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Effect of coverage and double peening treatments on the fatigue life of a quenched and tempered structural steel

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ABSTRACT

The effects of shot peening treatments comprising different degrees of coverage and also the influence of double treatments applied to a quenched and tempered medium-carbon alloyed steel were analyzed. The latter consisted, in one case, of high intensity peening followed by a lower intensity peening treatment and, in the other, of the removal of the damaged surface layer. Surface roughness, subsurface hardening and the residual stress profiles were determined and compared. Furthermore, the fatigue life corresponding to the different shot peening treatments was assessed on a rotating beam machine under alternative stresses of 50% of the tensile strength of the steel. The full coverage peening treatment gave rise to the best fatigue behavior, as under-coverage produces a heterogeneous surface stress field, while overlong shot peening treatments probably lead to surface damage. On the other hand, double surface treatments are at least partially able to mitigate the surface damage produced by a first high intensity peening treatment. Nevertheless, none of the applied double treatments was able to exceed the fatigue life of the optimal single shot peening.

1. Introduction

Shot peening is a widely used mechanical surface treatment in the automotive and aerospace industries to improve the fatigue life of metallic components. It consists in bombarding the surface of the component with a stream of small high hardness spheres, called shots. The indentation of each impact produces local plastic deformation (increase in hardness) whose expansion is constrained by the adjacent deeper material, giving rise to a field of surface compressive stresses [1,2]. The effectiveness and repeatability of the shot peening process are usually ensured using two control parameters: peening intensity (Almen intensity) and peening coverage. The Almen intensity is related to the amount of kinetic energy transferred from the shot stream to a target component during the shot peening process and is governed by the velocity, size, weight and hardness of the shots as well as by the angle at which the stream of shots impinges on the surface of the workpiece. The method commonly used to quantify peening intensity was introduced by Almen and Black [3] and consists in peening standardized SAE 1070 cold rolled spring steel test strips presenting a standard hardness of 44–50 HRC (Almen strip) clamped to a mounting fixture by means of four bolts. These strips have dimensions of 76 × 19 mm for three available thicknesses (type A: 1.29 mm, type N: 0.79 mm and type C: 2.39 mm). In order to determine the intensity of a given peening process, a number of Almen strips are peened using the same peening parameters for different exposure times according to SAE specifications. Representing the height attained at the central point of the Almen strips against their exposure times, the intensity of the treatment is defined as the first point of the curve that, if the exposure time is doubled, the arc height increases by 10%. Full procedures and the specifications for intensity measuring equipment can be found in SAE standards [4–6].

Coverage is defined as the ratio of the area covered by the shot impacts to the complete surface of the treated sample, expressed as a percentage. The degree of coverage does not increase linearly as a function of the peening time, the approximation to full coverage being exponential, so that full coverage is conventionally assessed when the target has an impacted area of 98% [1,7]. Under this assumption, a degree of coverage of 200% corresponds to a peening treatment twice as long as the full coverage treatment. Incomplete coverage of the surface produces a heterogeneous surface compressive stress field resulting in earlier nucleation of fatigue cracks, while an overlong peening time gives rise to excessive surface plastic deformation, which can also worsen the fatigue performance of the material [8].

On the other hand, different authors have demonstrated the possibility of increasing the fatigue life of a component using double peening treatments [9–11]. Double peening treatments consist of first applying a high intensity peening treatment, which prominent effect is to produce a deep region submitted to high magnitude compressive stresses, followed by a low intensity peening treatment, the principal effect of which is to reduce the roughness of the first treatment and mitigate the damage produced in it.

The aim of this paper is to present the systematic study of the effects of the degree of coverage on the roughness, surface hardening, residual stress profiles and fatigue life of a quenched and tempered steel with a

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tensile strength of 1200 MPa submitted to an optimal peening intensity of 10 A. Moreover, these same effects were studied in double treatments consisting of high intensity 21 A peening, followed, in one case, by a second low intensity peening treatment and, in the other, by the removal of the damaged surface layer produced by the aggressive first peening treatment.

2. Materials and methods

2.1. Steel and mechanical properties

The chemical composition of the F1272 steel (equivalent to 4340) is given in Table 1. This grade, after a quench and tempering treatment, possesses a good combination of strength, ductility and toughness and is used in particularly severe service conditions under cyclic loading: bearings, aircraft and truck parts, gears, fittings, machine tool arbors, pressure vessels, etc. [12].

The steel was supplied in bars with a nominal diameter of 16 mm, in a quenched and tempered condition (austenitization at 850 °C for 45 min, quenched in water and tempered at 590 °C for 150 min). The microstructure of the bar was uniform and any significant difference was detected along the radius of the bar.

The tensile properties of the steel, obtained using specimens with a diameter of 10 mm and a calibrated length of 50 mm (elastic modulus, E, yield strength, σ_{ys}, tensile strength, σ_R, and elongation, A), are given in Table 2, along with its Vickers hardness, HV.

2.2. Shot peening treatments

Shot peening was performed by means of a direct compressed air machine (GUYSON Euroblast 4 PF) using conditioned cut wire shots with rounded off edges (CW, 670–730 HV, with an average diameter of 0.4 mm) and 2 bar in order to obtain an Almen intensity of 10 A, which was previously demonstrated to be the optimal peening intensity to improve the fatigue performance of this steel [13]. Fig. 1 presents the fatigue results respectively obtained on the fatigue specimens submitted to the different shot peening treatments (from 8 A to 21 A) under an alternative maximum stress corresponding to 50% of the tensile strength of the steel, along with the results obtained using conventional machined (non-treated) specimens. As regards Fig. 1, note that all the shot peening treatments were able to increase the fatigue life compared to the non-treated specimens, while the greatest enhancement in fatigue life was obtained with the 10 A treatment.

The shot peening intensity applied in this work was produced according to SAE J442 [4] and J443 [5] specifications by means of Almen strips type A. The shot peening treatment was produced using a nozzle with a diameter of 5 mm, a distance between the nozzle and the work piece of 240 mm, an impact angle of 90° and 100% coverage, which was determined using image analysis under an optical microscope. A low coverage treatment (80%) and another treatment involving 200% coverage were performed in order to analyze the effect of coverage on the fatigue life of the steel. The attainment of the 80% coverage consumes a time less than 40% of the time required for the full coverage, while the 200% coverage corresponds to twice this time.

Double peening treatments consisting of a high intensity treatment (21 A), followed by lower intensity peenings (8 A or 5 A) were also tested. The 21 A peening treatment was performed employing CW shots with an average diameter of 0.7 mm under 4 bar, while the 8 A and 5 A peening treatments respectively used CW steel shots of 0.3 mm and 0.2 mm glass shots, under 2 bar. The first treatment was applied with a full coverage, while the coverage of the second treatment was always 200% in order to assure at least also full coverage, as it was applied to a previously hardened surface. An alternative approach is to remove the damage surface layer by chemical or mechanical methods, so in a second series of surface treatments, following the high intensity peening (21 A), a surface layer of approximately 0.04 mm was removed using two different procedures, mechanical grinding using 600 grit abrasive paper, and electro-polishing. Table 3 shows the parameters used in all the peening treatments.

Table 1
Chemical composition of F1272 steel (wt%).

%C	%Mn	%Si	%Cr	%Ni	%Mo	%Cu
0.41	0.71	0.26	0.87	1.92	0.24	0.21

Table 2
Mechanical properties of the steel.

	E (GPa)	σ_{ys} (MPa)	σ_R (MPa)	A (%)	HV
F1272	193	914	1197	11.4	341

All the shot peening treatments were applied to polished samples cut transversally from the bars and also to the fatigue specimens. These samples were ground and polished following standard procedures.

Surface roughness was characterized on a DIAVITE DH-6 roughness tester by means of the average roughness, R_a, and R_{max}, which is the mean 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. These values are known to be the most representative parameters of the roughness profile as they are directly related to the provided stress concentration factor, as shown respectively by Bhuvaraghan et al. [14] and Li et al. [15]. Six different roughness profiles (three in the longitudinal direction and another three in the transversal direction) were performed on each sample and the average results were reported.

2.3. Hardness and X-ray diffraction

After the shot peening treatments, the samples were cut transversally, embedded in a cold-mount resin and metallographically prepared in order to determine the increase in hardness due to shot peening. Vickers microhardness indentations with a load of 200 g using a dwell time of 10 s were performed from the treated surface until a depth at which the initial hardness was not modified by the treatment. These tests were performed using a Buehler Micromet 2100 microhardness tester according to the ASTM E384 standard.

Shot peening residual stress profiles were determined by X-ray diffraction (XRD) and incremental layer removal by electropolishing. The X-ray diffraction technique employed in the present study to determine residual macrostresses was the $\sin^2\psi$ method [16,17], which does not require a stress-free reference.

Diffraction data were determined in three different directions on the sample plane, 0, 45 and 90°, subsequently calculating the average result. Measurements were made using an X-stress 3000 G3R device manufactured by Stresstech. A Cr-Kα X-ray source was used employing a wavelength of 0.22897 nm and measurements were taken on the (211) diffraction peak of the martensite, which was recorded at a 2θ angle of approximately 156°; the diffraction elastic constant of the selected diffraction plane, $E/(1+\nu)$, being 168.900 MPa [17,18]. Nine ψ tilt angles between −45 and +45° and a collimator with a diameter of 2 mm were also used.

The slight stress relaxation produced by layer removal was also taken into account and corrected in accordance with Sikarskie [19], who has developed a methodology based on the Moore and Evans procedure [20]. The calculated residual stress maximum measurement error of our diffraction procedure at the 95% confidence level was ±45 MPa, while the error with respect to depth was negligible [21]. Furthermore, peak broadening profiles (defined by the full width at half maximum, FWHM) were also measured in the present study, as this parameter is related to the near surface lattice distortion, the dislocation density and the so-called type II micro residual stresses, although some instrumental broadening is always also present [16].