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An evaluation of shot peening, residual stress and stress relaxation on the fatigue life of AISI 4340 steel

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Abstract

Shot peening is a method widely used to improve the fatigue strength of materials, through the creation of a compressive residual stress field (CRSF) in their surface layers. In the present research the gain in fatigue life of AISI 4340 steel, used in landing gear, is evaluated under four shot peening conditions. Rotating bending fatigue tests were conducted and the CRSF was measured by an X-ray tensometry prior and during fatigue tests. It was observed that relaxation of the CRSF occurred due to the fatigue process. In addition, the fractured fatigue specimens were investigated using a scanning electron microscope in order to obtain information about the crack initiation points. The evaluation of fatigue life, relaxation of CRSF and crack sources are discussed.

Keywords: Shot peening; Residual stress; 4340 Steel; Fatigue

1. Introduction

Fatigue is an important parameter to be considered in the behavior of mechanical components subjected to constant and variable amplitude loading. Mechanical, metallurgical and environmental variables can influence the fatigue resistance of a structural component [1]. In structural engineering applications, nucleation and propagation of fatigue cracks are some of the most important considerations in the mechanical properties of metals. In high strength steels, surface and subsurface defects play an important role in the reduction of the fatigue limit [2]. AISI 4340 steel is widely used in the aircraft industry for fabrication of structural components, in which strength and toughness are fundamental design requirements.

One of the known ways to improve fatigue resistance is by using the shot peening process to induce a compressive residual stress in the surface layers of the material, making the nucleation and propagation of fatigue cracks more difficult [3,4].

The shot peening results depend on various parameters. These parameters can be grouped in three different classes according to Fathallah et al. [5]: parameters describing the treated part, parameters of stream energy produced by the process and parameters describing the contact conditions. Kobayashi et al. [6] presented a mechanism of creation of compressive residual stress by shot peening through an experiment by dropping a large steel ball on a thick plate specimen. In industries shot peening is controlled with the help of Almen plates. They are standardized thin plates that are placed in parallel to the treated material, receiving therefore, the same treatment. This treatment induces residual stresses in small plates that become deformed. This deflected shape caused by the process is called Almen intensity, and its value is appropriate to adjust the shot peening parameters [7,8].

There are basically two ways of modeling the Compressive Residual Stress Field (CRSF) caused by shot peening. The first is through finite element analysis [7,9,10] and the second is through empiric models based

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on experimental data [11,12]. However, relaxation of the CRSF induced by shot peening has been observed over the fatigue life [13–15]. Kodama [16] shows that the residual stress relaxation of annealed carbon steel varied with fatigue cycles. This relaxation during the fatigue cycles was divided into two stages: the surface yielding in the first cycle and gradual change in the following cycles. In these two stages the residual stress of shot peened specimens decrease considerably when compared to those with no fatigue cycles. Furthermore, Farrahi et al. [17] worked with the AFNOR 60SC7 spring steel and showed that fatigue life improvement, resulting from shot peening, can be attributed to the maximum residual stress and also to the depth of the plastically deformed layer. A correlation was found between the fatigue life and the area under the residual stress curve.

In general, fatigue crack initiation occurs on the specimen surface. Wang et al. [18] demonstrated that fatigue crack can be initiated from the interior of many materials in the case of high-cycle fatigue (HCF). In the high-cycle regime ($>10^7$ cycles), all crack sources were found at non-metallic inclusions located in the interior of the specimen. Shengping et al. [19] showed that the shot peening process pushes the crack initiation points beneath the compressive residual stress zone in all the cases studied except for 0.45% carbon steel. In this research, the possibility of relaxation of CRSF during the fatigue process was not considered. Yet Zeller [20] demonstrates the residual stress relaxation on the aforementioned steel caused by fatigue loading.

In the present research, the rotating bending fatigue strength of AISI 4340 steel is evaluated as a function of shot peening in the conditions used in industries. In order to study the shot peening influence on fatigue life, the behavior of CRSF during the fatigue process and the crack initiation points of fatigued specimens were studied.

2. Experimental work

The chemical composition of AISI 4340 used was 0.41 C–0.73 Mn–0.8 Cr–1.74 Ni–0.25 Mo–0.25 Si, wt%. The mechanical properties of this alloy are: (50–53)HRC, yield strength of 1511 MPa, ultimate tensile of 1864 MPa, and fatigue limit of 800 MPa (54% of yield strength). These properties were obtained by means of quenching from 815°C followed by tempering in the range (230±5)°C for 2 h. This material was treated with four intensities of shot peening: 0.0027 A (8 psi), 0.0063 A (13 psi), 0.0083 A (18 psi), 0.0141 A (45 psi), all of them with an outflow of 3 kg/min, a speed of 250 mm/min, a distance of 200 mm and rotation of 30 rpm. The shot used was S 230 (ϕ 0.7 mm) with a coverage of 200% carried out on an air-blast machine according to standard MIL-S-13165. The shot peening treatment was done with high quality control, in which the shots are automatically selected and kept in perfect conditions. For all series of different shot peened specimens and the base material, the S/N curves were determined according to ASTM E 739. The specimens used (Fig. 1) were tested in rotating bending fatigue tests ($R=-1$) at frequency of 50 Hz, at room temperature. The fracture planes of the fatigued specimens were examined using a scanning electron microscopy model LEO 435 vpi in order to identify the crack initiation points. The CRSF induced by shot peening was determined by X-ray diffraction method, using the Raystress equipment, whose characteristics are described in [21]: ψ goniometer geometer, Cr–k_α radiation and registration of {221} diffraction lines. The accuracy of the stress measurements was $\Delta\sigma=\pm$ 20 MPa. In order to obtain the stress distribution by depth, the layers of specimens were removed by electrolytic polishing with a non-acid solution.

3. Results and discussion

3.1. Fatigue

The S/N curves for the base material and for the four peening conditions analyzed are shown in Fig. 2. Although 20 tests have been done for each curve, only the average points are presented for each stress level. The five stress levels indicated in Fig. 2 are not all of the levels tested, but they will be references of stress in the studies done throughout the text. It is possible to observe in Fig. 2 an improvement in the fatigue resistance of the specimens shot peened, compared to the base material. In relation to the base material, the shot peening influence in high stress (level 1: 1370 MPa) was null in the number of cycles until failure, except in the 0.0027 A condition, in which a slight improvement was observed. Nevertheless, for medium and high cycles an increase in fatigue life resulted from the shot peening treatment. It is interesting to remark that the best fatigue life conditions were found in the intermediate peening conditions: 0.0063 and 0.0083 A. There was almost no difference in the fatigue limit between the lowest and the highest peening intensities tested 0.0027 and 0.0141 A. Yet, the shot peening for the studied conditions represents an enhancement of the fatigue limit from 9% (0.0027 A) to 12% (0.0063 A) when comparing to the base material. For intermediate conditions (10^5 cycles, level 3: 1007 MPa and level 4: 931 MPa), however, the fatigue gain in relation to the base material was much more expressive, from two (0.0027 A) to maximum ten times (0.0063 A).

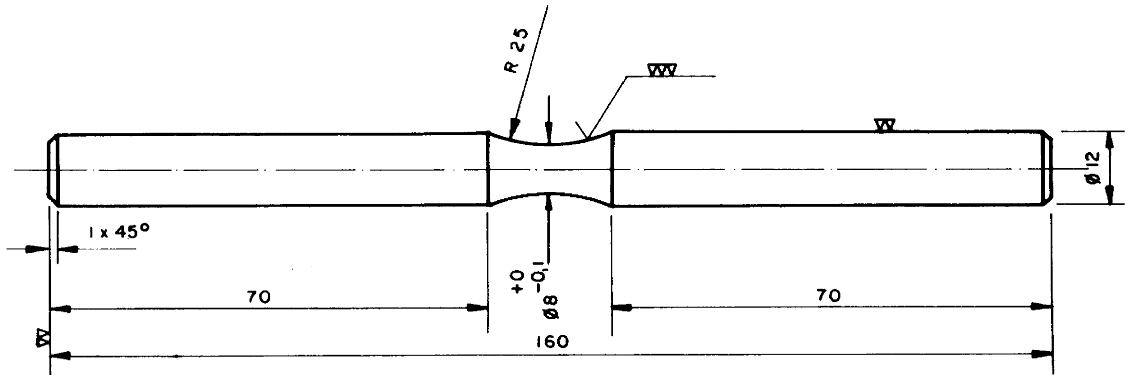

Fig. 1. Rotating bending fatigue testing specimens.

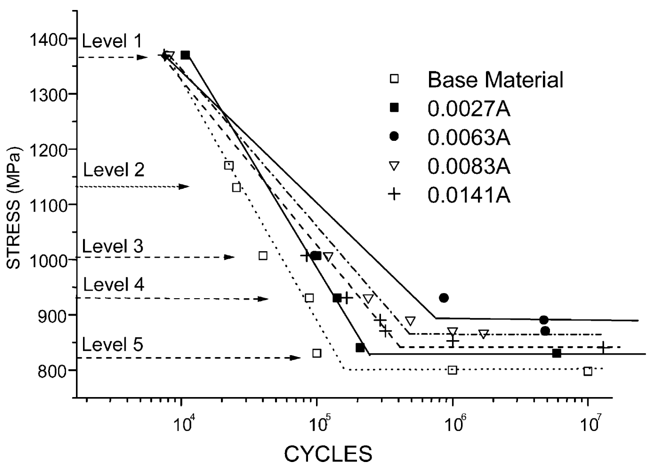

Fig. 2. S–N comparative curves of the base materials and shot peening conditions.

3.2. Compressive residual stress field

Fig. 3 shows the CRSF for all the peening conditions studied. For the fitting of experimental points, cubic equations were used [22]. It is possible to observe in Fig. 3 that the greater the peening intensity, the greater the depth and width of the CRSF. On the other hand, the residual stress on the surface, except in the 0.0141 A peening condition, is approximately the same. These results agree with the observations made by [12], in which it was stated that the surface stresses are more related to mechanical characteristics (hardness and elastic recuperation) and surface condition than to the shot peening intensity. Besides, it is also possible to note that when the shot peening intensity increases, the depth of the maximum value of the CRSF rises too. As the improvement in fatigue life is a consequence of the compressive stress field induced by shot peening, it was expected to find an increase in fatigue life with a greater CRSF [17,23]. However, the correlation between CRSF parameters and fatigue life improvement was not clear. For the 0.0141 A condition, a lower residual stress value on the surface did not correspond to the lower fatigue life. On the other hand, for this condition the largest depth and width of the CRSF also did not correspond to the largest fatigue life. Other examples can be given by observing results for the 0.0063 and 0.0083 A conditions. In both cases, the best fatigue strength compared to the other peened conditions was obtained in medium and high fatigue cycles, but its depth and width had intermediate values in the CRSF curves. This demonstrates that the fatigue behavior in the material studied due to the shot peening treatment is more complex than the single study of the CRSF induced by it. To have a better understanding of this issue, fracture surface analyses of the shot peened and unpeened specimens were performed, to identify the positions of fatigue crack sources.

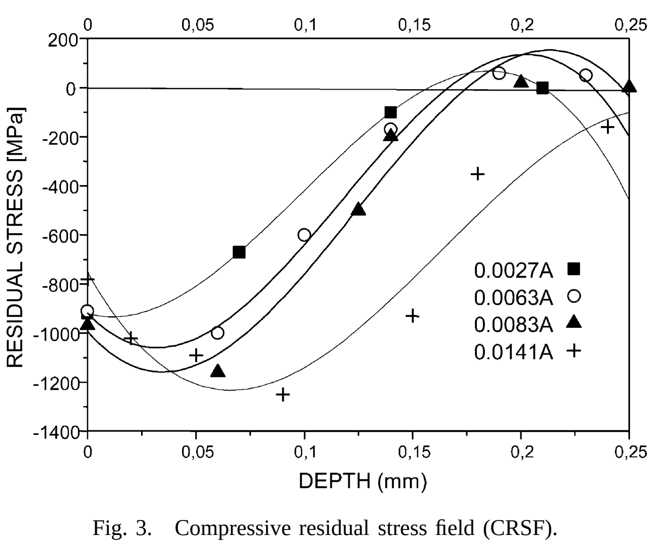

Fig. 3. Compressive residual stress field (CRSF).

3.3. Crack initiation points

From Figs. 4–12 several typical micrographics found are shown. In Figs. 4 and 5 the crack sources are noticed beneath the surface, showing clearly the influence of CRSF. They show that many times the point of crack initiation is well defined (Fig. 5) and many times it is not

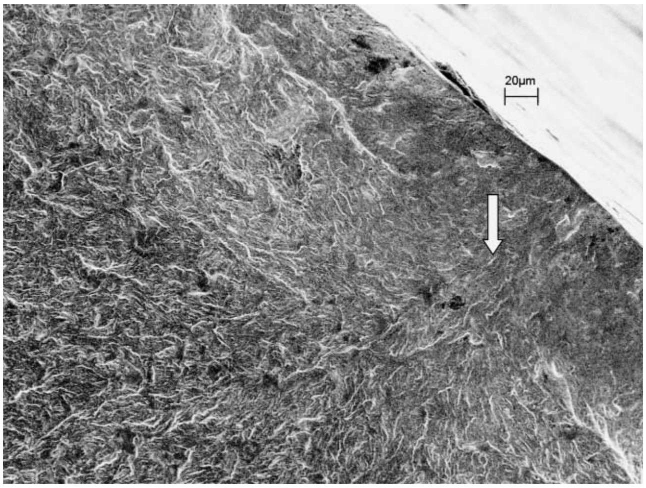

Fig. 4. Fatigue fracture surface of specimen 7D (Table 1).

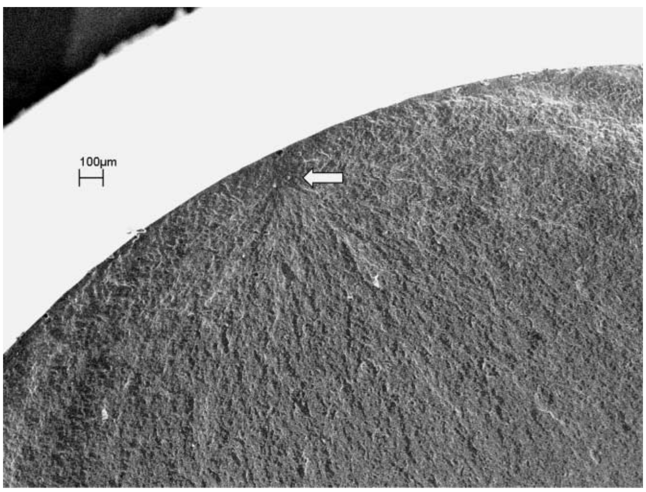

Fig. 5. Fatigue fracture surface of specimen 9D (Table 1).

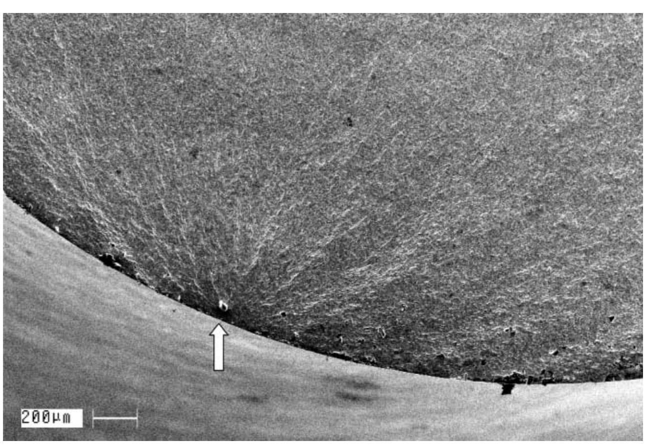

Fig. 6. Fatigue fracture surface of specimen 9B (Table 1).

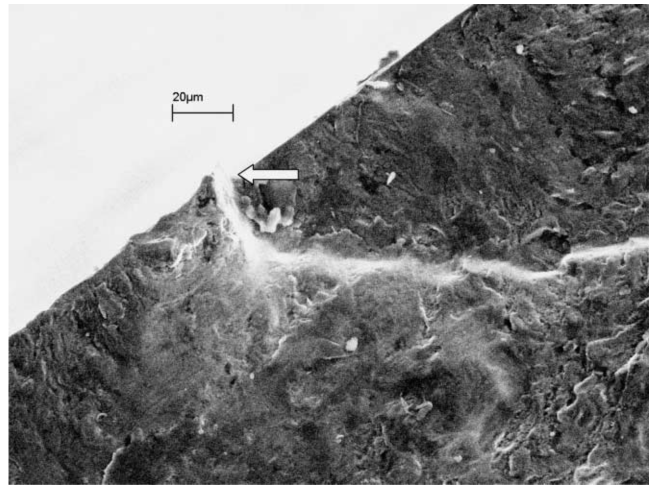

Fig. 7. Fatigue fracture surface of specimen 12E (Table 1).

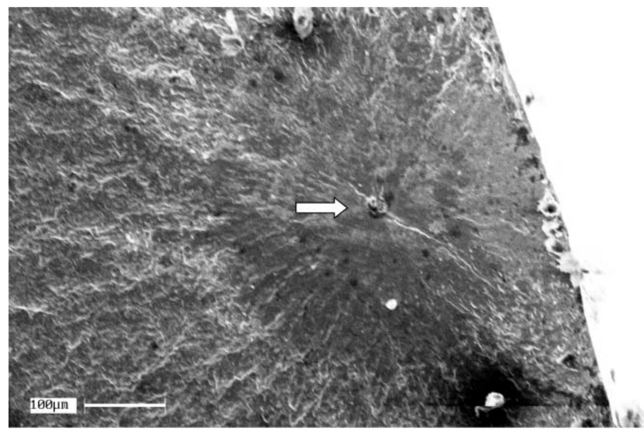

Fig. 8. Fatigue fracture surface of specimen 8C (Table 1).

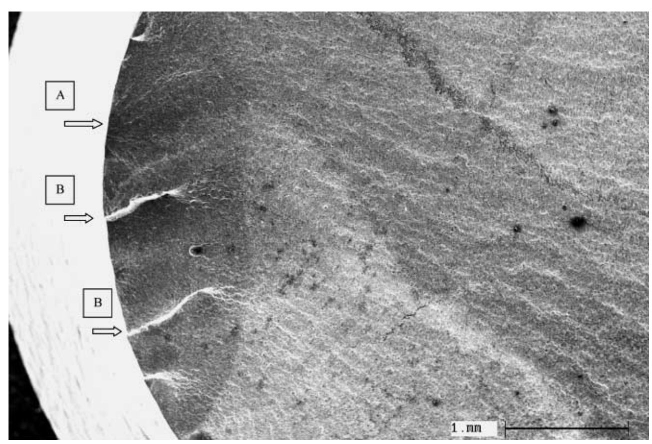

Fig. 9. Fatigue fracture surface of specimen 2E (Table 1).

(Fig. 4). Since the CRSF is bigger in the initial layers, it is expected that the crack source takes place at a distance from the surface where the applied tension stress would be able to supplant the compressive stress effect created by shot peening. Fig. 6 illustrates a case in which the

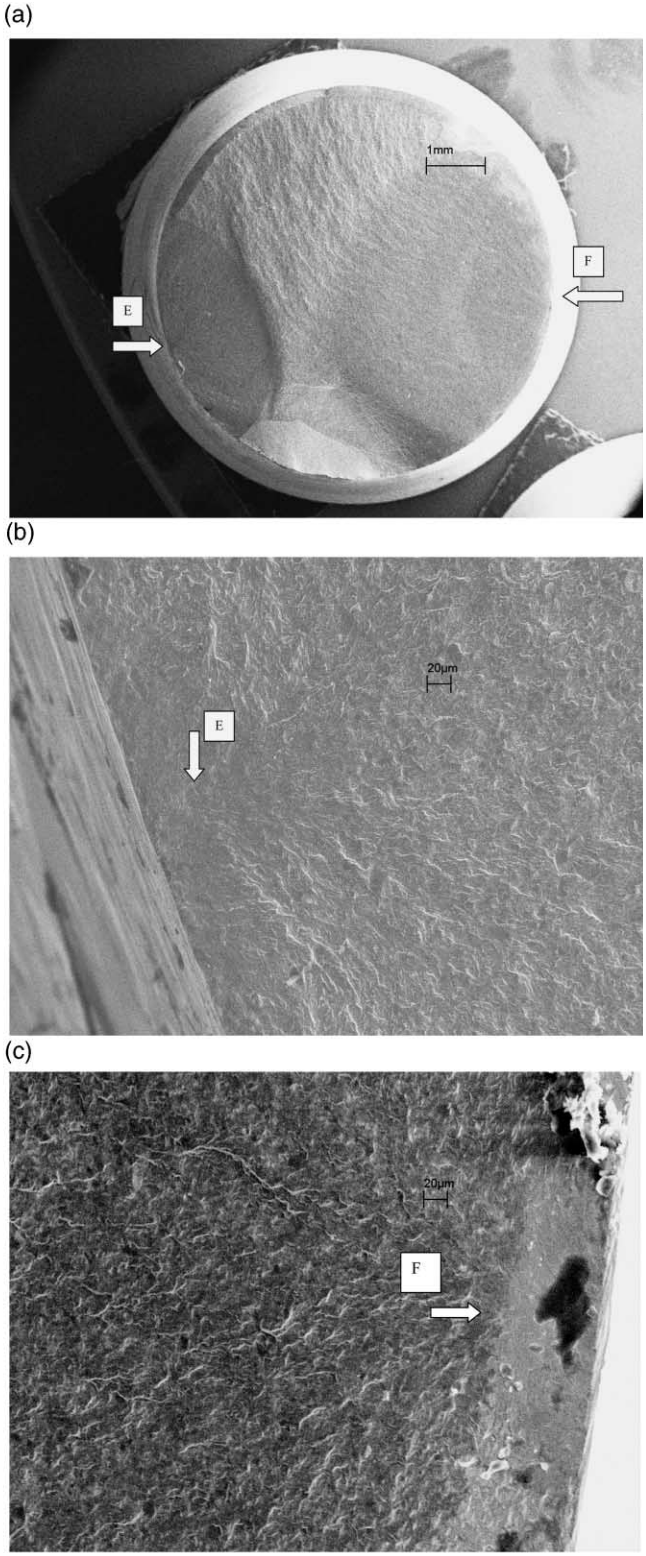

Fig. 10. (a) An overview of the fatigue fracture surface of specimen 5D (Table 1); (b) part E-detail; (c) part F-detail.

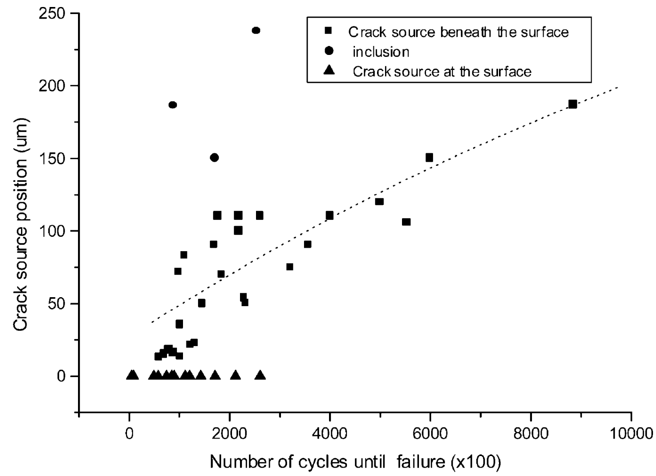

Fig. 11. Crack source position versus number of cycle until failure.

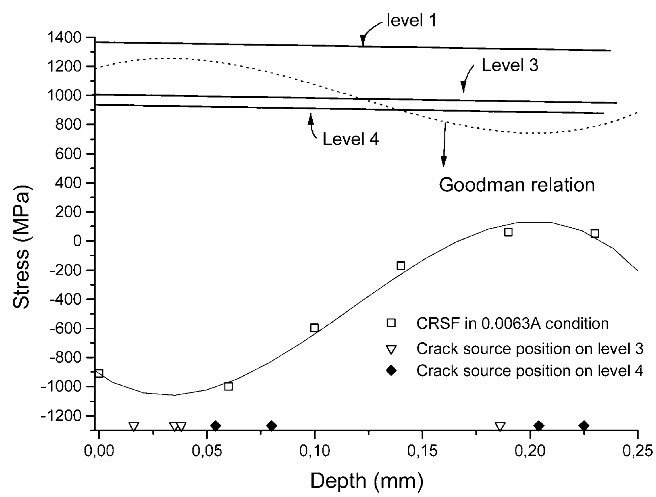

Fig. 12. Analysis of stresses existing versus cracks sources position.

crack originated from the surface. All the specimens with shot peening in low cycle fatigue (level 1, Fig. 2) or without shot peening had their cracks originated from the surface. This fact can be explained since the high applied tension stresses always surpass the CRSF in cases of low cycle condition. In specimens without shot peening it is natural that the crack source comes from the surface, where the maximum tension stress occurs, induced by the test characteristics. Nevertheless, some fracture situations in stress levels 3 and 4 (Fig. 2), with shot peened specimens, also had their crack initiation points at the surface. It was interesting to observe, however, that there was a consistent gain in fatigue life in relation to the base material. Another remarkable event was the appearance of cracks at the surfaces caused by a clear defect in the surface, although these cases were significantly less frequent (Fig. 7). The appearance of cracks from surface texture shows that stress concentrations at the surface can superimpose with residual stresses created by the shot peening treatment. Another important root for the stress concentrations are the inclusions. Fig. 8 clearly shows the crack source from the inclusion below the surface. Fig. 9 shows a specimen with several crack initiation points. The start of the propagation point was point A, but other sources occurred nearby and are shown by letter B. These cases happened in the greatest stress level analyzed (level 1) in which, apparently, there was no influence from the CRSF. Finally in Fig. 10(a), another typical case of crack source, in which two different propagation fronts can be found, E and F, both with their crack initiation points below the surface (Fig. 10(b) and (c)). This is justified by the bending fatigue test performed. A summary of this discussion can be seen in Fig. 11. The square points, independently from the shot peening condition, show the position of the crack source versus the number of fatigue cycles until failure. A tendency can be observed: the greater the depth of the crack source, the greater the numbers of cycles until failure. The dotted line in the graph is used to show this tendency. The triangular points show the number of fatigue cycles when the crack sources originate at the surface. In some of these cases the number of cycles until failure was the same of those, in which the crack initiation points were originated beneath the surface. The circular points shown in the figure are not in agreement with the square points; they represent the crack sources that were originated from inclusions. The inclusions superpose the existing stress state anticipating the crack nucleation and consequently decreasing the fatigue life. It is possible to find in the square and triangular points the same number of fatigue cycles until failure with crack source from the surface and beneath it. It is possible to speculate about the influence of two different mechanisms acting simultaneously. In the first, the CRSF pushes the crack source under the material surface and in the second the CRSF delays the crack propagation until failure, when the crack source is at the surface. Back to Fig. 2, some analyses can be done: (a) for low cycle condition (level 1) all the cracks were originated from the surface. The slight increase in fatigue life observed for the lower peening intensity condition (0.0027 A) can be due to better target conditions, caused by a less intense shot peening process; (b) for the medium and high cycle condition, apparently the two mechanisms described are acting simultaneously. The combination of these two mechanisms can help to explain the best performance in intermediate shot peening conditions (0.0063 and 0.0083 A) in relation to fatigue life.

3.4. Relation between crack source and local stress

A more detailed analysis was done for the stress levels 3 and 4 (1007, 931 MPa) in which fatigue life showed a significant improvement, and level 1 (1370 MPa) as a comparative parameter. The results are presented in Table 1. On the left-hand side of the table, the peening conditions used in this study can be seen. On the first horizontal line, the levels of applied stress in the fatigue tests are shown. The first column represents each analyzed sample; the second has the number of cycles until failure; the third shows the distance value of the crack source from the surface; the fourth shows the fatigue strength for each mean stress (in this case the mean stress is the compressive residual stress) calculated from the well-known Goodman relation in each point of crack source. The value shown for the base material (800 MPa) is the fatigue limit found for the AISI 4340 (53HRc), free of residual stress. It can be observed at level 1 that all the crack sources came from the surface. However, at levels 3 and 4 several crack sources were originated beneath the surface as a consequence of the shot peening treatment. For the base material condition, as mentioned before, all the crack sources came from the surface. The 0.0063 and 0.0083 A conditions showed the best fatigue life results, and in both these conditions most of the crack sources were beneath the surface. The 8C and 11E were specimens in which the crack sources came from the inclusions. In specimen 12E the crack was clearly created due to defect on the surface. In this last situation a smaller number of cycles until failure could be seen compared to the 10E specimen. It was observed in Table 1 that fatigue strength from the Goodman relation at level 1, for all the peening intensities, were smaller than the applied alternating stress (1370 MPa). At levels 3 and 4, however, the applied alternating stresses (1007 and 931 MPa), were smaller than the fatigue strength for practically all the specimens. Fig. 12 illustrates this observation for the 0.0063 A condition. The squares in Fig. 12 show the distribution of the induced original residual stress by the shot peening. The straight lines correspond to the applied alternating stresses by fatigue tests at all levels considered in Table 1 (1, 3 and 4). It is possible to notice that the fatigue strengths estimated by the Goodman relation were bigger than the applied stresses from the surface up to approximately a depth of 120 μm for level 3 and from the surface up to approximately a depth of 140 μm for level 4. The diamond points over the abscissa represent the position of crack sources for level 4 (12C, 11C, 10C, 9C) and the triangles represent them for level 3 (7C, 6C, 5C and 8C). Observing Fig. 12 and Table 1 it can be verified in 9C and 10C specimens that the crack sources occurred in the position where the applied stresses surpass the fatigue strength. For specimens 11C and 12C, however, it did not occur. For level 3 the situation of 11C and 12C was repeated for specimens 5C, 6C and 7C. It is important to recall that in specimen 8C the crack source came from an inclusion, which is an unusual situation. When the crack source is at the surface, it is reasonable to suppose that possible stress concentrations at the surface, would enable the crack initiation to occur with a stress smaller

Table 1
Summary of experimental results

Level 1: 1370 MPa				Level 3: 1007 MPa				Level 4: 931 MPa			
S	Nf ($\times 10^2$)	CS (μm)	FS (MPa)	S	Nf ($\times 10^2$)	CS (μm)	FS (MPa)	S	Nf ($\times 10^2$)	CS (μm)	FS (MPa)
Base											
1A	67	0	800	5A	452	0	800	9A	1225	0	800
2A	59	0	800	6A	419	0	800	10A	980	0	800
3A	59	0	800	7A	360	0	800	11A	703	0	800
4A	56	0	800	8A	353	0	800	12A	624	0	800
Average	60	SD=5		Average	396	SD=48		Average	883	SD=274	
0.0027 A											
1B	125	0	1194	5B	1457	50	1152	9B	2117	0	1194
2B	112	0	1194	6B	1111	0	1195	10B	1307	23	1198
3B	100	0	1194	7B	892	0	1195	11B	1201	0	1194
4B	91	0	1194	8B	578	0	1195	12B	1013	14	1202
Average	107	SD=15		Average	1010	SD=370		Average	1410	SD=487	
0.0063 A											
1C	100	0	1193	5C	1097	38	1257	9C	19602	225	794
2C	92	0	1193	6C	1014	35	1258	10C	9048	204	762
3C	75	0	1193	7C	875	16	1242	11C	3567	80	1163
4C	46	0	1193	8C	869	186	775	12C	2295	54	1237
Average	78	SD=24		Average	964	SD=111		Average	8628	SD=7881	
0.0083 A											
1D	101	0	1225	5D	1848	70	1247	9D	5529	105	1114
2D	100	0	1225	6D	1425	20	1287	10D	1697	90	1177
3D	86	0	1225	7D	986	72	1241	11D	1224	22	1289
4D	42	0	1225	8D	590	13	1272	12D	1115	0	1225
Average	82	SD=28		Average	1212	SD=544		average	2391	SD=2107	
0.0141 A											
1E	86	0	1121	5E	1202	0	1121	9E	2320	50	1323
2E	85	0	1121	6E	743	0	1121	10E	2097	0	1121
3E	82	0	1121	7E	741	0	1121	11E	1707	150	1149
4E	47	0	1121	8E	681	15	1212	12E	485	0	1121
Average	75	SD=19		Average	842	SD=242		Average	1652	SD=818	

S= Specimens; Nf= Number of cycles until failure; CS= Distance of crack source from the surface; FS= Fatigue strength by the Goodman relation; SD= Standard deviation of fatigue date life.

than the fatigue strength estimated by the Goodman relation. However, when the crack source occurs below the surface, it is likely that the crack initiation point takes place where the fatigue strength was smaller than the applied stress. This happened with the specimens 9C and 10C, but both were exceptions for levels 3 and 4. The results above motivated the following analyses.

3.5. Relaxation of CRSF

For the study of the reported situation, additional tests were performed to verify the possible variation of the residual stresses induced by shot peening under cyclic loading. One possible relaxation of the CRSF, as found by Kodama [16], could decrease the fatigue strength estimated by the Goodman relation. The shot peened specimens were again subjected to cyclic loading and removed from the rotating bending machine before failure occurred, and then, new CRSF was measured. For each stress level and each number of cycles analyzed, one different specimen was used. The first test was carried out in a 0.0141 A condition which was the greatest CRSF measured, at levels 2, 4 and 5 as indicated in Fig. 2. For level 2, shot peened samples underwent 10^3 and 10^4 cycles. For level 4 the tests were carried out at 10^4 and 10^5 cycles and for level 5 at 10^7 cycles. These numbers of cycles were smaller than the ones expected in fatigue failure. All the residual stresses were measured at the surface and at 0.05, 0.10 and 0.15 mm depths. The test results are shown in Figs. 13–15. In Fig. 13 the results for level 4 can be found. It is possible to observe a great variation between the original CRSF and the fields measured at 10^4 and 10^5 cycles. In spite of not having a significant change in the surface stresses at level 4, a decrease is observed in the stresses beneath the surface with the increase of the number of cycles. Fig. 14 shows the residual stress at level 2 with interrupted fatigue test in 10^3 and 10^4 cycles. In this situation,

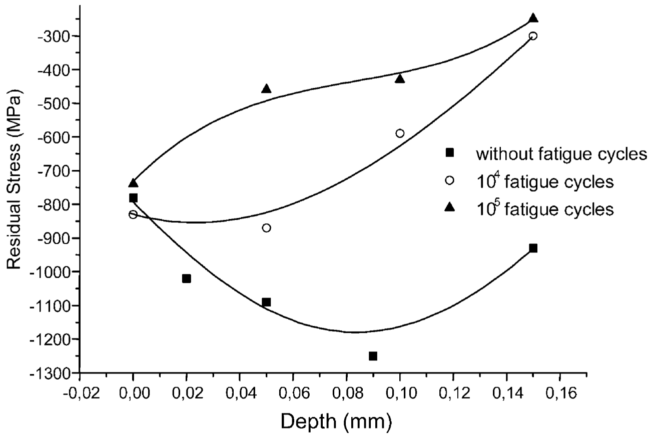

Fig. 13. Relaxation stresses in 0.0141 A condition on level 4.

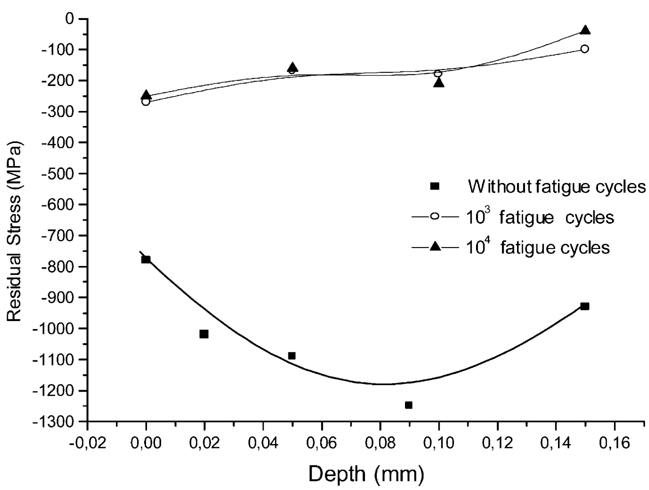

Fig. 14. Relaxation stresses in 0.0141 A condition on level 2.

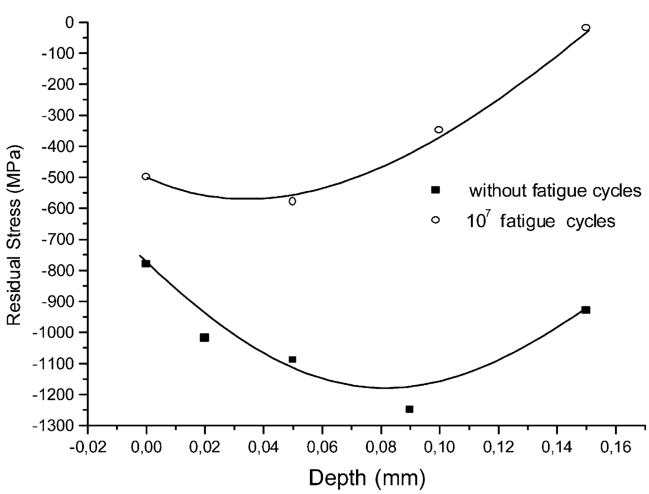

Fig. 15. Relaxation stresses in 0.0141 A condition on level 5.

the variation occurred both at the surface and beneath it. Another important observation was that the stress had no difference between 10^3 and 10^4 cycles, suggesting stabilization. It is important to notice that the CRSF relaxation was greater at level 2 (1130 MPa) than at level 4 both at 10^4 cycle condition and demonstrates that the greater the applied tension, the greater the relaxation stress. Fig. 15 shows the relaxation stress that occurred at level 5 (840 MPa), which is a stress level lower than the fatigue limit, of the shot peening conditions (Fig. 2). A great relaxation in the residual stress was also noticed here, both at the surface and beneath it, when compared to the original stress field. The situation represented in Figs. 14 and 15 are supposed to be the limit conditions for the stress relaxation within the project parameters. The first situation (Fig. 14) due to high stress level applied, and the second (Fig. 15) due to the high number of cycles. By adding compressive stress of the cycle loading to the CRSF at the surface, the results are very close, 1380 ± 20 MPa (-1130 and -250 MPa) and 1340 ± 20 MPa (-840 and -500 MPa). This stress relaxation is justified when in the rotate bending fatigue test the compressive stress applied is added to the local compressive residual stress induced by shot peening. If the result of this superposition is big enough, there will be a plastic deformation and consequently a rearrangement of the stresses, causing relaxation of the original CRSF. With the continuity of the tests, due to the stress relaxation, the algebraic addition of the stresses will decrease. At a certain time, it is possible that the superposition of the stress stays below the cyclic yield strength, so the CRSF can become stable. Other measurements were carried out for the 0.0083 A (Fig. 16) and 0.0063 A (Fig. 17), which both had the best fatigue life result. They were also done at level 4 with 10^4 and 10^5 cycles, in which the greatest dispersion and gains in fatigue life could be observed (Table 1). Analyzing Fig. 16, the existence of a progressive relaxation is noted. In this case the stresses on the surface decreased with the fatigue loading and kept themselves at approximately

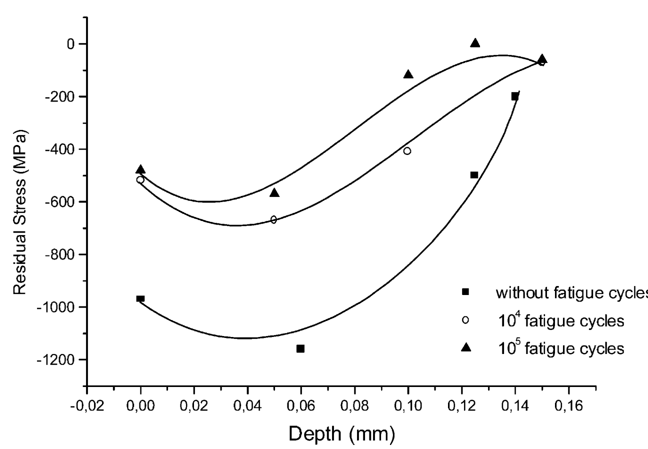

Fig. 16. Relaxation stresses in 0.0083 A condition on level 4.

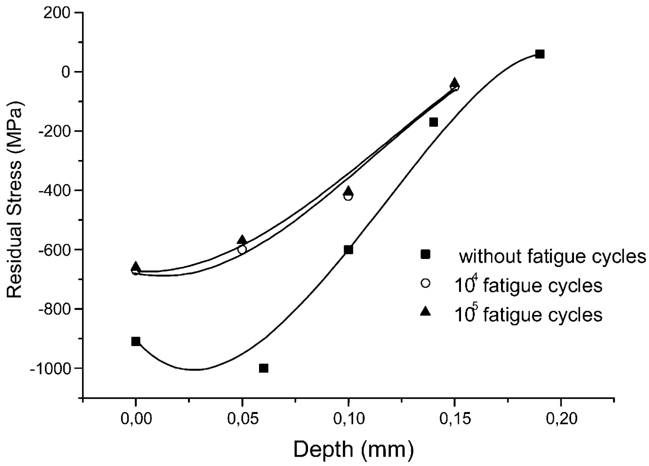

Fig. 17. Relaxation stresses in 0.0063 A condition on level 4.

−500 MPa both for 10^4 and 10^5 cycles. The decrease in the CRSF with the applied cyclic loading was observed, as in the previous conditions, also at 0.0063 A. Table 2 shows a comparison of the CRSF values in the 0.0063, 0.0083 and 0.0141 A conditions with 10^5 cycles in which the dispersion of results was the greatest. Comparing the 0.0063 and 0.0083 A it is noted that the stress relaxation was smaller in the 0.0063 A condition and this can explain the best performance in fatigue life. However, if the 0.0141 A condition is examined in Table 2, it can be noted by the stress values that a better or equal performance would be expected in fatigue life in relation to 0.0063 A condition. Yet, it did not happen. Observing Table 1 it can be seen that almost all the cracks at 0.0141 A were originated from the surface (11E was from an inclusion), due to surface texture created by the biggest shot peening intensities. It was demonstrated that better fatigue life results are achieved when the crack initiation points are beneath the surface. For the 0.0063 A condition all the cracks were originated below the surface.

4. Conclusions

An increase in shot peening intensity resulted in an increase in the maximum compressive residual stress and the width of the CRSF. However, the surface residual stress was nearly independent of the peening conditions.

An increase in the shot peening intensity, and consequently, the increase of the original CRSF size, does not necessarily increase the fatigue life of AISI 4340 steel with 53HRC hardness.

The shot peening treatment pushes the crack sources beneath the surface in most of medium and high cycle cases due to the CRSF induced. All the specimens with shot peening in low cycle or without shot peening had their cracks originated from the surface. Some correlation between gain in fatigue life and crack initiation point below the surface was demonstrated.

The CRSF enables a better fatigue life for AISI 4340 steel. However, the CRSF suffers a decrease in the stress absolute value during the fatigue process in rotating bending tests. This stress relaxation is directly related to the applied stress and the number of fatigue cycles to which the specimens were subjected.

It is very complex to determine the best shot peening condition to increase the fatigue strength, because it depends on many variables. It was demonstrated here that the shot peening intensity that produces best results in fatigue life is influenced by several factors: relaxation of induced compressive stresses during the fatigue process; surface conditions created by shot peening; and the possibility of the CRSF to push the crack source beneath the surface.

Table 2
Residual stress values for 10^5 cycles at 0.0063, 0.0083 and 0.0141 A peening conditions

	Depth			
Peening intensities (A)	0	0.05 (mm)	0.10 (mm)	0.15 (mm)
0.0063	−660 MPa	−600 MPa	−420 MPa	−40 MPa
0.0083	−480 MPa	−570 MPa	−120 MPa	−60 MPa
0.0141	−870 MPa	−460 MPa	−430 MPa	−250 MPa

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