Shot peening intensity optimization to increase the fatigue life of a quenched and tempered structural steel

A. T. Vielma, V. Llaneza and F. J. Belzunce

Material Science Department, University of Oviedo, Campus Universitario, 33203, Gijón, Spain

Abstract

A quenched and tempered medium-carbon alloyed steel was subjected to different shot peening treatments of varying intensities, from a low intensity 8A to a high intensity 21A, with 100% coverage. The surface roughness, subsurface hardening and residual stress profiles thus obtained were determined and compared. In addition, the fatigue lifes corresponding to the different shot peening treatments were evaluated on a rotating beam machine under alternative stresses of 45 and 50% of the tensile strength of the steel. Although all the shot peening treatments improved the cyclic behavior of the untreated specimens, the best fatigue behavior corresponded to the 10A treatment. High intensity shot peening treatments gives rise to worse fatigue behavior, in spite of an increase in surface hardening and deeper compressive residual stress fields, due to surface damage. This damage was not appreciated under the scanning electron microscope, but was indirectly detected by means of the relaxation of the surface residual stress.

Keywords: shot peening; Almen intensity; fatigue

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, given rise to a field of surface compressive stresses [1,2]. Although the effect of the intensity of the shot peening treatment (Almen intensity) on the fatigue life of steels with different mechanical properties has been studied by many researchers, treatment optimization is a subject which still requires further work. The optimum fatigue life corresponds to a certain Almen intensity, which depends on the mechanical properties of the peened alloy, and it is not easy to foresee. In the case of underpeening, the depth of the compressive residual stress field is too low; but when overpeening, the introduction of surface damage gives rise to a major decrease in fatigue life.

With the aim of clarifying this topic, a systematic study was carried out on the effects of the Almen intensity on the roughness, surface hardening, residual stress profiles and fatigue life of a quenched and tempered steel with a tensile strength of 1200 MPa, subsequently identifying and justifying the optimal peening treatment.

2. Material and methods

The chemical composition of the F1272 steel (equivalent to 4340) is given in Table 1.

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

<table>
<thead>
<tr>
<th>%C</th>
<th>%Mn</th>
<th>%Si</th>
<th>%Cr</th>
<th>%Ni</th>
<th>%Mo</th>
<th>%Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.41</td>
<td>0.71</td>
<td>0.26</td>
<td>0.87</td>
<td>1.92</td>
<td>0.24</td>
<td>0.21</td>
</tr>
</tbody>
</table>

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 minutes, quenched in water and tempered at 590°C for 150 minutes).

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, \( \sigma_y \), tensile strength, \( \sigma_R \), and elongation, A), are given in Table 2, along with its Vickers hardness, HV.

Table 2. Mechanical properties of the F1272 steel.

<table>
<thead>
<tr>
<th>E (GPa)</th>
<th>( \sigma_y ) (MPa)</th>
<th>( \sigma_R ) (MPa)</th>
<th>A (%)</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1272</td>
<td>193</td>
<td>914</td>
<td>1197</td>
<td>11.4</td>
</tr>
</tbody>
</table>

Shot peening was performed by means of a direct compressed air machine (GUYSON Euroblast 4 PF) using cut wire shots (CW, 670-730 HV) of different diameters (0.3, 0.4, 0.5 and 0.7 mm) and varying the air pressure between 1.5 and 4 bar, in order to obtain different Almen intensities. Shot peening intensities were produced in compliance with SAE J442 [3] and J443 [4] specifications by means of A-type Almen strips. Table 3 gives the shot peening conditions used to obtain the different Almen intensities. All the shot peening treatments were produced using a distance between the nozzle and the work piece of 100 mm, an impact angle of 90° and 100% coverage, which was determined using image analysis under an optical microscope.

Table 3. Applied shot peening conditions.

<table>
<thead>
<tr>
<th>Almen intensity (deflection of the Almen strip, in mm)</th>
<th>Shot size (mm)</th>
<th>Pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8A (0.2 mm)</td>
<td>CW-0.3</td>
<td>2</td>
</tr>
<tr>
<td>10A (0.25 mm)</td>
<td>CW-0.4</td>
<td>2</td>
</tr>
<tr>
<td>12A (0.3 mm)</td>
<td>CW-0.5</td>
<td>2</td>
</tr>
<tr>
<td>14A (0.35 mm)</td>
<td>CW-0.4</td>
<td>3</td>
</tr>
<tr>
<td>16A (0.4 mm)</td>
<td>CW-0.7</td>
<td>1.5</td>
</tr>
<tr>
<td>19A (0.475 mm)</td>
<td>CW-0.7</td>
<td>3</td>
</tr>
<tr>
<td>21A (0.52 mm)</td>
<td>CW-0.7</td>
<td>4</td>
</tr>
</tbody>
</table>

These treatments were applied to polished samples cut transversally from the bars and also to the fatigue specimens. Surface roughness was measured on a DIAVITE DH-6 roughness tester using the maximum roughness, \( R_{\text{max}} \), as a comparison. Six roughness profiles (three in the longitudinal direction and another three in the transversal direction) were performed along a total length of 30 mm for each sample and the average results were reported.

After the shot peening treatments, the samples were cut transversally, embedded in a resin and metallographically prepared in order to determine the increase in hardness due to shot peening. Microhardness indentations with a load
of 200 g 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 sin²ψ method [5,6]. Measurements were made using an Xstress 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 20 angle of approximately 156°, the diffraction elastic constant of the selected diffraction plane, E/(1+ν), being 168.900 MPa [6,7]. 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 [8], who has developed a methodology based on the Moore and Evans procedure [9]. 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 [5].

The fatigue tests were carried out on a four-point load R.R. Moore rotating beam testing machine. The
ground and dimensions of the specimen are shown in Fig. 1.

The applied maximum surface stress was respectively 50 and 45% of the tensile strength of the steel (599 and
539 MPa).

Fatigue tests were performed on conventional machined specimens, polished specimens and also on shot peened
specimens submitted to the aforementioned Almen intensities (100% coverage). The number of fatigue tests
performed under each condition varied between three and six. Fatigue tests were considered finished after complete
breakage of the specimen or on reaching 4 million cycles (run outs). The fatigue results are expressed as average
values.

3. Results and discussion

Table 4 shows the evolution of the maximum sample roughness, R_max, with the applied coverage for the different
Almen intensities. In general, roughness increases until 100% coverage and then stabilizes for higher degrees of
coverage. At first, shot indents significantly increase the roughness of the polished surfaces. However after attaining
full coverage, roughness seems to saturate for most treatments, as the increase in surface hardness reaches its
maximum value. Moreover, roughness increases with increasing Almen intensity, although the shot size is also a
parameter to consider, as it can be seen by comparing the roughness of the 14A and 16A treatments. As regards full
coverage, shot peening with a 16A treatment gives rise to a lower roughness than the 14A treatment: the shot sizes
of these two treatments were different, the shot size of the 16A peening being larger, as it can be seen in Table 3.

Shot peening treatments always produce a significant increase in hardness due to plastic deformation of the
surface regions of the sample. The Vickers microhardness measured in some of the shot peening treatments was
plotted against the sample depth, as shown in Fig. 2a. A layer of increased hardness of about 0.8 mm was observed
in all the shot peening treatments, although the most significant increase in hardness corresponds to the first 0.2 mm.
Nevertheless, the maximum increase in hardness was relatively low, about 40 Vickers units, which corresponds to a
percentage increase just over 10%. 
Table 4. Evolution of the maximum roughness (R_{max}) with the coverage degree.

<table>
<thead>
<tr>
<th>%C</th>
<th>8A R_{max} [µm]</th>
<th>10A R_{max} [µm]</th>
<th>12A R_{max} [µm]</th>
<th>14A R_{max} [µm]</th>
<th>16A R_{max} [µm]</th>
<th>19A R_{max} [µm]</th>
<th>21A R_{max} [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>42%</td>
<td>16.3</td>
<td>25%</td>
<td>17.7</td>
<td>31%</td>
<td>23.8</td>
<td>55%</td>
<td>31.2</td>
</tr>
<tr>
<td>80%</td>
<td>21.9</td>
<td>67%</td>
<td>21.6</td>
<td>90%</td>
<td>28.9</td>
<td>85%</td>
<td>31.4</td>
</tr>
<tr>
<td>100%</td>
<td>19.8</td>
<td>100%</td>
<td>27.2</td>
<td>100%</td>
<td>29.5</td>
<td>100%</td>
<td>37.1</td>
</tr>
<tr>
<td>200%</td>
<td>23.7</td>
<td>200%</td>
<td>27.9</td>
<td>200%</td>
<td>32.0</td>
<td>200%</td>
<td>42.2</td>
</tr>
</tbody>
</table>

Additionally, the full width at half maximum (FWHM) of the diffraction peak is a parameter obtained during the diffraction experiments which is directly related to cold deformation [1]. Fig. 2b shows the evolution of the FWHM parameter with sample depth in all the shot peening treatments. The evolution of this parameter in the shot peened samples produced on this steel (quenched and tempered steel) is worth highlighting. There is a clear increase in this parameter (hardening) near the surface of the samples, although it reaches a minimum at a depth of between 0.1 and 0.25 mm from the surface and subsequently increases until attaining the level corresponding to the base steel (2.9º). The plastic deformation induced in the shot peening treatments gives rise to surface hardening, ignoring the first 0.05 mm, in which some relaxation takes place as a result of the multiple successive shot impacts. However, some softening was also been recorded at a certain depth, probably due to structural recovery.

Fig. 3 shows the compressive residual stress profiles measured under the different shot peening treatments. It was observed that the maximum compressive residual stress does not depend on the shot peening intensity (the average...
maximum compressive residual stress was 621 MPa, which corresponds to 52% of the base steel tensile strength), although the surface residual stress does decrease slightly as the shot peening intensity increases (see Table 5). This is because these treatments produce a certain degree of relaxation in the surface region promoted by the multiple successive shot impacts and also, possibly, as a result of the initiation of some surface damage. A similar phenomenon was also observed in the case of the FWHM parameter, where the more intensive shot peening treatments led to lower hardening in the near-surface region (see Fig. 2b).

Table 5. Surface compressive stress and maximum compressive stress versus Almen intensity.

<table>
<thead>
<tr>
<th></th>
<th>8A</th>
<th>10A</th>
<th>12A</th>
<th>14A</th>
<th>16A</th>
<th>19A</th>
<th>21A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{c}^{\text{max}}$</td>
<td>-522</td>
<td>-621</td>
<td>-549</td>
<td>-634</td>
<td>-480</td>
<td>-627</td>
<td>-439</td>
</tr>
<tr>
<td>$\sigma_{c}^{\text{max}}$</td>
<td>-609</td>
<td>-513</td>
<td>-628</td>
<td>-443</td>
<td>-595</td>
<td>-448</td>
<td>-636</td>
</tr>
</tbody>
</table>

Finally, Fig. 4 and 5 present the fatigue results respectively obtained on the fatigue specimens submitted to the different shot peening treatments under alternative maximum stress corresponding to 50% and 45% of the tensile strength of the steel, along with the results obtained using conventional machined (non-treated) as well as polished specimens. As regards Fig. 4, note that all the shot peening treatments were able to increase the fatigue life compared to the non-treated specimens, while the greater enhancement in fatigue life was obtained with the 10A treatment. This shot peening treatment led to more than a three-fold increase in the fatigue life of the non-treated specimens and almost a two-fold increase with respect to the polished specimens. Similar though even more spectacular results were obtained under an alternative maximum load of 45% of the tensile strength of the steel (Fig. 5). In this case, the 10A shot peening treatment also gave rise to the best fatigue behavior, producing a 50-fold increase in fatigue life compared to the non-treated specimens. It is well known that the effect of the shot peening treatment increases as cyclic testing conditions approach the fatigue limit.

![Fig. 4. Fatigue life under an alternative maximum stress of 50% of the tensile strength.](image)

It is also worth noting that although they also improve the fatigue behavior of the non-treated specimen, the high intensity shot peening treatments (higher than 10A), produce worse results than the 10A shot peening treatment despite producing a greater increase in surface hardening (Fig. 2a) and, especially, a much larger region submitted to high compressive stresses (Fig. 3). Furthermore, the other important negative consequence of applying an over-intensive shot peening treatment is the nucleation of surface damage, which can trigger a rapid initiation of fatigue cracks. Although all the shot peened surfaces were observed under the scanning electron microscope in order to detect any kind of damage, none was observed. Only the increase in roughness shown in Table 4 constituted an indirect indicative parameter of such damage. Nevertheless, the compressive stress at the surface of the treated sample can also be an indirect measurement of surface damage, as this stress gave a maximum absolute value in the case of the 10A shot peening treatment, as can be seen in Table 5. The relaxation observed in the surface residual stress can be a sign of damage initiation.
4. Conclusion

Shot peening treatments always produced an increase in hardness due to plastic deformation of the surface regions of the sample, although the maximum hardness increase was relatively low. On the other hand, the FWHM parameter provides an indirect measure of the induced surface hardening produced by shot peening and is easily determined, ignoring the first 0.05 mm, in which some relaxation takes place as a result of the multiple successive shot impacts. The FWHM parameter is seen to be directly related to the applied Almen intensity.

An approximate linear relationship was obtained between the depth submitted to compressive residual stresses and the intensity of the shot peening treatment, although the maximum subsurface compressive stress was not dependent on peening intensity, always attaining a magnitude close to half the tensile strength of the steel.

All the shot peening treatments increased the fatigue life of the steel compared to the non-treated specimens, the greatest enhancement in fatigue life being obtained with the 10A treatment in tests performed under alternative loads of 45% and 50% of the tensile strength of the steel. Although they were also able to improve the fatigue behavior of the non-treated specimens, the high intensity shot peening treatments provide worse results than the 10A shot peening treatment, despite producing greater surface hardening and a much larger region submitted to high compressive stresses. Finally, an indirect measure of the surface damage initiated in these high intensity shot peening treatments is provided by the relaxation of the surface compressive stress, which attained its highest value in the case of the optimum peening treatment, 10A.

References