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The influence of shot peening on the fatigue behaviour of duplex stainless steels

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Abstract

Stainless steel bars are currently used to reinforce large concrete structures when they need to guarantee a reliable service in saline environments. As these structures are also usually submitted to cyclic loads, their fatigue performance is an important issue to take into account. It is also well known that shot peening is a process largely employed to improve the fatigue behaviour of metal products. In this process the metallic surface of a component is peened with small spherical shots in order to induce plastic deformations which generate compressive residual stresses and, consequently, the component fatigue resistance is significantly enhanced.
AISI 2205 duplex stainless steel bars, already largely used for concrete reinforcement, was the material choice in this work. The bars were hot rolled and afterwards different shot peening treatments were applied, which were fully characterised by means of Almen intensity and coverage ratio. Residual stresses were also measured by means of X-ray diffraction. The S-N fatigue curves of the bars submitted to the different shot peening treatments were determined and the improvement due to shot peening explained taking into account the shot peening effects on the surface of the bars.

Keywors: *Duplex stainless steel; Shot peening; Almen intensity; Residual stresses*

1. Introduction

The in-service performance of large reinforced concrete structures placed in aggressive environments can be greatly improved using stainless steel bars. Furthermore, these structures are usually subjected to cyclic loads, so that good fatigue behaviour must be guaranteed [1]. In this context, the use of duplex stainless steel corrugated bars is a really interesting option [2].

On the other hand, shot peening is one of the most common industrial processes used to increase the fatigue life of metallic components [3]. In this process, the plastic deformation produced by the impact of a stream of small spherical projectiles on the surface of a metallic element, generates a residual stresses field under the surface of the treated component, which results in an enhanced fatigue performance. Another direct consequence of the shot peening treatment is the modification of the surface finish of the treated component [4]. If the peening parameters are not carefully controlled, the roughness generated after peening could deteriorate the fatigue behaviour of the part, and the benefits of the compressive residual stress field could be significantly reduced.

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While shot peening is a widely used process in the aeronautic and automotive industries, its use in civil constructions has not been until now referenced. In this paper, a duplex stainless steel reinforcing bar was selected and peened under different conditions, whit the aim to better know the effects of the shot peening process on the fatigue behaviour of this product.

In a first stage, reinforced bars were subjected to an industrial shot peening treatment. Then, smooth specimens were machined, in order to eliminate the effect of the ribs and all the surface defects present onto the bars, and they were peened using a new well controlled and more intensive peening treatment. The residual stress field generated after both peening processes was characterized by means of X ray diffraction. Finally, the S-N curves corresponding to both peening treatments were experimentally obtained, and were compared with the S-N curves corresponding to the as-received bars and to the smooth un-peened specimens.

2. Materials and experimental procedure

All the work was performed onto AISI 2205 duplex stainless steel reinforcing bars. This kind of steel is usually used in the construction of mesh reinforcements in large concrete structures, especially when these structures are subjected to aggressive environments. Duplex stainless steels have a microstructure composed by ferrite an austenite (about 50/50 %), which gives them excellent mechanical properties and very high corrosion resistance [5]. Table 1 summarizes the chemical composition of the bars.

Table 1. Chemical composition of the material

	C	Si	Mn	Cr	Ni	Mo	N	Cu	S	Ti
Weight (%)	0.029	0.39	1.72	22.49	4.72	3.22	0.174	0.24	0.001	0.027

The material was supplied by *Roldán S.A*. (Ponferrada, Spain) as ribbed bars with a nominal diameter of 16 mm, and manufactured using a hot rolling process [6]. Average values of hardness and tensile test properties (*E*: Young´s module, σ_{ys}: yield strength, σ_{us}: tensile strength and *A*: elongation) are shown in table 2.

Table 2. Hardness and tensile properties of the hot rolled bars

HV 500g	E [GPa]	σ_{ys} [MPa]	σ_{us} [MPa]	A [%]
335	166	630	793	51

The industrial shot peening process was carried out by Roldán S.A. by means of a centrifugal machine, which operates with 8 turbines, and using cast steel shot S-230. Another peening treatment, defined as *controled peening*, was designed in our laboratory, and it was carefully developed under laboratory controlled conditions. A pneumatic direct pressure machine, which can operate with a work pressure between 1.5 and 6 bar, was used to perform the treatment. In order to compare the results obtained with the two treatments, S-230 cast steel shot media were also used in this case, in conformity with SAE J444 specification [7]. Moreover, trying to assure a high quality shot peening treatment, the peening media was fully characterized in size and shape by means of image analysis techniques.

The Almen intensity applied in the two peening treatments was determined using the “10% rule”, according with SAE J442 [8] and SAE J443 [9] specifications. Grade 2, class “A” Almen strips were used firmly screwed to Almen blocks. The arcs generated in the strips were measured using an Almen gage provided by a magnetic support system with an uncertainty of 0.001 mm.

The data obtained in these experiments were fitted by means of the following four parameters equation:

$$h = a \cdot (1 - e^{-b \cdot t^{c}}) + d \cdot t \quad (1)$$

where h is the measured arc produced in the Almen strip, t is the exposure time, and a, b, c and d are the four parameters that give the best fit of the experimental data.

In addition, the evolution of the coverage level has been found to be well fitted by equation (2), known as the Avrami equation:

$$C = 100 \cdot (1 - e^{-A \cdot R \cdot t}) \tag{2}$$

where C is the coverage level (percent of the treated area covered by hits at least once), A is the area of each individual dimple, R is the flow rate (number of dimples produced by unit of time and surface) and t is the exposure time.

It should be noted that in both peening treatments, 98% theoretical coverage was achieved, which in practice, stands for total coverage. The work pressure in the controlled peening treatment was 3 bar, the distance between the nozzle and the treated material was 240 mm, and the angle of impact was 90º.

While industrial shot peening was made onto the as-received reinforced bars, figure 1 (a), the controlled shot peening treatment was performed onto machined specimens, as shown in figure 1 (b). All the surface irregularities of the bars was eliminated in the machined specimens, with the aim to study its effect on the fatigue behaviour.

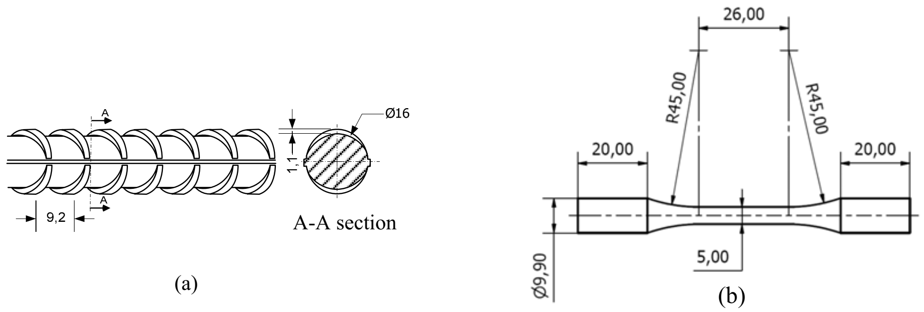


Fig. 1. (a) Geometry of the as-received corrugated bars (units in millimetres); (b) Geometry and dimensions of the machined specimens (units en millimetres)

Then, the compressive residual stress fields generated after the peening treatments were characterize by means of X ray diffraction. These measures were carried out with the technical support of the Politecnico di Milano, Italy. The tests were made in Ψ mode, according with SAE HS-748 [10].

Finally, the S-N fatigue curves were determined for both industrial and controlled peening treatments, as well as for the non-treated material. In addition, due to the random component of the fatigue phenomenon, a statistical fatigue model was used to determine the S-N curves (Castillo et al. model) [11]. This model defines the S-N field as the cumulative distribution function of the fatigue life, N, for a given constant stress range $\Delta\sigma_i$, i.e.:

$$F(\log N_i; \Delta\sigma_i) = 1 - \exp\left[\left(-\frac{(\log N - B)(\log \Delta\sigma_i - C)}{D} + E\right)^A\right] \tag{3}$$

from which the percentiles curves (isoprobabilistic curves) are given by:

$$(\log N - B)(\log \Delta\sigma - C) = D\left[\left[-\log(1 - P)\right]^{1/A} - E\right] \tag{4}$$

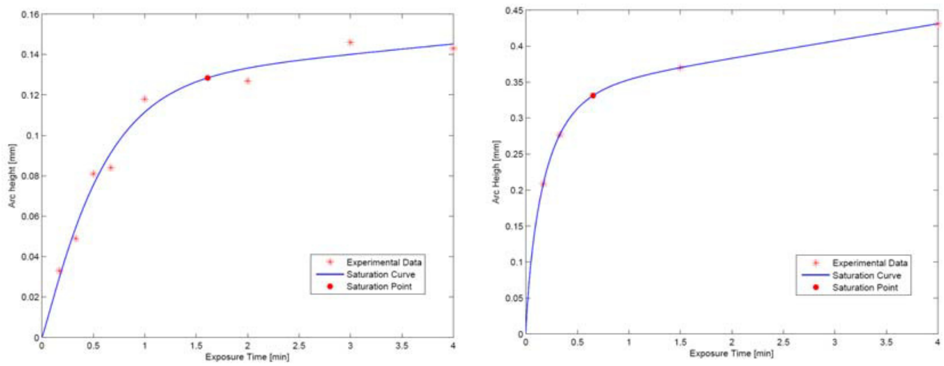
where N is the mean fatigue life (cycles), $\Delta\sigma$ the stress range, P the failure probability and A, B, C, D and E the model parameters to be adjusted with the experimental results. A is the Weibull shape parameter, B the threshold value for *N* or the limit number of cycles), *C* the endurance limit, *D* the scale parameter and *E* the parameter that defines the location of the corresponding zero-percentile hyperbola.

All fatigue tests were carried out at different stress range levels ($\Delta\sigma = \sigma_{max} - \sigma_{min}$), obtained using as minimum stress the 25% of the material yield stress and varying the maximum stress. This strategy tries to reproduce the in-service working conditions of the bars, which have to support, at least, the weight of the structure. All tests were performed at room temperature under axial loading and constant sinusoidal amplitude.

3. Results and discussion

3.1. Shot peening treatments

The saturation curve obtained in the case of the industrial shot peening is shown in figure 2(a). These experimental measures were carried out in the industrial installation, and give way to an Almen intensity of 5A. On the other hand, previous works [12] had shown that duplex stainless steels were nearly not affected by low intensity peening, so in this work, a new treatment, called controlled shot peening, with a significant higher intensity, was developed. Figure 2 (b) shows the saturation curve of this new treatment, designed at the Escuela Politécnica de Ingeniería de Gijón, where an intensity of 13A was attained. In both cases, the chosen saturation curve produced an excellent fit to the experimental data.



(a) (b)

Fig. 2. Saturation curves obtained for: (a) Industrial shot peening (5A); (b) Controlled shot peening (13A)

3.2. Residual stresses

Residual stresses measurements were made on the surface of the bars, before and after the industrial peening. Although it was noticed that most of the failures took place in the bar-rib transition region [13], it is virtually impossible to carry out reliable measurements in this zone, so the measurements have been done in the uniform regions between ribs. The values shown in table 3, are the result of the application of the rule of mixtures, since X-ray measurements were carried out in the austenite and also in the ferrite phases. It can be appreciated that shot peening processes induce surface compressive residual stresses in the treated parts, giving way to an increment of 367 MPa for the industrial peening and 631 MPa in the case of the controlled peening. So, the controlled shot peening treatment was, as expected, much more effective, from the point of view of the induced compressive residual stress field. By the other hand, the residual stresses measured on the surface of the as-received corrugated bars, can be considered as negligible.

Table 3. Average residual stresses measured on the surface of the bars (region between ribs)

	As-received	Industrial shot peening	Controlled shot peening
Surface residual stress	72 MPa	-295 MPa	-559 MPa

It should be highlighted that, because of the technical difficulties found to carry out practical residual stress measurements on the corrugated bars (unpeened as well as industrial peened), a new strategy to measure the residual stresses generated after controlled shot peening treatments was developed, by peening the flat surface obtained after a transversal cutting of the bars. Then, the residual stress evolution was measured on these surfaces until a depth of 0.35 mm.

Figure 3 illustrates the residual stress profile obtained with the as-received bars and after both industrial and controlled shot peening treatments. The profile obtained in the case of the controlled peening attains a maximum compressive stress (-740 MPa) at about 0.04 mm depth, while the industrial peening induces a maximum compressive stress of -383 MPa, at about 0.03 mm. In adittion, the total thickness of the compressive layer generated by the controlled peening treatment was much deeper (more than 0.35 mm) than the one generated by the industrial peening. These results confirm that the residual stress field induced by the controlled shot peening treatment is much more efficient than the industrial one.

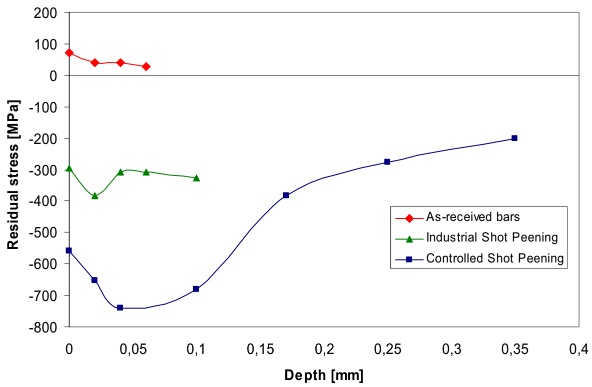


Fig. 3. Residual stress profiles measured into the as-received bars and after controlled and industrial peening treatments

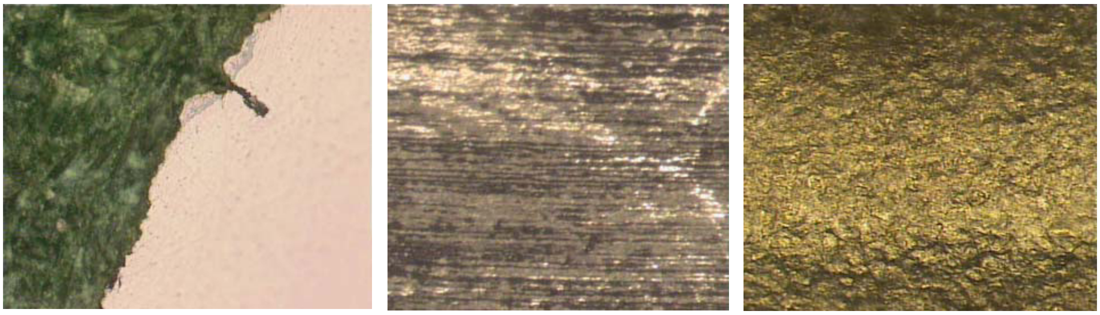
3.3. Roughness

Table 4 summarizes the measured values of the roughness parameter R_a determined onto both bars and machined specimens, before and after peening treatments. It must be noticed that, before peening, machined specimens have a much smoother surface than reinforced bars. Moreover, many surface defects were detected in the unpeened bars (figure 4 (a))[6]. On the other hand, although the R_a values obtained after both industrial and controlled peening treatments are quite similar, the roughness increment is larger in the case of the machined specimens (162%) than in the bars (82%), and this fact decreases the effectiveness of the shot peening treatment. So, from the point of view of surface morphology, industrial peening treatment is more efficient over the bar surface than controlled peening over the smooth machined specimen surface.

Table 4. Average roughness measured before and after the peening treatments

Ra (μm)	Bar	Machined specimen
Before peening	1.48	0.90
Industrial peening	2.69	--
Controlled peening	--	2.36

Figure 4 (b) shows the superficial aspect of the reinforced bars before peening, showing the presence of grooves oriented in the rolling direction, while figure 4 (c) shows the morphology of the bar surface after the industrial shot peening treatment. In this later case, the grooves have disappeared and a more uniform surface finish was attained so that a better fatigue performance would be expected.

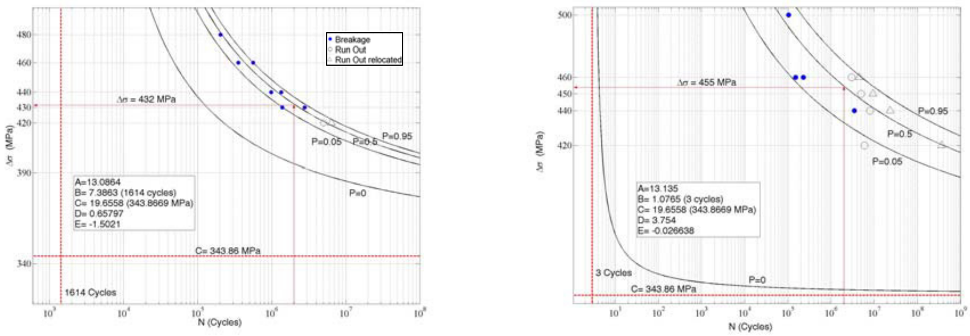


(a) (b) (c)

Fig 4. (a) Large defect in radial direction detected on the surface of an as-received corrugated bar; superficial aspect of the reinforced bars: (b) Unpeened; (c) After the industrial peening treatment

3.4. Fatigue behaviour

Figure 5(a) shows the S-N curves for the unpeened machined (smooth) specimens, and fig 5(b), the curves corresponding to controlled peened machined specimens, including the 0, 5, 50 and 95% probability of failure percentiles curves. It can be appreciated that the peening process gives way to a light improvement in the product fatigue strength, approximately quantified in 5%, from 432 to 455 MPa (for a fatigue life of 2 million of cycles). The effect of the compressive residual stress field induced by shot peening surpasses the contrary effect due to the induced roughness increase.



(a) (b)

Fig. 5. S-N curves of (a) machined specimens (unpeened); (b) controlled peened machined specimens

Figure 6 collects all the S-N experimentally obtained curves for the studied material (the S-N curves for the as-received, and after the industrial peening treatment corrugated bars, were obtained in a previous work [14]). It must be took into account that peening treatments are more effective when they are applied to rough surface finished parts or onto notched elements [15,16]. This is the reason because the industrial peening, conducted on the corrugated bars which had a surface with a lot of defects, results in an improvement in the 2 million cycle fatigue strength of 45% (95 MPa), while the controlled peening, characterized by a larger Almen intensity but conducted onto smooth polished specimens, just improves it only a 5% (23 MPa).

On the other hand, it can be clearly observed that the effect of the original ribbed and notched surface is the most critical factor affecting the fatigue strength of the corrugated bars. The fatigue strength at 2 million cycles increases from 210 MPa to 432 MPa (106% increment) as a result of eliminating the original surface of the bars by machining and improving the product roughness (see table 4).

When comparing the fatigue behaviour of the as-received bars with the machined specimens subjected to controlled peening, a 2 million cycles fatigue strength increase of 117% is observed (from 210 to 455 MPa), being 90% of this increment just due to surface morphology modification while the remaining 10% can be attributed to the shot peening treatment.

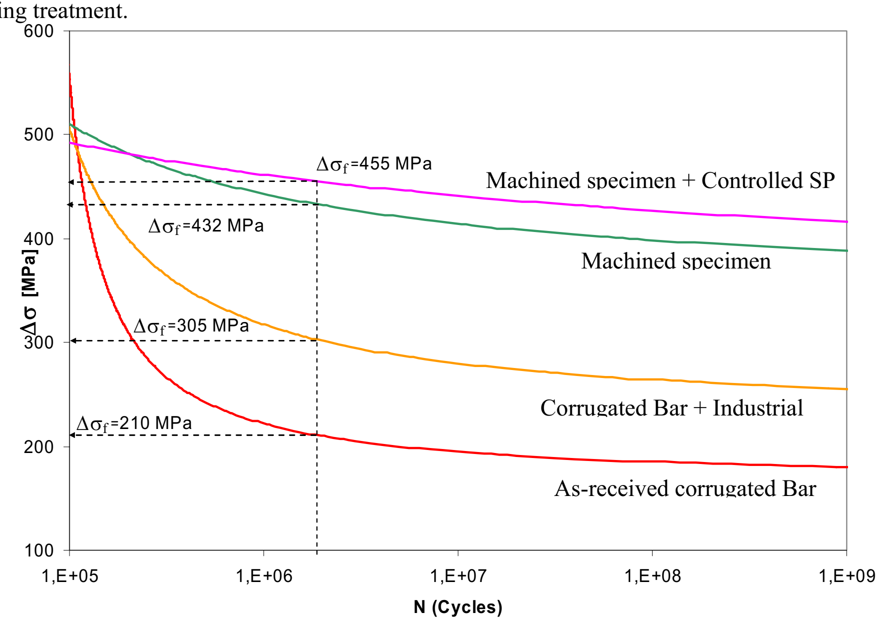


Fig. 6. S-N curves (P=50%) of corrugated bars and machined specimens before and after peening treatments

Finally, table 5 summarizes the fatigue strength values corresponding to an infinite life (parameter *C* in the statistical model) and to a life of $2{\cdot}10^6$ cycles ($\Delta\sigma_f$).which is the usual reference life in most reinforced bars standards.

Table 5. Fatigue strength for an infinite life (C) and for a life of $2{\cdot}10^6$ cycles ($\Delta\sigma_f$).

Fatigue strength	Corrugated as-received bar	Corrugated bar + Industrial SP	Machined specimens	Machined specimen + Controlled SP
C (MPa); N=∞	164	225	344	364
$\Delta\sigma_f$ (MPa); $N=2{\cdot}10^6$ cycles	210	305	432	455

4. Conclusions

Shot peening is a well known process which is commonly used in aeronautic and automotive industries in order to improve the fatigue behaviour of many different components. In this paper, shot peening treatments were studied as an interesting method to improve the fatigue performance of civil constructions made with reinforced concrete.

It has been found that the fatigue performance of duplex stainless steel reinforced bars can be enhanced by means of shot peening treatments, and it has been proved that peening treatments are much more effective when they are applied onto surfaces with high roughness, regardless of the applied Almen intensity.

Two peening treatments on two different surface conditions were carried out, and it has been demonstrated that the surface finish was the critical factor for the enhancement of the fatigue behaviour of the reinforced bars: being 90% of the total fatigue improvement due to the elimination of surface stress raisers and the improvement of the product roughness and only 10% is due to the compressive residual stress layer induced by shot peening. Moreover, in the case of the shot peening treatment applied onto smooth specimens, the effect of the compressive residual stress field induced by shot peening slightly surpasses the contrary effect due to the induced roughness increase.

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