Surface & Coatings Technology 340 (2018) 25–35

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Effects of low intensity shot peening treatments applied with different types of shots on the fatigue performance of a high-strength steel

E. Segurado*, F.J. Belzunce, I. Fernández Pariente

Escuela Politécnica de Ingeniería de Gijón, University of Oviedo, Campus universitario, 33203 Gijón, Spain

A R T I C L E I N F O

Keywords:
Fatigue
Shot peening
Surface treatments
Residual stress
Structural steels

A B S T R A C T

The aim of this research is to study the fatigue life enhancement produced in a quenched and tempered AISI4340 steel with a tensile strength of 2000 MPa after being submitted to shot peening surface treatments. These treatments generate compressive residual stress fields in a superficial layer of the material at the same time as inducing some kind of damage on the surface. Different kind of projectiles were chosen to perform the treatment (ceramic and steel shots), studying the way these affected the fatigue life of the specimens.

The surface topography of the samples was analysed using a roughness tester and by means of scanning electron microscopy (SEM). The compressive residual stress profile induced by these treatments was measured using X-ray diffraction (XRD) plus electro-polishing. The fatigue behaviour of the treated samples was subsequently studied by means of 4-point rotating bending tests and their fracture surfaces were analysed using SEM.

The best fatigue performance was obtained after shot peening with ceramic beads under an 8A Almen intensity. The main difference in relation to the treatment performed under the same intensity but using steel cut wire shots was the much lower surface damage induced by the impacts with the ceramic shots compared with the cut wire projectiles, which in turn is justified by the greater geometric perfection and hardness of the former. Furthermore, fatigue specimens shot peened with ceramic beads under an 8A intensity always gave rise to internal fatigue crack initiation, which took place outside the zone subjected to residual compressive stresses. Moreover, fatigue initiation was always linked to the presence of hard and rigid alumina inclusions, which acted as microstructural stress concentrators.

1. Introduction

Shot peening is a widely used surface treatment in the aerospace and automotive industries to improve the fatigue life of metal components. When these components are submitted to bending or torsion loads and also when there are stress concentrators, the largest stress occurs on the surface and it is precisely here where fatigue cracks initiate under cyclic loads and then grow until failure of the component.

Shot peening is a mechanical surface treatment specially designed to improve the fatigue behaviour of engineering components. Shot peening consists in blasting tiny spherical beads or balls at high speed onto the metal surface of the component to induce a surface plastic deformation that produces a compressive residual stress profile with a sufficient depth to delay or even avoid the growth of surface cracks under fatigue loads. Shot peening also modifies the surface finish. Furthermore, if the intensity of the treatment is excessive, it can produce superficial defects that may facilitate the easy initiation of surface cracks and thereby impair the fatigue life of the product [1–3].

There are many parameters involved in shot peening which need to be controlled in order to produce the expected increase in fatigue performance. There are parameters depending on the shot, as shot shape, size, density and hardness, others depend on the shot peened component or target, as geometry, yield strength, hardness and work-hardening characteristics and, finally, there are other parameters depending on the process, as mass flow rate, air pressure, impact angle and velocity, stand-off distance and coverage.

Numerical models are very efficient tools for simulating shot impacts on specific targets for establishing quantitative relationships between shot and target parameters and residual stress profiles. Nevertheless, the complexity of numerical modelling is evident, as shot peening is a dynamic problem in which a huge number of tiny impacts are involved and a great computational cost is required. A stream of so many shots impacting on a target, along with shot-shot collisions and interactions between incoming shots and rebounding shots is difficult to be modelled by means of finite element methods. Another important aspect to perform a reliable simulation of the shot peening process is the selection of the constitutive model that better describes the behaviour of the target material, which must take into account strain rate

* Corresponding author.
E-mail address: seguradomaria@uniovi.es (E. Segurado).

https://doi.org/10.1016/j.surfcoat.2018.02.033
Received 12 September 2017; Received in revised form 6 February 2018; Accepted 9 February 2018
Available online 09 February 2018

effects and cyclic stresses. Many recent contributions were published in this topic [4–7].

The optimal peening intensity to obtain the best fatigue performance, which depends on the hardness or the mechanical strength of the treated steel, has been experimentally studied by numerous researchers [8–11]. Menéndez et al. [12,13] studied the effects of shot peening onto an AISI4340 steel obtained after quenching and tempering at the same temperatures used in this work, reporting an optimal Almen intensity ranges of 14A. These authors also showed that, under optimal shot peening treatments, fatigue cracks could initiate below the surface at a depth where the compressive residual stresses induced in the shot peening treatment disappeared. Hence, under these optimized treatments, the compressive layer should be able to fully protect the surface region and crack initiation would be displaced to deeper sites, related to the presence of microstructural heterogeneities or stress concentrators, such as hard and rigid non-metallic inclusions.

For the mechanical surface treatment of high strength steels, such as AISI 4340 quenched and tempered at low temperatures, single peening using fine ceramic shots under low Almen intensities are recognized and used industrially to obtain significant high fatigue life improvements under quite low operating peening costs. Peng et al. [14] studied the effects of using alumina ceramic beads with a diameter of 0.3 mm and a hardness of 700 HV under an Almen intensity of 6A compared to using cast steel balls with a diameter of 0.6 mm and a hardness of 610 HV under an Almen intensity of 20A. Higher compressive stresses and hardness in the first 25 μm were measured in the samples peened with ceramic beads, though a lower compressive residual stress depth. In this respect, zirconia is a very interesting ceramic medium, characterized by quite a high specific gravity (4.6 g/cm^3), high hardness (1000 HV) and excellent toughness. The possibility of obtaining residual stress profiles as deep as those obtained with steel shots using lower Almen intensities has also been reported, while shot consumption can be reduced for the same Almen intensity as zirconia beads are much stronger than other ceramic shots [15].

In this paper, the effectiveness of fine zirconia ceramic beads for shot peening high strength steels was verified and compared with the use of steel shots with the ultimate goal of increasing the fatigue performance of the steel. In this respect, it should be noted that there are scarcely any scientific references in the literature comparing the effect of using zirconia ceramic beads with steel shots on this particular application.

2. Experimental procedure

2.1. Materials

The study was performed on a 41NiCrMo7-3-2 steel (AISI 4340) supplied in bars with a nominal diameter of 16 mm. Table 1 shows the chemical composition of the steel.

The bars were austenitized at 850 °C for 45 min, quenched in water and tempered at 200 °C for 2.5 h. The heat treated steel had a final hardness of 552 HV. The aforementioned heat treatment was carried out on several steel bars measuring 300 mm in length. Subsequently, two different types of specimens were machined: (a) flat slices with a thickness of 10 mm, obtained cross-sectioning the bar, and (b) fatigue specimens.

Table 2 shows the values of the elastic modulus (E), yield strength (σ_y), ultimate tensile strength (σ_u), tensile elongation (e), reduction of area (RA) and the constants k and n of the Hollomon hardening law ($\sigma = K\varepsilon^n$), obtained in previous studies [12,13].

Table 1
Chemical composition of AISI 4340 steel, in weight %.

C	Mn	Si	Ni	Cr	Mo	Cu
0,41	0,71	0,26	1,92	0,87	0,23	0,21

Table 2
Tensile properties of AISI 4340 steel (Q + T200 °C).

E (GPa)	σ_y (MPa)	σ_u (MPa)	e (%)	RA (%)	n	k (MPa)
200	1596	2000	11	50	0.24	5029

Table 3
Shot characteristics and peening conditions.

	CW0.3	CW0.5	CW0.7	ZS0.3
Shot type	Steel	Steel	Steel	Zirconia
Granulometry (mm)	0.3	0.5	0.7	0.3
Hardness (HV)	670–730	670–730	670–730	1000
Density (g/cm^3)	7.8	7.8	7.8	4.6
Air pressure (bar)	2	3	3	2
Almen intensity	8A	14A	19A	8A
Coverage	100%	100%	100%	100 and 200%

2.2. Shot peening treatments

Shot peening treatments were performed using a direct compressed air machine (Guyson Euroblast 4 PF) with a 5 mm diameter nozzle, a distance between the nozzle and the workpiece of 230 mm and an impact angle of 90°, in accordance with the SAE J442 [16] and J443 [17] specifications.

These treatments were performed using two different types of shots: cut steel wire with rounded off edges (CW) with diameters of 0.3 mm, 0.5 and 0.7 and zirconia beads, Zirshot Y300 (ZS), with a diameter of 0.3 mm. Table 3 shows the most relevant shots characteristics and peening conditions. An Almen intensity of 8A was used in the comparison of both shots, though higher intensities were also applied with the steel shots. Coverages of 100% were applied and an additional coverage of 200% was also employed when using the ceramic shots.

Fig. 1 shows SEM images of all the shots, steel cut wire (different sizes) and zirconia beads, while Fig. 2 compares the 0.3 mm steel and ceramic projectiles at a higher magnification. The plastically deformed surface of the steel shots and the perfect spherical shape of the zirconia beads are worth noting.

2.3. Roughness measurements

The roughness measurements were performed using a Mahr Marsurf M300 roughness tester. Roughness was measured in all specimens after the different treatments. Five roughness profiles were plotted for each specimen and the mean value of the average roughness, R_a, and the maximum roughness, R_{max}, parameters were obtained. R_{max} is the maximum of the five R_{imax} within the assessment length of 4.8 mm, where R_{imax} is the maximum peak-to-valley height of the profile in each of the five aforementioned measurements.

2.4. Determination of the compressive residual stress profile

Residual stress was determined by means of the X-ray diffraction technique using the $\sin^2\psi$ method onto flat slices with a thickness of 10 mm obtained cross-sectioning the bar, while the FWHM parameter (diffraction peak width at half maximum height) was simultaneously measured as a parameter related with the induced hardening [18,19]. It was demonstrated in a previous work the good correspondence between the residual stress profile measured using flat and fatigue specimens [20]. In order to define the residual stress profiles, thin layers of material were progressively removed step-by-step by electro-polishing using a mixture of 94% acetic acid and 6% perchloric acid as electrolyte under a voltage of 40-50 V. The slight stress relaxation produced by