided laser shock peening

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ABSTRACT

Laser shock peening (LSP) is considered as a well-established technology for inducing compressive residual stresses under the surface of metallic components. As a result, fatigue life is increased and the material becomes more resistant to corrosion and wear. This paper studies the effect of a significant parameter of LSP, the advancing direction of the laser scanning pattern, on the induced residual stress fields and the fatigue life of stainless steel 316L samples using experiments and 3D finite element analysis. The chosen material is of interest for nuclear and biomedical applications. Two different laser shock processing strategies (two different pulse sequences varying the advancing direction) were performed on the specimens. Their fatigue lives were compared revealing the decisive role played by the advancing direction of the treatment and the generated residual stresses. Fatigue life in laser peened specimens was increased from +166% to +471% by optimizing the pulse sequence. This improvement is explained by stress–strain analysis.

1. Introduction

Laser shock peening (LSP) is considered as a well-established technology which imparts a layer of beneficial residual compressive stress under the surface of metallic components. As a result, treated materials becomes more resistant to fatigue [1], corrosion [2] and wear [3]. LSP is based on the application of a high intensity pulsed laser beam (intensity >1 GW/cm^2) with a duration of nanoseconds on a metallic target producing a sudden vaporization of its surface into a high-temperature and high-density plasma. The generated plasma immediately expands inducing a shock wave which propagates into the material, generating plastic strains and compressive residual stresses that improve superficial material properties. A transparent confining material, normally water, is used for increasing the pressure in the generated plasma. The phenomena forming the basis of the LSP was first reported in [4]. Throughout the following decade, the characteristics of the laser–materials interaction and the mechanical response to the induced shock waves were investigated. Jones researched the LSP conditions for generating plastic strain and residual stress [5]. Fairand and Clauer explained the effect of water and paint coatings on the magnitude of laser-generated shocks [6]. Later, the research of the process took two different paths. One path has been the development of the process and hardware for industrial use to enhance the fatigue properties of metal work-pieces. The other path has been the academic pursuit of a deeper understanding of the physics of LSP and broader investigation of its effects on material properties. In order to increase the fatigue life of the treated specimens, both magnitude and distribution of the LSP induced residual stresses are decisive as they have influence on crack initiation and propagation. Spot size, energy per pulse, pulse duration, laser wavelength and mechanical properties of the material are critical parameters which have been analyzed in isolation though years, demonstrating their critical effect on the generated residual stresses and the compressed depth in multiple alloys [7] (pure aluminum, 316L steel and 12% Cr steel) and [8] (Al2024-T351 and Ti6Al4V). Although significant experimental work has been conducted in order to assess LSP capability to provide enhanced mechanical properties, only limited attempts have been developed in the way of predictive assessment of the characteristic physical LSP processes with a specific consideration of full 3D geometry and pulse overlapping over extended areas, taken into account the important role played by the realistic work-piece geometry and its constraint during the process [9] (this reference shows the simulation of residual stress fields induced by LSP in a DD6 blade). In addition, previous studies have indicated that the pulse sequence during the process affects the induced residual stress distribution and it can be optimized in order to make even greater the fatigue life enhancement of the component. However, this latter

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phenomenon has been only proven in two different light alloys (Ti–6Al–2Sn–4Zr–2Mo [10] and Al2024-T351 [11]). In this paper, with the aid of the 3D non-linear FEM (Finite Element Method) model developed by the authors, the effect of the pulse sequence during the LSP processing of stainless steel, in particular AISI 316L (it was chosen due to its widespread use in nuclear and biomedical applications), on the induced residual stress distribution and the fatigue life has been investigated. The importance of 3D FEM simulation lies in the possibility of analyzing the real distribution of residual stresses in each point of the volume, even in the inaccessible zones for typical measurement techniques such as hole-drilling and X-ray diffraction. Results show how LSP treatment not only induces beneficial compressive residual stresses, LSP also generates undesirable tensile residual stresses in the mid-thickness. Simulations reveal that residual stress distribution depends strongly on the scanning direction adopted in the pulse sequence and the treated geometry. FEM simulations allow to optimize the irradiation strategy, controlling the magnitude and distribution of tensile stresses and increasing the life of treated 316L steel specimens in fatigue tests.

2. Materials and methods

2.1. Fatigue specimens: material and geometry

The material selected for this study was 6 mm-thick AISI 316L stainless steel (DIN 1.4404; SIS 2348; AFNOR Z 2 CND 17-12). It is a stainless steel which belongs to 316 grade, the second most common austenite steel, also called marine grade stainless, used primarily for its increased resistance to corrosion. For this latter reason and its high biocompatibility, stainless steel 316L is an alloy of interest for nuclear and biomedical applications. The chemical composition of the samples used in the present study is: Fe, Cr 16.46 wt.%, Ni 9.78 wt.%, Mo 2.34 wt.%, Mn 1.90 wt.% and Si 0.26 wt.% (see Fig. 1)

"Dog-bone" shaped specimens with an overall length of 150 mm and a width of 15 mm at the minimum width (see Fig. 2) were used for fatigue testing.

The initial mechanical properties of the bulk material were experimentally determined according to ASTM E8/E8M standard [12] and they are presented in Table 1.

2.2. Experimental setup

The experimental setup used for the LSP experiments is displayed in Fig. 3. The laser source is a Q-switched Nd:YAG pulsed laser. The laser operates at 10 Hz. The FWHM (Full Width at Half Maximum) of the generated pulses is 9 ns, wavelength is 1064 nm and the maximum energy is 2.4 J/pulse which can be reduced by an attenuator. Using a flat mirror and a convergent lens (f = 200 mm), the laser pulse is focused on the target. Both optical components are coated for 1064 nm, which guarantees high transmittance efficiency. The convergent lens is used to control the transmitted laser energy. The spot diameter is set to 1.5 mm, a value which was previously optimized for preceding works from the authors [11]. Water is used as confining medium. Control of water purity is important in order to avoid the formation of water bubbles or the concentration of impurities coming from the material ablation due to laser treatment. These elements can affect the LSP process by their interaction with the high-energy laser pulses. A water jet is a good solution to avoid these detrimental elements. The water jet has been implemented to form a thin water layer on the sample to be treated. The test piece is fixed on a holder and is driven along x and y directions by means of an anthropomorphic robot. Predefined pulse overlapping strategies are used for the irradiation of extended areas of material. All the tests in this paper have been done with an overlapping distance of 0.33 mm, which is equivalent to fire 900 pulses/cm^2. Two different pulse sequences were used: (i) Strategy 1, treating the patch with the advancing direction parallel to the fatigue load (x direction); (ii) Strategy 2, treating the patch with the advancing direction perpendicular to the fatigue load (y direction). Applied LSP treatments were performed without coating (also known as LSPwC). Both the upper and the bottom surface were treated (also known as double-sided LSP) in order to provide a better residual stress profile.

Tension–tension fatigue tests were performed in load-control mode on a MTS 810 servo-hydraulic machine with a load capacity of 100 kN, at room temperature in air. The test frequency was 10 Hz, and the load ratio R = 0.1. A ramp of 1 kN/s was used until reaching the mean stress value. Fatigue tests were performed in unpeened specimens and peened specimens (strategies 1 and 2).

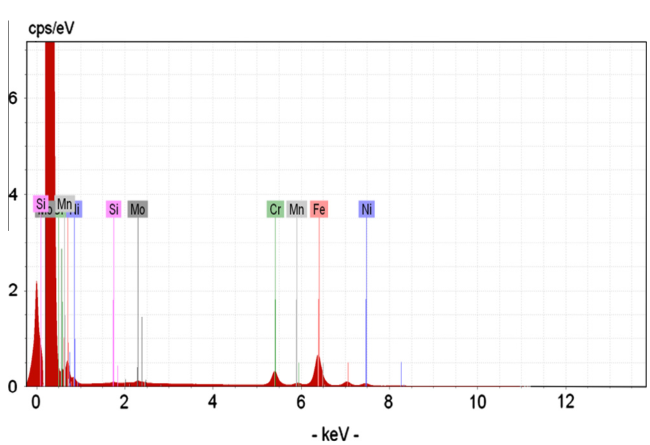

Fig. 1. Chemical composition of the stainless steel 316L samples.

3. Calculation

3.1. Description of the numerical model

For the study LSP 3D problems, we have developed a 3D non-linear model FEM based in the Abaqus/Explicit software [13]. It solves the shock wave propagation problem into the solid material, with specific consideration of its elastic–plastic behavior. From the point of view of time differencing, the usual strategy of explicit differencing for the initial fast shock propagation phase followed by standard implicit differencing for the analysis of the final residual stresses equilibrium is not used, instead only explicit differencing has been used with long-time evolutions in order to reach stress equilibration. From the geometrical point of view, a full 3D configuration for the real geometry and for the sequential overlapping strategy of pulses has been considered. The FEM elements used are eight-node bricks (namely C3D8R) with reduced integration and hourglass control in the treated area and a six-node trilinear prisms (namely C3D6) in the rest of the geometry, where there is no applied load, making easier to mesh complex geometries (see Fig. 4). The element size, in the treated area, is $100 \times 100 \times 25$ μm, being the maximum element size which allows to maintain calculation convergence and whose value has been calculated by a conducted convergence analysis with the model itself. A total of 645,736 elements are used in the whole mesh.

All simulations were run using parallel execution (domain-level method which splits the model into a number of topological domains) with two Intel® Xeon® CPUs E5530 clocked at 2.40 GHz and 48 GB of RAM memory. As a result, the developed FEM model