Optics and Laser Technology 93 (2017) 208–215

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Fatigue behavior of superferritic stainless steel laser shock treated without protective coating

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ARTICLE INFO

Article history:
Received 30 November 2016
Received in revised form 1 February 2017
Accepted 5 March 2017

Keywords:
Superferritic stainless steel
Laser shock peening
Fatigue
Microstructure

ABSTRACT

The laser shock peening (LSP) is a new technique that improves the fatigue life of metallic components by inducing deep compressive residual stresses through the surface. However, the beneficial effects of LSP depend on the persistence and stability of such residual stress fields under cyclic loading and temperature. Moreover, if no absorbent coating is used in LSP operation, thermal effects can occur on the metallic substrate. The purpose of this work is to study the influence of LSP, without protective coating and with different pulse densities, on the low cyclic fatigue behavior of a superferritic stainless steel UNS S 44600. These results are correlated with observations performed by means of transmission electron microscopy (TEM) and scanning electron microscopy (SEM) with electron diffraction spectroscopy (EDS). The hole-drilling method is used to measure residual stresses. The micro-hardness and roughness profiles are also presented. This paper shows that LSP without coating produces beneficial compression residual stresses. However, in the first 10 μm beneath the surface, thermal effects occur that induce intergranular corrosion. This intergranular corrosion deteriorates the fatigue properties of a superferritic stainless steel UNS S 44600.

1. Introduction

In order to improve the material properties, surface engineering is recommended, since without changing the bulk properties of a material their surface properties can be enhanced, allowing the use of a cheaper material. In this sense, two kinds of surface treatments can be done: heat treatments (nitriding, cementation) [1–4] and mechanical treatments (deep rolling, shot peening, or the current laser shock peening) [5–9]. All the mechanical surface treatments produce roughness, increase dislocation density and induce compressive residual stresses. The compressive residual stresses that are produced on the surface through different mechanical methods have shown to delay the fatigue crack nucleation as well as its propagation in different metals [7]. Since 1960 the possibility of generating shock waves by using pulsed lasers began to be studied. These shock waves cause permanent plastic deformation in metals generating compressive residual stress. This new technique is known as laser shock processing or laser shock peening (LSP) and it has wide applications in the manufacturing industry of engines, boats, cars and planes [7–9]. To generate shock waves of high amplitude, so as to plastically deform metals and generate compressive residual stress fields, laser pulses of high intensity and short duration are required. Nowadays, the lasers that meet these requirements are solid state lasers, which incorporate a Q-switch device that allows pulses in the nanosecond range. Thus, it is possible to achieve peak powers of GW. This high energy laser beam vaporizes the material and the vapour rapidly reaches temperatures above several tens of thousands degrees, whereupon the electrons are ionized from the atoms and the vapour is transformed into plasma. During this process, the plasma expansion generates a pressure wave that spreads into the material. Due to the high temperature the plasma reaches on the surface, heat propagation also occurs leading, depending on the alloy, to the ablation and fusion of 1–100 μm. Some authors recommend the use [8–11] of an absorbent coating (usually black paint) on the metal surface to protect it from thermal effects that can occur during the process. However, the parts to be peened are not always accessible to apply an ablative overlay or its use in an industrial configuration is expensive. Hence, a lot of research has driven to study laser peening without protective coating (LSPwC) [12,13]. In literature, the effects of LSPwC are referred to just a few stainless steel grades [14–17]. Additionally, in order to avoid that the plasma rapidly expands from the surface and thereby so as to increase the shock

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http://dx.doi.org/10.1016/j.optlastec.2017.03.003
0030-3992/

wave intensity, a transparent overlay to radiation (confining medium) is also placed in the material surface. Water is the most commonly used coating for its versatility and availability [8,9].

The LSP processes have emerged as an effective alternative to the traditional processes to improve the fatigue properties in metallic materials. However, the magnitude of these beneficial effects depends on the microstructural changes produced by LSP in each alloy [17–20] and the degree of relaxation of the compressive stresses during cycling [21–23]. As regards stainless steels, scarce attempts have been developed to assess the LSP capability to enhance the low cycle fatigue properties [23]. Most researches deal with the beneficial effects of LSP on the high cycle fatigue regime (HCF), mainly in austenitic stainless steels [16,23–25].

Recently, significant research has been devoted to the development of cost-efficient stainless steels containing low Ni and Mo content. Thus, superferritic stainless steels, with lower cost alloying elements, has found increasing applications in many industries [26].

Therefore, the purpose of this research is to analyze the influence of LSPwC on the low cycle fatigue (LCF) behavior of a superferritic stainless steel. Special interest is placed on relating the cyclic behavior with the microstructure in order to discern the limit of cyclic deformation where LSP is effective.

2. Material and experimental procedure

The studied material is a superferritic stainless steel UNS S 44600 with the chemical composition (wt.%): C: 0.058; Cr: 23.58; Ni: 0.33; Mo: 0.13; Mn: 0.65; Si: 0.4; Cu: 0.15; V: 0.13; P: 0.02; N: 0.098, Nb: 0.09. This steel was received in the form of hot rolled square bar of 50.8 mm × 101.6 mm × 500 mm. From the bar, plates of 80 mm × 40 mm × 5 mm were cut in the rolling direction. The plate surfaces were polished with different grade SiC papers (from 60 to 320 grit) to eliminate the manufacturing effect of the original plates. These samples which received no further treatment are referred to as received (AR).

The LSP treatment were performed with a Q switched Nd:YAG laser operating at 10 Hz with a wave length of 1064 nm, energy of 1 J/pulse and the FWHM of the pulses was 6 ns. The spot diameter was 1.5 mm and the power density is held at a constant value of 9.4 GW/cm^2. A special device has been implemented to produce a controlled water jet that forms a thin water layer on the sample to be treated. Specimen treated area was 20 mm × 20 mm on both sides of the plates. No protective coating was used during LSP. A 2D motion system was used to control specimen position and generate the pulse swept. Controlling the velocity of the system, the desired pulse density was obtained.

Table 1 presents the variations in the LSP conditions employed in this work.

Through ASTM standard E837-1 [27] the residual stress distribution was measured by the hole-drilling method. Strain gage rosettes CEA-06-062UL-120 were used. Microhardness measurements were carried out in Shimadzu HMV-2 Vickers microhardness tester. The Vickers indentations were performed with loads of 245.2 mN during 10 s. The surface roughness of the steel with and without LSP was measured using a profilometer (Mahr Pocket Surf, Germany) with roughness filter cut off wavelength of 0.25 mm over the range of 1.75 mm. For each condition, the average roughness (R_a) was measured.

Table 1
LSPwC conditions.

Specimen	Overlap percentages (%)	Peening duration /cm^2 (minutes/cm^2)
1600 pulses/cm^2	79	2.66
2500 pulses/cm^2	83	4.16
5000 pulses/cm^2	88	8.33

From the plates with and without LSP, flat specimens for low cycle fatigue (LCF) were machined by electro-erosion. Fig. 1 shows the geometry of the fatigue specimens with the coverage area as well as the swept direction of LSP. LCF tests were conducted at room temperature under fully reversed plastic strain control, with plastic strain ranges of $\Delta\varepsilon_p = 0.1\%$ and $\Delta\varepsilon_p = 0.3\%$. In this study, the nomenclature of 'Peak Tensile Stress' is referred to the maximum stress (σ_{max}) in each cycle.

Specimens for optical metallographic observation were polished with diamond paste and electrolytically etched in 50% nitric acid in water solution at room temperature. Scanning electron microscopy (SEM) equipped with an energy dispersive spectroscopy (EDS) device was used. In order to observe the nearer dislocations structures to the surface in a transmission electron microscope (TEM), for the preparation of thin foils the following steps were followed: (i) At a depth of 1 mm from the surface, slices were cut; (ii) From the opposite side of the surface an initial thinning of the material until slices of 100 μm of thickness were obtained, was performed; (iii) 1 mm diameter discs were cut with a precision punch; (iv) The central regions of both sides of the discs were finally thinned with a double jet in a solution of 10% perchloric acid in ethanol. Therefore, the dislocations structures observed in this work represent the dislocations structures from the surface till approximately 100 μm.

3. Results and discussion

3.1. Near surface microstructure

Fig. 2 shows the optical micrographs obtained from the surface of UNS S44600 without and with LSP. Equiaxed grains are the characteristic microstructural feature in both AR and laser treated samples. Moreover, from this figure it is worthwhile to note that no evidence of discernible changes in grain size occurs by LSP. So as to corroborate this statement, the intercept method was used to determine the grain size. It was confirmed that no grain refinement was produced by LSP. In this sense, the AR and LSP treated specimens have an average grain size of 45 μm. Consistent with previous works [13,16], it seems that a single LSP impact causes no effect in grain size. On the other hand, grain refinement after multiple LSP impacts is reported in literature [9,28].

Whereas an electrochemical etching is needed to reveal the grain boundary in the steel without LSP, Fig. 2(a), the LSP without protective coating severely delineates the grains boundaries without any chemical attack, Fig. 2(b). This phenomenon is independently of the pulse density applied. Although LSP is actually considered as a mechanical surface treatment, thermal effects caused by the laser irradiation are unavoidable if the process is carried out without an ablative layers (LSPwC) [8,11,16]. Fig. 3 shows that through the observation of the cross section of the treated steel the depth of intergranular attack caused by the LSPwC reaches about 10 μm. In order to get further information to rationalize these results, constituent element distribution along the grain boundary was obtained by EDS (Fig. 4). In the material without LSP, Fig. 4(a), the chemical composition remains unchanged when passing through grain boundaries. However, independently of the pulse density, the samples with LSP evidence a decrease in the Cr content near the grain boundaries and an increase of the content of C and N in the grain boundary, Fig. 4 (b). This increase in the C and N content would be associated with the presence of carbides and nitrides. In ferritic stainless steels, intergranular corrosion is usually the result of the precipitation