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Evaluation of the residual stress and microstructure character in SAF 2507 duplex stainless steel after multiple shot peening process

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ABSTRACT

In this study, multiple shot peening treatment was implemented to the SAF 2507 duplex stainless steel. The residual stress, microstructure and strain-induced transformation in the shot-peened specimens were evaluated by X-ray diffraction line profile analysis. Results pointed out that multiple shot peening was helpful to develop deep layer of high compressive residual stress with moderate work hardening. After triple shot peening treatment, a maximum compressive residual stress of −1070.5 MPa (at the surface for austenite) and −910.5 MPa (at 10 μm depth for ferrite) were obtained. The multiple shot peening is more effective in producing the microstructure refinement than single shot peening. The depth of the refinement layer with domain size smaller than 100 nm reached to 150 μm in the austenite and 100 μm in the ferrite phase of the dually shot-peened specimen, the maximum magnitudes of which after single shot peening were 100 μm and 75 μm, correspondingly. The quantitative measurement of stained-induced martensite in the shot-peened samples by X-ray phase analysis revealed that larger amount of α′-martensite formed after multiple shot peening compared to that of single shot peening, nearly 31.6% α′-martensite was formed at the impacted surface of triply peened specimen. The results also demonstrated that multiple shot peening could significantly decrease the surface roughness and help to improve the surface quality.

1. Introduction

Duplex stainless steel (DSS), consisting of approximately equal proportions of ferrite (δ) and austenite (γ) phases, are being increasingly employed in numerous branches of the industry due to its desirable mechanical strength and corrosion resistance [1]. In applications, materials are sensitive to residual stress caused in thermal treatment or manufacturing process, especially when they are subjected to fatigue loading. Furthermore, duo to the different coefficients of thermal expansion between the two phases, thermal microstresses are often introduced during the cooling process of isothermal ageing or welding [2]. Since the tensile stresses can accelerate the initiation and growth of cracks, surface mechanical techniques are often employed to enhance fatigue durability of components. It has been widely confirmed that the SP induced compressive residual stress (CRS) can prevent cracks from propagating and delay fatigue failure [3–8]. Whereas traditional SP uses one shot media at a specified intensity range, the bombardment of the surface with the shot often leads to enhancement of microcracks and surface roughness, which may outweigh the beneficial effect of the compressive stresses [9]. In previous work, many studies have been conducted on single (one step) SP process. However, scarce information exists related to the multiple SP operations. In this process, the workpiece is firstly peened using steel beads with big diameter at a high intensity, and then followed by dual or triple peening operations which use smaller steel or ceramic media that is peened at a lower intensity than the preceding operation. By using multiple SP, it is possible to maximize beneficial residual stress, and improve surface properties [10,11].

In this study, multiple SP treatments with different intensities and peening media were implemented to DSS SAF 2507 in order to optimize the residual stress distribution and improve the surface quality. The variations of residual stress, microstructure as well as strain-induced transformation in the austenite phase in shot-peened specimen were characterized by X-ray diffraction (XRD) for various reasons. First, XRD is a well-known NDT technique with good repeatability. Second, XRD can provide simultaneous quantification of the stress states and of diversified microstructural characters in the processed specimen, including domain sizes, microstrain, lattice parameters, macroscopic

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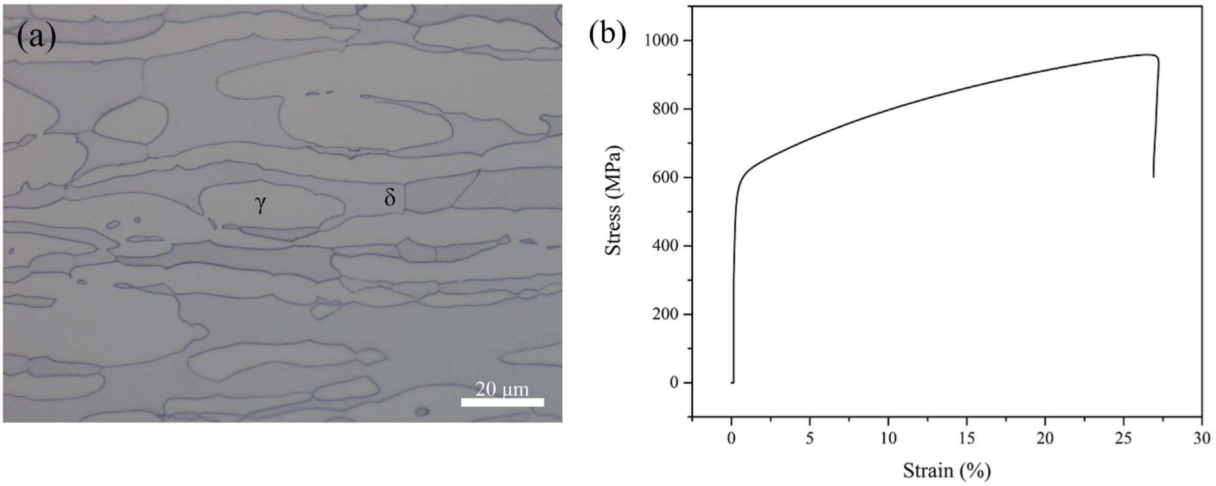

Fig. 1. (a) Optical microstructure and (b) true stress-strain curve of the SAF 2507 specimen annealed at 1030 °C for 1 h and then water quenched.

residual stresses and dislocation densities. Third, the collection of XRD patterns at different depths from the impacted surface is relatively simple, facilitating the quantification of depth-profile changes in the stress state and the wide range of microstructural features mentioned above [12].

2. Experimental method

2.1. Material

The material used in this investigation is the DSS SAF 2507, supplied by Shanghai Baosteel Group Corporation. The steel was obtained by continuous casting, and then was fabricated into hot-rolled plates with a thickness of 30 mm. Finally, a solution annealing heat treatment at 1030 °C was carried out followed by quenching in water in order to avoid secondary phase precipitations. The chemical composition in weight percent is: C (0.015), N (0.243), Mn (0.69), P (0.029), Ni (6.74), Cr (25.15), Mo (3.43), Si (0.55), Cu (0.13), S (0.002) and balance Fe. Fig. 1(a) shows the microstructure of as-received material, which displays a typical DSS structure that the elongated austenite (γ) islands are embedded in the gray etched ferrite (δ) matrix (the darker phase). Fig. 1(b) exhibits the true stress-strain curve of the studied SAF 2507 steel, which is measured by the tensile test. The tensile properties are summarized in Table 1.

2.2. Shot peening process

Multiple SP treatments were carried out on SAF 2507 plates with a dimension of 20 × 20 × 8 mm by using the air blast machine. Steel plates were machined and ground with 800-grit SiC before SP. SP intensities were measured by the arc height of Almen specimen (A type). The first SP process with a peening intensity of 0.51 mmA was conducted using steel shot (S230) of 0.6 mm in diameter. Subsequently, a secondary peening operation was implemented using a smaller steel shot (S110) of 0.3 mm in diameter, the peening intensity was 0.19 mmA. After that, ceramic beads (B60) with a diameter of 0.125 mm were employed to conduct the third SP, and the intensity was 0.11 mmA. The diameter of the peening nozzle was 15 mm and the distance between the nozzle and specimen was 100 mm. After SP, an optical inspection was implemented to ensure the peening coverage. The coverage for single peening was 100%. The detailed parameters of different SP treatments are displayed in Table 2.

Table 1
Tensile properties of the studied SAF 2507 steel.

Material	$\sigma_{0.2}$/MPa	σ_b/MPa	A%	E/GPa
SAF 2507	572	950	26.6	175

2.3. Residual stresses and microstructure measurements

Successive steps of material removal from the impacted surface to ~350 μm depth through electrochemical polishing were conducted in order to perform residual stress measurements in depth. The XRD patterns at each depth were measured using Rigaku UItima IV diffractometer (Cu K_α radiation) with a D/tex1D high-speed detector. The voltage, current, scan speed and step were 40 kV, 30 mA, 1°/min and 0.01°, respectively. The residual stress was measured by X-ray stress analyzer (LXRD, Proto, Canada) using $\sin^2\psi$ method. The Mn K_a radiation with a wavelength $\lambda = 2.10314$ Å and Cr K_α radiation with a wavelength $\lambda = 2.2897$ Å were used to determine the austenite (311) and ferrite (211) diffraction peak, respectively. During the stress testing, the sample was fixed on the sample platform, and only the X-ray and detector were oscillated with ψ angles. The spot size of the X-ray beam is about 1 × 3 mm, the irradiated area is adequate for the data collection. The penetration depth of the incident X-ray beam is about 6 μm, thus the magnitude of residual stress measured in this study, in fact, represents the average value between the tested surface and following 6 μm depth. The surface morphology and roughness of the sample were evaluated using scanning electron microscope (SEM, JEOL JSM-700F) and 3D optical surface profiler (ZeGage Plus). The depth profiles of the micro-hardness of the peened specimen were measured using a digital micro-hardness tester with experimental force of 1.96 N and loading time of 15 s.

In order to investigate microstructure changes of the specimen caused by SP, the domain size and microstrain were determined from the XRD profiles by using Voigt method, calculating from the broadening of the (111) peaks for austenite and of (110) peaks for ferrite. The observed distribution of X-ray intensity $h(x)$ can be expressed as [13]:

$$h(x) = \int_{-\infty}^{+\infty} f(x)g(x-y)dy \tag{1}$$

where $f(x)$ is the instrumental profile, $g(x)$ is the structurally broadened profile. The detected XRD data cannot be used directly in the Voigt method until the instrumental profile has been separated out. Fig. 2 shows the surface XRD pattern of triply shot-peened specimen, the peak broadening caused the overlapping of γ(111) and δ(110) peak. A Pearson type VII function was utilized to resolve the overlapped peaks, the results are shown in the inset of Fig. 2. In the present work, the Stokes deconvolution method [14] was applied to the observed X-ray profile to obtain the real diffraction profile and the results are shown in