Fatigue Fract. Engng Mater. Struct. Vol. 18, No. 2, pp. 211–220, 1995


8756-758X/95 $6.00+0.00


# EFFECT OF SHOT PEENING ON RESIDUAL STRESS AND FATIGUE LIFE OF A SPRING STEEL

G. H. Farrahi*[1], J. L. Lebrun[2] and D. Couratin[3]

[1]Faculty of Engineering, Bu- Ali Sina University, Hamadan 65174, Iran

[2]École Nationale Supérieure d'Arts et Métiers (ENSAM) 151, Bd de l'Hôpital, 75013 Paris, France

[3]Renault S.A., 8–10 Avenue Emile Zola, 92109 Boulogne-Billancourt, France

*Received in final form 28 October 1994*

**Abstract**—This study describes shot peening effects such as shot hardness, shot size and shot projection pressure, on the residual stress distribution and fatigue life in reversed torsion of a 60SC7 spring steel. There appears to be a correlation between the fatigue strength and the area under the residual stress distribution curve. The biggest shot shows the best fatigue life improvement. However, for a shorter time of shot peening, small hard shot showed the best performance. Moreover, the superficial residual stresses and the amount of work hardening (characterised by the width of the X-ray diffraction line) do not remain stable during fatigue cycling. Indeed they decrease and their reduction rate is a function of the cyclic stress level and an inverse function of the depth of the plastically deformed surface layer.

## INTRODUCTION

Shot peening is a widely used method for improving the fatigue life and stress corrosion resistance of components. The process involves the firing of hard steel balls under controlled velocity on to the critical zone of the surface of the component. The improvement in fatigue behaviour of the component is usually a consequence of (i) the strain hardening of surface layers which increases the yield stress of the material, (ii) the compressive residual stresses in surface layers induced by the shot peening, and (iii) the final surface finish quality and structural changes. The effect of these factors varies with the original structure, with the strengthening method (for example, the modification to the surface finish can have a detrimental effect), with strength or hardness of the material, with the geometry of the workpiece and with the applied stress. The quality and effectiveness of peening depends on several parameters, amongst these are the following: type and size of shots, shot peening intensity, surface coverage (shot peening time), and the properties of the material.

It is very helpful to know the magnitude and distribution of residual stresses and also to know the effect of shot peening parameters on the stress magnitude and distribution. It is also interesting to know the peening conditions for obtaining the optimum residual stress distribution in relation, for instance, to fatigue behaviour. In addition to the beneficial effects of shot peening, there is another effect which could have an undesirable consequence: the surface of the component becomes slightly dimpled due to plastic flow. This causes an increase in surface roughness. The influence of surface roughness due to shot peening has been investigated by Ypsilantis *et al.* [1], who carried out fatigue tests on peened specimens under the same conditions except that one was emery polished after shot peening. Taking into consideration the removal of a peened layer by polishing, the fatigue life was modified by polishing. After a shot peening of 10C intensity, a

*Previously a Senior Research Fellow, SIRIUS, University of Sheffield, U.K.

further specimen underwent a second peening of a lower intensity of 14A. Residual stresses on the surface and depth had a negligible increase which can not be taken into consideration for fatigue strength. The surface roughness was improved. It was better than 10C's but not better than 14A's. The fatigue life due to this double peening was three times better than from 10C shot peening. It must be mentioned that residual stresses are greater and the plastically deformed layer is deeper in 10C peening in comparison with 14A peening. Hence, the fatigue life improvement in 10C is better than in 14A. Therefore the difference between 10C peening and double peening is the surface roughness and the fatigue life improvement can be attributed to a better surface roughness [1].

A number of characteristics which are often found in residual stress distributions after shot peening can be pointed out; namely (i) the maximum magnitude of compressive residual stresses appears at a distinct distance below the surface, (ii) the depth of the maximum magnitude of residual stresses increases with an increasing shot intensity produced either with a large shot diameter or an enhanced shot velocity (or projection pressure), or a higher coverage, and (iii) an enhanced shot velocity together with a higher coverage also raise the maximum magnitude of residual stresses.

As a general rule, small shots, produce lower Almen intensity and a shallower depth of plastic deformation. Surface residual stress increases with shot peening time and approaches a saturated value before full coverage time. Iida and Tosha [2] showed that the value of surface stress is not so affected with the kinetic energy of the shots. Robertson [3] also found that the residual stresses resulting from four different shot sizes were not greatly different. However, the maximum stress occurred at a lower subsurface level as the shot size increased. Coombs [4] found a linear relationship between the depth at which maximum residual stress occurred and the shot size for a spring steel of 531 HV. On aluminium parts, large shot produces a greater effect than small shot at the same Almen intensity [5]. Several authors have shown that shot peening improved the fatigue strength but shot size had little effect on the extent of the endurance limit. However, a smaller shot size showed better improvements on the fatigue life of a spring steel [6]. Lepand [7] obtained a higher residual stress for harder shot. He found that over-peening caused a reduction in the endurance limit and that reduction was greater for harder shots. He also shot peened a chromium steel with a 0.9 mm shot for different hardnesses of 360, 460, and 640 HV. The results showed that the surface roughness increases with increasing shot hardness and coverage. On harder steel, for instance, shot of greater hardness produces more fatigue improvement than softer shot even when both produce the same intensity measured by the Almen strip [5]. Mattson [8] showed that once saturation (100% coverage) is reached, further projection did not have any important effect on fatigue life. Residual stress behaviour during fatigue has attracted the attention of many researchers. A number of combinations of load and material have been investigated and some relaxation models have been put forward. James [9] proposed a model for relaxation based on an effective shear stress acting on primary slip planes oriented at an angle to the surface. Nevertheless, more knowledge is required to understand the mechanisms of relaxation and to acquire data on materials for design use and predictive models. Kodama [10] found the residual stress relaxation of an annealed mild steel varied linearly with the logarithm of the fatigue cycles while the relaxation rate was proportional to the stress amplitude. Castex [11] found that Kodama's observation was true only when the applied stress was higher than the endurance limit. When the applied stress was lower than the endurance limit, the residual stress remained unchanged for as long as $10^5$ cycles. After that it dropped rapidly. The present study examines the influence of shot size, projection pressure and shot peening time on the distribution of residual stresses and therefore on the fatigue life of a silicon–manganese steel.

## EXPERIMENTAL DETAILS

This study was performed on an AFNOR 60SC7 spring steel of composition (wt.%) 0.62 C, 1.75 Si, 0.66 Mn, 0.31 Cr, 0.11 Ni, 0.04 Mo, 0.18 Cu, 0.011 S, 0.012 P and remainder Fe. Specimens were tempered at 643 K for 1 h after quenching in oil from their austenitized temperature at 1123 K. After this heat treatment the specimens had a hardness of 52 HRc, a 0.2% offset yield strength of 1620 MPa and an ultimate tensile strength of 1900 MPa. Two sets of specimens were used. One set, called "shot peened specimens", was made from 18.5 mm diameter bar. These specimens were used for residual stress measurements after having been peened. Another set of specimens, called "fatigue specimen" was used for torsion fatigue tests. They were smooth, hour-glass shaped specimens with a gauge diameter of 0.8 mm and shot peened under the same conditions as the corresponding shot peened specimens. Fatigue tests were carried out on a Schenck torsion testing machine ($R = -1$).

The characteristics of the four cast steel shots employed in this study are presented in Table 1. We had intended to investigate the effects of four different shots with a combination of two hardnesses and two shot sizes. According to the specifications provided, the diameters of shots were 0.5 to 0.7 and 0.315 to 0.4 mm and also two different hardness values of each of the two shot size groups. SEM observations of shots for controlling their state and quality after having been fired at the specimens, showed that shot sizes were different from those that had been specified. This was unfortunate, because it makes it more difficult to interpret the conclusions related to shot size. Hence, the shot diameters stated in Table 1 are the measured values from the SEM observation. For residual stress measurements the X-ray method was employed. The broadening of the diffraction peak can be analysed in terms of micro-strain. We measured the width of the diffraction line at 0.4 of the height of the diffraction peak and this parameter may be used to characterise the micro-strain and the plastic deformation. Residual stresses were determined on shot peened specimens with a SIEMENS X-ray stress measurement apparatus equipped with a scintillation detector using a PDP computer. Stress measurements on fatigue specimens were carried out on an automated goniometer equipped with a linear detector using a computer. Chromium radiation ($\lambda_{K\alpha} = 0.22895$ nm; 35 kV, 22 mA) using a Vanadium filter was used to examine the {211} peak ($2\Theta = 156°$). The irradiated spot on the specimens was 1 mm in diameter. In order to determine the stress distribution by depth, the surface layer of specimens was progressively removed by electrolytic polishing. The surface roughness was measured by a profilometer. The impact size on the specimen was measured from SEM micrographs. We measured the hardness of the shots by a micro-hardness tester. Almen test strip type A (SAE 1070, 44 HRc) was employed for measuring shot peening intensity.

Table 1. Characteristics of shots and shot peening intensities

| Shot no | Shot diameter mm | Shot hardness Hv | Almen intensity C3 | C6 | L3 | L6 |
|---|---|---|---|---|---|---|
| 1 | 0.7-0.9 | 580 | 6A | 10A | 12A | 22A |
| 2 | 0.4-0.6 | 966 | 5A | 10A | 9A | 13A |
| 3 | 0.5-0.7 | 580 | 4A | 9A | 10A | 16A |
| 4 | 0.3-.04 | 966 | 4A | 8A | 6A | 12A |

Table 2. Details of different conditions of shot peening

| Condition | Peening time seconds | Projection pressure Kg/Cm$^2$ |
|---|---|---|
| L6 | 30 | 6 |
| L3 | 30 | 3 |
| C6 | 2.5 | 6 |
| C3 | 2.5 | 3 |

## RESULTS AND DISCUSSION

Figure 1 shows shot peening intensity curves for the shots described in Table 1 under thr different air projection pressures (3, 4.5 and 6 bar). The results show that Almen intensity, expected, is higher for the bigger shot and also for the higher pressure of projection. However, t time necessary for saturation was longer for the bigger shot. In our case, comparing the four sho revealed that the effect of shot hardness in comparison with the effect of shot size was negligib For the following tests, we set two shot peening times; one short time of 2.5 s (shown C) and longer time of 30 s (shown L). The shot peening time for the cylindrical samples, correspondir to the above two times was calculated as a function of their rotation under the jet. We also ke the 3 and 6 bar pressure samples for the following tests. Thus, the shots are marked by numbe 1, 2, 3 and 4, shot peening time by C or L and the projection pressure by 3 or 6 (see Table 2 Because it was intended to study only the effect of shot peening, the layer affected by heat treatmer on cylindrical specimens was removed by chemical milling. The reduction in the width of th diffraction line confirmed the effectiveness of this operation. After shot peening, residual stres distribution on the surface and in depth was determined. Figure 2 and Table 3 show the result obtained for the four shots. The residual stress distribution profiles show that: (i) the residua stresses on the surface do not follow the same trend as the Almen intensity. In other words, highe Almen intensity does not correspond to higher residual stress, as can be seen from Tables 2 an 3. One reason may be because the Almen test strip and the shot peened specimens are fron different materials with different hardness and different properties. (ii) The plastically deforme surface layer, for the same coverage, is deeper for the biggest shot. (iii) The maximum residua stress increases with the shot peening intensity. For shot no. 4, the shot peening time is not a

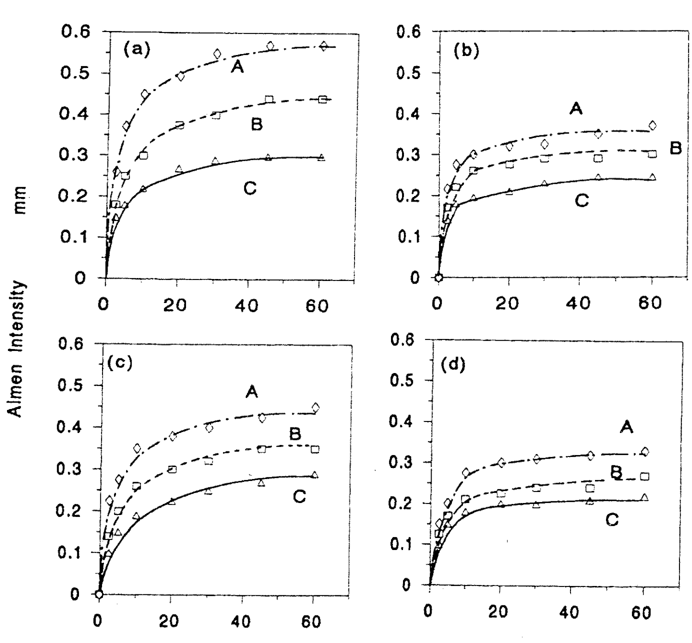


Fig. 1. Saturation curves of shot peening intensity for three different projection pressures. (A) 6 kg/cm$^2$, (B) 4.5 kg/cm$^2$, (C) 3 kg/cm$^2$; (a) shot no. 1; (b) shot no. 2; (c) shot no. 3; (d) shot no. 4 (details of shots given in Table 2).

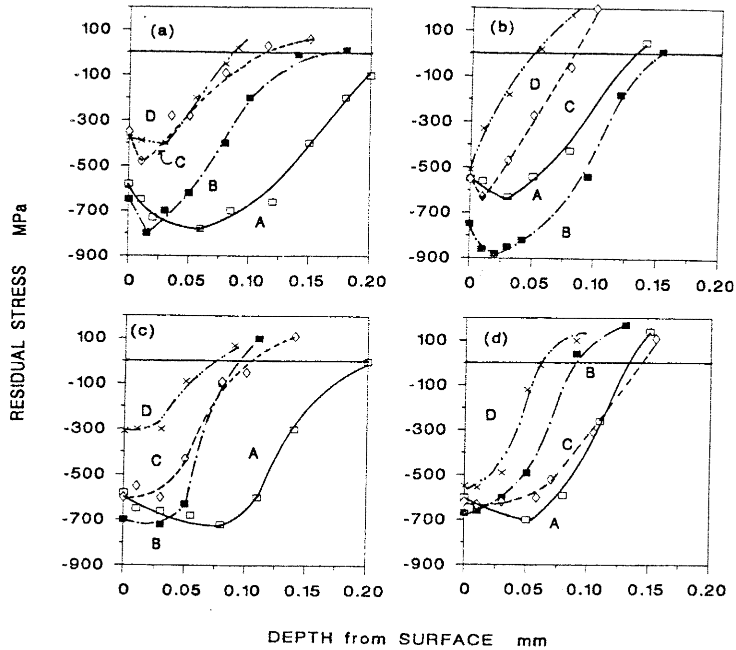


Fig. 2. Residual stress distribution in depth for different conditions of (A) L6, (B) L3, (C) C6, (D) C3 (see Table 1); (a) shot no. 1; (b) shot no. 2; (c) shot no. 3; (d) shot no. 4.

Table 3. Residual stress and depth of deformed layer for different shot peening conditions

| Shot no. | Depth at $\sigma_{max}$ μm | | | | Depth of deformed layer μm | | | | Maximum Residual Stress MPa | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C3 | C6 | L3 | L6 | C3 | C6 | L3 | L6 | C3 | C6 | L3 | L6 |
| 1 | 25 | 10 | 20 | 60 | 90 | 100 | 150 | 230 | -400 | -480 | -800 | -780 |
| 2 | 0 | 10 | 20 | 30 | 50 | 82 | 150 | 130 | -510 | -630 | -880 | -650 |
| 3 | 20 | 30 | 30 | 65 | 65 | 100 | 95 | 200 | -310 | -600 | -720 | -730 |
| 4 | 10 | 20 | 0 | 40 | 60 | 140 | 85 | 140 | -550 | -630 | -670 | -710 |

important parameter because the shot is small and full coverage (saturation) is reached immediately. The effect of hardness and shot size on the maximum residual stress can not be distinguished from our results. (iv) The depth at which the maximum residual stress occurs, increases with the shot peening time, the projection pressure and the shot size. Surprisingly, the shot hardness does not show any effect on our material, and (v) the above observation is true for the depth of the plastically deformed layer which increases with the shot peening time (coverage), projection pressure and shot size. Again the hardness seems less important. It can be observed that for shot no. 4, time is not important because as explained above, the saturation and full coverage are reached very quickly and further peening does not increase the depth of the affected layer. This was confirmed by electron microscopy observations.

Figure 3 shows the fatigue test results. For comparison purposes, the fatigue life at a stress amplitude of 750 MPa is given in Table 4. Shot no. 1, which is the biggest, shows the best fatigue life improvement. However, for a shorter time of shot peening, Shot no. 4 showed the best

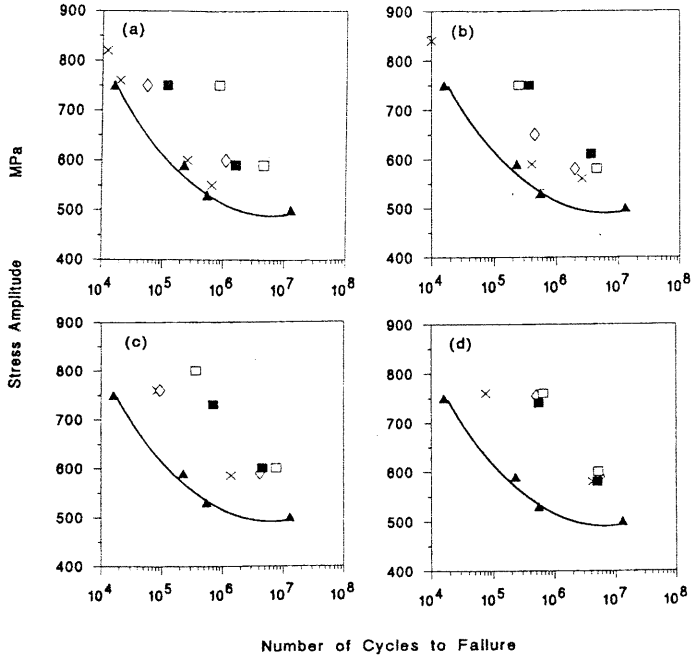


Fig. 3. Fatigue endurance results for different conditions of: × C3, ◇ C6, ■ L3, □ L6, ▲ plain specimen (see Table 1); (a) shot no. 1; (b) shot no. 2; (c) shot no. 3; (d) shot no. 4.

Table 4. Fatigue life and the area under the residual stress distribution curve for different shot peening conditions (plain specimen had a fatigue life of 16,000 cycles at a stress amplitude of 750 MPa)

| Shot no. | Area under residual stresses distribution curve N/mm | | | | Fatigue life at $\sigma_a$ = 750 MPa 1000 cycles | | | |
|---|---|---|---|---|---|---|---|---|
| | C3 | C6 | L3 | L6 | C3 | C6 | L3 | L6 |
| 1 | 22.5 | 25 | 58 | 116 | 20 | 60 | 120 | 850 |
| 2 | 11 | 31 | 58 | 54 | 35 | 150 | 360 | 250 |
| 3 | 13 | 36.5 | 47 | 96 | 85 | 95 | 550 | 720 |
| 4 | 23 | 39 | 62 | 71 | 75 | 500 | 450 | 650 |

Table 5. Surface roughness of L6 type specimen (plain specimen had a surface roughness $R_a$ of 0.

| Shot no. | Surface roughness Ra / µm | Impact size µm |
|---|---|---|
| 1 | 1.84 | 120-160 |
| 2 | 3.32 | 40-80 |
| 3 | 1.67 | 100-150 |
| 4 | 2.27 | 30-60 |

performance. Nevertheless, the micrograph of shots showed that hard shots are fragile and in order to eliminate the broken shots, continuous control is needed. From looking at the overall results it is impossible to find any clear relationship between the fatigue life and the maximum residual stress magnitudes or the depth of the maximum residual stresses. But it seems that a correlation can be found between the fatigue life and the area under the residual stress distribution curve (Fig. 4). One can see a similar trend in Fig. 5 which shows the fatigue life at a stress amplitude of 750 MPa versus the depth of the plastically deformed layer at a −400 MPa residual stress. The fatigue life improvement resulting from shot peening cannot be attributed to the maximum residual stress only, but also to the depth of the plastically deformed layer. The importance of these two parameters on the fatigue life improvement depends upon the material.

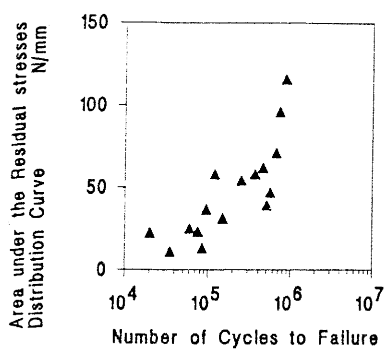


Fig. 4. Fatigue life versus the area under the residual stress distribution curve.

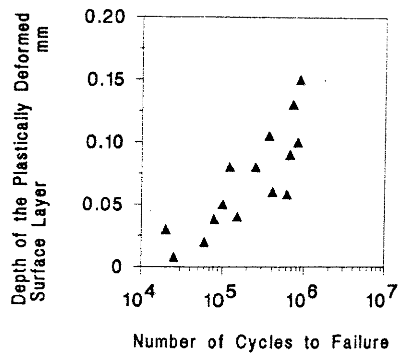


Fig. 5. Fatigue life for a 750 MPa stress amplitude versus the depth of the plastically deformed layer at a −400 MPa residual stress.

Shot peening has been found to remove all traces of the previous manufacturing operations [12]. It also modifies the surface roughness. Table 5 shows the surface roughness for L6 type specimens. Modifications in surface roughness is, therefore, a function of the hardness and the size of shots. However, hardness has clearly the dominant effect. The fatigue life of specimen 2L6, taking into consideration the area under the stress curve, was lower than expected. This reduction could be attributed to an undesirable surface roughness $R_a$ of 3.32.

For checking the stability of residual stresses and the micro-strain during the fatigue life, we selected three conditions of shot peening: 3L6, 2L3 and 1C3. The studies were carried out on two sets of specimens by imposing fatigue cycling at an amplitude of 600 MPa on one set of the specimens and at 750 MPa on the other set. Transferring the specimens, at intervals, from the fatigue testing machine to the X-ray diffractometer, we measured the residual stress and the width of the diffraction peak during fatigue cycling. The results are presented in Fig. 6. Residual stresses measured on the surface, showed a reduction during the life. An initial decrease in the compressive residual stress was noted after the first few cycles, whereafter it decreased continu-

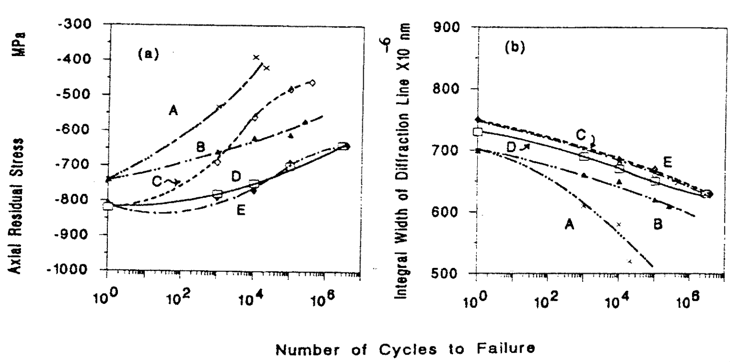


Fig. 6. Development of (a) residual stress; (b) width of the diffraction line (micro-strain) in the course of fatigue tests. (A) shot peened by shot no. 1 at C3 condition and stressed at 750 MPa, (B) the same conditions as above but stressed at 600 MPa, (C) shot peened by shot no. 2 at L3 condition and stressed at 750 MPa, (D) the same conditions as in (C) but stressed at 600 MPa, (E) shot peened by shot no. 3 at L6 condition and stressed at 600 MPa (see Table 1 for different conditions of shot peening).

ously throughout subsequent cycling. This reduction was quicker when the fatigue loading was higher. Nevertheless the residual stress and the width of the diffraction peak seemed more stable when the plastic layer was deep. However the residual stress remained compressive even after the fracture. Misumi [13] also showed that the compressive residual stresses at the surface went down to half of the initial value until $10^4$ cycles, after that a small decrease followed, but dropped rapidly before final failure.

Regarding the width of the diffraction line, which may be used to characterise the micro-strain, we noticed similar trends. The width reduced during fatigue; see Fig. 6(b), which shows softening of the material. It is known that the width of the diffraction line depends upon the microscopic residual stress and dislocation morphology. As we know, the heterogeneity of the substructure of low temperature martensite is rather high and there may exist microscopic residual stress peaks, so the width value is usually large. Cycling loading has, to some extent, relaxed local microstress peaks and reduced the width of the diffraction line. It has been seen that fatigue [14] and fretting [15] could cause a change in the width value of the diffraction line. The shot peening process also leads, in high strength steel, to recovery of the heavily distorted martensitic structure in the surface layers which is manifested by changes in the width of the diffraction peak [16,17].

Lemaitre's measurements [12] of residual stresses and the width of the diffraction peak on a high strength steel during fatigue tests showed that these parameters were stable after an initial plastic deformation that might occur during the first few cycles. Wohlfahrt [18] noticed that, for materials with great hardness, residual stresses remained unchanged during fatigue test unless the applied stress is very high. It seems there is a hardness value which defines three different behaviours regarding the width of the diffraction peak during fatigue tests, namely:

1. that for a given hardness value, the width of the diffraction line does not change;
2. lower than this hardness, the width of the diffraction line increases;
3. higher than this hardness, the width of the diffraction line decreases.

As explained previously, the improvement of fatigue strength after surface plastic deformation can be attributed to three fundamental factors: macroscopic residual stress, surface finish and structural changes. The effect of these factors depends on the original structure, the strengthening method and the applied stress. At higher residual values and deeper plastically deformed surface layers less attenuation of residual stress occurs during cyclic loading. Obviously, if the effect of structural changes is ignored, the effect of residual stress would be overestimated. Shot peening can cause structural damage in materials of low strength when the shot peening intensity is too high, but the compressive residual stresses overcome the harmful action caused by this damage [16].

We did not measure the crack lengths on our specimens. Therefore, we are not able to discuss the role of shot peening on crack initiation and crack propagation. But it is known that crack growth rate decreases because of the compressive residual stresses induced by shot peening [19,20]. In a study carried out by Berns and Weber [21] on low alloy high strength steel, all cracks started at the surface. Crack initiation is delayed by shot peening. However, the ratio of cycles to crack initiation and cycles to fracture, is reduced as the surface stresses by peening are raised. They noticed that stable crack growth is slowed down in the beginning and accelerates as the peened layer is surmounted. By shot peening the period of crack growth is prolonged more than the period of crack initiation. Misumi and Ohkubo [22] also showed that shot peening resulted in a deceleration of crack growth only when the crack was small and the crack grew faster than in unpeened specimens after a particular level of crack length.

## CONCLUSIONS

From this work, the following conclusions can be made:

1. Almen intensity, as expected, is higher both for the bigger shot and for the higher projection pressure. However, the time necessary for saturation to be achieved was longer for the bigger shot. Comparing the four shots revealed that the effect of shot hardness in comparison with the effect of shot size was negligible in the case reported in this paper.
2. Higher Almen intensity values did not correspond to higher residual stress values.
3. Shot peening time is not an important parameter in relation to the residual stress when the shot is small and full coverage (saturation) is reached immediately.
4. The depth of the plastically deformed layer and the depth of the maximum residual stress increase with shot peening time, projection pressure and the shot size. Surprisingly, shot hardness does not show any effect in our tests.
5. The biggest shot size shows the best fatigue life improvement. However, for a shorter time of shot peening the smallest shot size showed the best performance.
6. The 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. Hence, a correlation was found between the fatigue life and the area under the residual stress distribution curve.
7. Shot peening modifies the surface roughness. Modification of surface roughness is a function of the hardness and the size of shots. However, hardness has clearly the dominant effect.
8. Fatigue stressing produces a decrease in residual stresses and in micro-strain. This reduction is a function of the applied stress and the depth of the plastically deformed layer. Residual stress measured on the surface, showed a reduction during the life. This reduction was quicker when the fatigue loading was higher. Nevertheless both the residual stress and the width of the diffraction line seemed more stable when the plastic layer was deep. However, residual stress remained compressive even after final fracture. The width of the diffraction line, which was used to characterise the micro-strain, showed similar trends; the width reducing during fatigue. The width of the diffraction line depends upon the microscopic residual stress and the dislocation morphology. The heterogeneity of the martensite substructure is rather high and there may exist microscopic residual stress peaks, hence the width value is usually large. Cycling loading relaxed the local microstress peaks and lessened the width of the diffraction line.

*Acknowledgments*—The authors would like to thank Renault for its support for this program.

## REFERENCES

1. D. Ypsilantis, C. Mas and L. Castex (1984) Shot peening influence on the endurance limit in fatigue of the SAE9254 steel. *Conf. Groupement français pour l'analyse des contraintes par diffractometrie X*, Aix-en provence, France (in French), 159–183.
2. K. Iida and K. Tosha (1987) Behaviour of surface residual stress induced by shot peening. In: *Advances in Surface Treatments and Surface Finishing*, Vol. 3 (Edited by A. Niku-lari), Pergamon Press, Oxford. pp. 149–152.
3. G. T. Robertson (1971) *The effects of shot size on the residual stresses resulting from shot peening.* SAE 710284.
4. A. G. H. Coombs, F. Sherratt and J. A. Pope (1956) An analysis of the effects of shot-peening upon the fatigue strength of hardened and tempered spring steel. *Proc. Int. Conf. Fatigue of Metals*, Inst. Mech Engngrs, London. p. 227–234.
5. H. O. Fuchs (1957) *Shot peening effects and specifications in metals.* ASTM STP 196. pp. 22–32.
6. G. C. Bird and D. Saynor (1986) Effect of peening shot size on the performance of carbon steel spring. *Springs* **25**, 69–79.

7. H. Lepand (1965) Anderung des Dauerschwing-Verhaltens von Federstahl 50CrV4. Dissertation, Claus... University.
8. R. L. Mattson (1956) Fatigue, residual stresses and surface cold working. *Int. Conf. Fatigue of Me..* Inst. Mech. Engngrs., London. pp. 593–603.
9. M. R. James (1982) The relaxation of residual stresses during fatigue. In: *Residual Stress and St.. Relaxation.* Plenum Press.
10. J. Kodama (1971) The behaviour of the residual stress during fatigue stress cycles. *Int. Conf. Mechan... Behaviour of Materials*, Kyoto. pp. 111–118.
11. L. Castex (1982) Evolution of prestresses due to shot peening during an alternating torsion test. *C.. Groupement français pour l'analyse des contraintes par diffractometrie X*, Besancon, France (in Frenc.. 89–98.
12. R. Lemaitre and G. Maeder (1982) Role of shot peening in the manufacture of a torsion specimen.. variation of residual stresses in the course of dynamic tests. *Conf. Groupement français pour l'analyse de.. contraintes par diffractometrie X*, Besancon, France (in French), 113–126.
13. M. Misumi, T. Ohhashi and M. Ohkubo (1987) Effect of shot peening on surface crack propagation .. plane-bending fatigue. In: *Advances in Surface Treatments and Surface Finishing*, Vol. 3 (Edited b.. A. Niku-lari), Pergamon Press, Oxford. pp. 55–62.
14. H. Takechi, K. Namba, K. Rujiwara and K. Kawasaka (1981) Evaluation of subsurface fatigue damage in strip mill rolls by an X-ray diffraction method. *Trans. ISIJ*, **21**, 92–99.
15. G. H. Farrahi and G. Maeder (1992) An experimental study of fretting by means of X-ray diffracti.. *Fatigue Fract. Engng. Mater. Struct.*, **15**, 91–102.
16. N.-S. Hu and H.-J. Zhou (1981) The effect of surface plastic deformation on fatigue strength and .. mechanism. *First Int. Conf. on Shot Peening*, Paris (Edited by A. Niku-lari), Pergamon Press, Oxford.. pp. 351–357.
17. D. Hakimi (1984) Characterisation mécanique et métallurgique de la structure d'une couche grenaill.. Doct. 3ème Cycle Thesis, University of Paris-Sud, France.
18. H. Wohlfahrt (1973) Zum Eigenspannungsabban bei der Schwingbeanspruchung von Stehlen. *HTM* **28**, 288–293.
19. W. Elber (1974) *Effects of shot peening residual stresses on the fracture and crack growth propertie.. D6AC steel.* ASTM STP 559. p. 45.
20. L. Wagner, G. Lutjering and V. Sedlacek (1989) Fatigue crack growth retardation in an Al alloy 20.. a residual compressive stress field. *2nd Int. Conf. on Residual Stresses ICRS2*, Nancy (Edited by C. Be.. Elsevier Applied Science, London. pp. 803–808.
21. H. Berns and L. Weber (1987) Crack initiation and growth in shot peened and prestrained peened h.. strength steel. In: *Advances in Surface Treatments and Surface Finishing*, Vol. 3 (Edited by A. Niku-la.. Pergamon Press, Oxford. pp. 63–67.
22. M. Misumi and M. Ohkubo (1987) Deceleration of small crack growth by shot peening. *Int. J. Ma.. Prod. Techol.*, **2**, 36–47.