FATIGUE LIFE PREDICTION OF SHOT PEENED COMPONENTS

R.A. CLÁUDIO*[1], J.M. SILVA[2], C.M. BRANCO[3], J. BYRNE[4]

[1]Department of Mechanical Engineering, ESTSetúbal/Instituto Politécnico de Setúbal
Campus do IPS, Estefanilha, 2910-761 Setúbal.
[2]Department of Aerospace Sciences, Universidade da Beira Interior,
Edifício II das Engenharias, 6201-001, Covilhã.
[3]Department of Mechanical Engineering, Instituto Superior Técnico
Av. Rovisco Pais, 1049-001 Lisboa.
[4]Department of Mechanical and Design Engineering,
University of Portsmouth, Portsmouth, Hants PO1 3DJ, UK
rclaudio@est.ips.pt

ABSTRACT: Shot peening is one of the most effective surface treatments in order to prevent crack initiation and early crack propagation. Part of the studies to determine the fatigue performance of shot peening are based on experimental tests. Almost no work is published related with the prediction of shot peening behaviour. The present paper evaluates the ability of the current methodologies, used to predict fatigue life, on components treated with shot peening. The Finite Element Method was used to determine the stress, strain and strain energy due to shot peening of some specimens tested experimentally. These results were used to apply methods to predict the total fatigue life. A final discussion is presented about the ability of the methods used, to predict the fatigue life of the specimens tested experimentally.

Keywords: Shot Peening, Fatigue Life Prediction, Finite Element Method**.**

RESUMO: A grenalhagem é um dos tratamentos mais eficientes na prevenção da iniciação de fendas por fadiga e na fase inicial de propagação. Grande parte dos estudos sobre o feito da grenalhagem no comportamento à fadiga são experimentais. Praticamente não existem trabalhos publicados relativos ao estudo de previsão do comportamento da grenalhagem. Neste trabalho são usados modelos tradicionais, de determinação da vida à fadiga, em componentes grenalhados. O método dos elementos finitos é usado para determinar a tensão, extensão e energia de deformação de provetes grenalhados que foram testados experimentalmente. Estes resultados são usados em modelos de previsão da vida total à fadiga. É apresentada uma discussão sobre a capacidade dos modelos usados na previsão de vida à fadiga de provetes que foram testados experimentalmente.

Palavras chave: Grenalhagem, Previsão de Vida à Fadiga, Método dos Elementos Finitos.

1. INTRODUCTION

Shot peening is a cold work process that induces a protective layer of compressive residual stress at the surface of components. The objective of that compressive layer is to offset the applied stress, resulting in a benefit in terms of fatigue, corrosion-fatigue and fretting fatigue, [1]. In order to produce plastic deformation, a stream of metal, glass or silica particles ("shot") is animated at high velocity and projected against the surface of the metallic component in a defined and controlled way.

In reference [2] is a study of the increase in fatigue life that it is possible to achieve with an appropriate use of shot peening. Some of these examples are: leafs spring - 600% increase; helicoidal springs - 1300%; gears - 1500%. These are some impressive examples how much life improvement is possible with shot peening. The main importance of shot peening is because it acts at the surface of components reducing the effective stress due to the compressive layer. This layer is only of some hundreds of microns depth, but enough to be quite effective. Some improvement is also attributed to the strain hardening due to plastic work at surface. However it is also necessary to account for the increase of surface roughness which has a negative contribute to the fatigue improvement. Normally it is assumed that the contribute due to strain hardening is balanced by the increase in surface roughness.

Numerical modelling of fatigue behaviour of shot peened components is a main subject of a considerable number of papers oriented to the numerical simulation of the related residual stress fields [3-8]. Many other works can be found trying to model the effect of shot peening parameters on the residual stress profile, [9-15]. From all these works it is possible to conclude that much more is necessary to simulate the effect of shot peening. In many of these works, the shot peening model is limited to only one shot. Considering 3D simulations, the most complete model include the effect of only 3 shots which only proves that modelling of residual stress induced by shot peening is a quite complex matter which requires further developments.

The number of publications related with fatigue life prediction of shot peening is even scarcer. Sherrat [16], points some of the principal reasons why shot peening is so difficult to be fatigue predicted:

- Peening has influence on crack initiation as well on propagation. Fracture mechanics will give no guidance on this, and local strain calculations are little better;
- The surface left by peening will be complicated in its texture;
- Fracture mechanics does not predict the behaviour of short cracks, which is important in the shot peening calculation.

De Los Rios et al. [17], concluded that most of the analyses made up till 1995, were based on simple superposition of the residual stress in order to give the local surface stress, which is a very simplistic approach, as in the cases of the work of Li et al. [18] and John et al. [19].

A complete work about simulation of residual stress under high cycle fatigue (HCF) was published by Fathallah [10]. His model is based on a multi-axial fatigue criteria and it accounts for the residual stress profile, strain-hardening at the surface and surface imperfections but does not account for any cyclic relaxation. Apart from that, good experimental agreement was found.

Giuseppe and Taylor [21], presented a recent work modelling the effect of shot peening using the theory of critical distances (point and line method). The residual stress was treated as a mean stress using the Goodman approach, however the contents of this work are limited to HCF conditions.

In the present work, fatigue life will be predicted under low cycle fatigue conditions (LCF). The finite element method (FEM) will be used to determine the stress, strain and strain energy to apply in total fatigue methods. Some considerations about these methods can be found in [22].

2. FE MODEL

The geometry used as a reference for the FE analysis is a washer specimen presented in Figure 1. The “washer” specimen is used by Rolls Royce since it is representative of a critical region of a gas turbine aero engine compressor disc. The axis system represented will be used in the rest of this work. This specimen was used because it was previously fatigue tested, whose results can be found in [23].

A 2D non-linear FE model was built to determine the stress, strain and strain energy in specimens with both as machined and shot peened superficial conditions. These results will be used in fatigue life models, in order to predict the fatigue life, and to compare the numerical results with experimental. The final objective of this work is to evaluate which is the best method when considering the prediction of the shot penning effect.

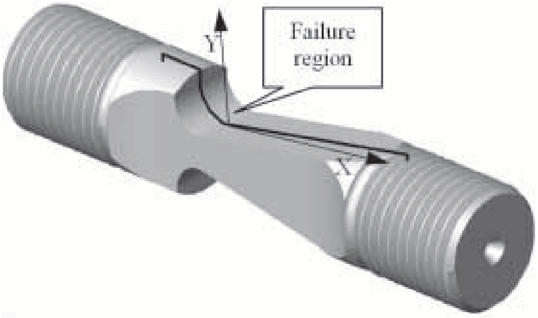

Fig. 1. Washer specimen and FE model.

Only half of the geometry was modelled because of symmetry conditions. A quadrangular mesh was made with biquadratic 2D plane strain elements (8 nodes), with two degrees of freedom per node. Boundary conditions and loading were set according to Figure 2. The applied load was normalized to the critical section, not considering the notch root, which has a cross sectional area (CSA) of $11\times5.08=55.88$ mm^2. In this region the specimen has a curvature radius of 4.5mm with an elastic stress concentration factor $K_t=1.32$. The values presented in the labels of some figures are the maximum load of the loading cycle. The loading cycle applied is trapezoidal with timings 1-1-1-1s and a loading ratio of *R=0.1*. These parameters are identical to those used in experimental tests [23].

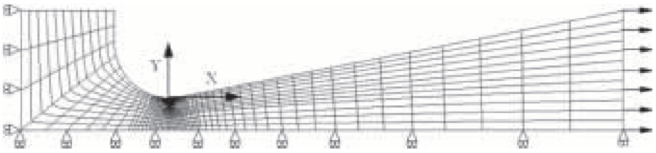

Fig. 2. Washer specimen 2D FE model for stress analysis.

In order to simulate residual stress due to shot peening a thermal gradient was introduced with the same profile as the residual stress in Figure 6. A direct relation between stress and temperature was guaranteed by setting the thermal expansion factor to 1/E, being E the young modulus of the material at 650ºC. This method was successfully applied before by Cook, Timbrell et al. [24]. More details can be found in [22]. Part of the FE model is similar to the one described in [25].

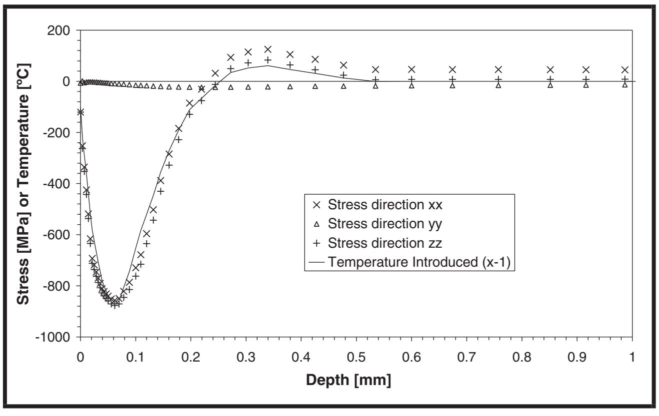

Fig. 3. Residual stress profile calculated by FE due to the introduction of a temperature profile.

3. MATERIAL PROPERTIES

The material considered in this investigation is a new generation nickel base superalloy developed using a powder metallurgy (PM) technique, whose commercial name is RR1000. Chaboche model was used to define cyclic material behaviour, whose parameters are listed below, [26].

Yield stress at zero plastic strain:

$$\sigma\big|_o = 695MPa$$

Kinematic hardening parameters,

$$C = 141\times10^2 \ MPa;\ \gamma = 391.61$$

Isotropic hardening parameters,

$$Q_\infty = 161.52 \ MPa;\ b = 7.13$$

In order to calculate fatigue life for the simulated conditions by FE, low cycle fatigue (LCF) data is needed. Zhan [27], made fatigue tests for five specimens, using the same frequency, same waveform and same temperature as the ones used in this work. The Coffin-Mason parameter, obtained from Zhan's experimental data, are given by equation (1):

$$\frac{\Delta\varepsilon}{2} = 0.440\times\left(N_f\right)^{-0.810} + 0.0055\times\left(N_f\right)^{-0.048} \quad (1)$$

Equation (2) gives the S-N equation for RR1000 tested at 650ºC by Zhan, [27]. Experimental data to build this S-N curve was taken from LCF tests, being the stress taken from completely stabilized cycles.

$$\sigma_a = 2708.3\times\left(N_f\right)^{-0.1606} \quad (2)$$

The total energy density, ΔW_t, was also used as a damaging parameter. Total energy density, is the summation of the elastic and plastic strain energy densities per cycle. To account for mean stress the elastic strain energy density was modified to account only for the tensile stress [28]. The total strain energy density is given by equation (3).

$$\Delta W_t = \Delta W_e^+ + \Delta W_p = f\left(N_f\right) = A\times N_f^\alpha + \Delta W_{FL} \quad (3)$$

where:

ΔW_e^+ is the modified elastic strain energy density

ΔW_p is the plastic strain energy density

A and α are material constants

ΔW_{FL} is the strain energy density at the fatigue limit of the material.

From Zhan's experimental tests [27] and using the Chaboche material parameters, a numerical simulation was done in a plain specimen in order to obtain the total strain energy density. This energy was calculated after cycle stabilization. Equation (4) gives the relation between strain energy and number of cycles to failure.

$$\Delta W_t = 10330.7\times N_f^{-1.2053} + 2.03 \quad (4)$$

4. STRESS, STRAIN AND STRAIN ENERGY IN THE CRITICAL SECTION

The stress, strain and strain energy were calculated using the FE solutions in order to apply fatigue life prediction methods. These quantities are plotted in Figures 4 to 7, from surface up to 0.5 mm depth (line between the notch root (coordinates (0, 0, 0)) and the middle of the specimen (coordinates (0, -2.54, 0)), Figure 2).

The results without shot peening are plotted in the graphs by open symbols and dashed lines. Results that included shot peening are with closed symbols and continuous lines. The stress level (nominal stress over the critical section, as described in section 2) was chosen so that failure should occur between 103 and 105 cycles. This information was taken from experimental tests. FE simulations were stopped when the cyclic hysteresis loop was stable. For almost all the loading situations, cyclic stabilization occurred after some tens of cycles. Because of computational resources and for some situations (mainly those with higher loading levels) the simulation was stopped after 400 cycles, even if the cyclic hysteresis loop was not totally completed.

The relaxation of residual stress, due to cyclic loading, was already studied is in a previous work [25].

Figure 4 presents the stress range considered for the situations studied. As it can be seen, shot peening does not affect the stress range, having effect only for mean stress levels, Figure 5. The effect of shot peening is perfectly clear up to 0.12 mm depth. At the surface, initial residual stress almost vanishes but it is still possible to notice a mean stress reduction of about 40 MPa. Mean stress is higher for depths deeper than 0.12 mm when initial stresses are introduced, being this effect related with the equilibrium of stress that must exist.

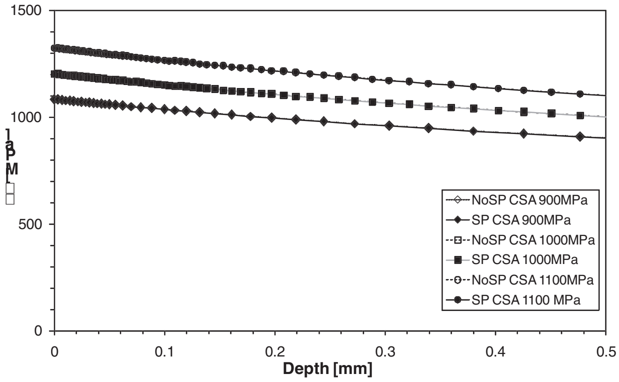

Fig. 4. Stress range after hysteresis loop stabilization for the washer specimen with and without shot peening (data points for NoSP and SP are coincident).

Similar conclusions taken for stress can be observed when analysing the strain curves. Figure 6 shows the strain range, for the conditions studied. Strain range is exactly the same for the conditions with and without initial residual stress, as verified for the stress.

Figure 7 shows the strain energy density range, for the conditions studied. The strain energy density plotted includes the modification to account for mean stress effects, [28]. For more information see [22].

Figure 7 allows inferring most of the conclusions formed when stress range and mean stress were analysed. Without a scratch it is possible to observe a large benefit of residual stress up to 0.12 mm, whilst, for higher depths, strain energy density evinces higher levels with the presence of residual stress. At the surface the benefit is quite small.

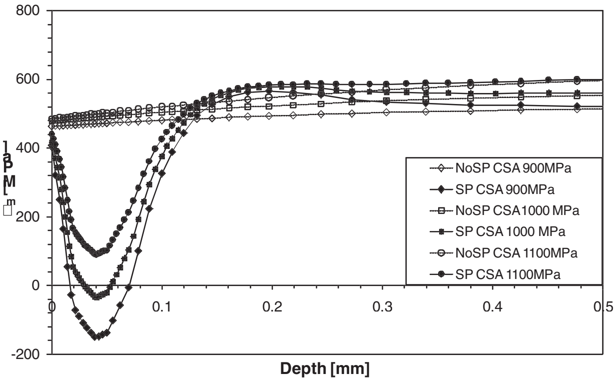

Fig. 5. Mean stress after hysteresis loop stabilization for the washer specimen with and without shot peening.

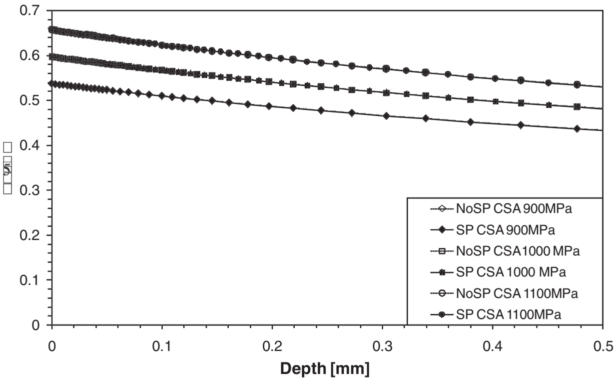

Fig. 6. Strain range after hysteresis loop stabilization for the washer specimen with and without shot peening.

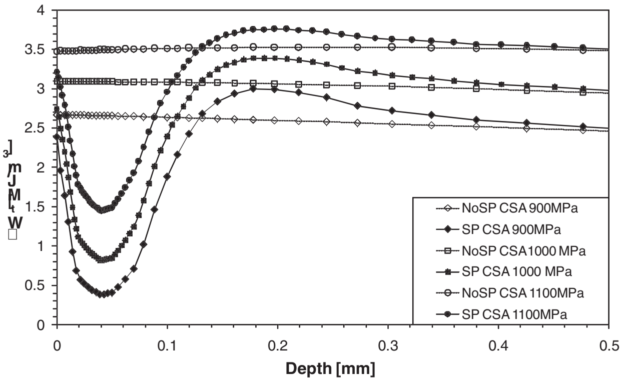

Fig. 7. Total strain energy range after hysteresis loop stabilization for the washer specimen with and without shot peening.

5. FATIGUE LIFE ASSESSMENT

Fatigue life was calculated from FE results, applying some total fatigue methods normally used to access fatigue life, to verify which one is the more appropriate to fit experimental results.

Table 1 presents the fatigue life predictions, for the stress life method, using different criteria to consider the used stress. The stress life method is more appropriate for HCF conditions, where elastic stress profiles are frequently used. For the application herein studied, the number of cycles to failure indicates LCF conditions. In order to try to apply the stress life method, to LCF conditions, the elastic-plastic stress profile was used instead of the linear elastic one. Simulations, not published, showed that life predictions with linear elastic stress profiles gave unrealistic life results. Fatigue life was obtained from the Basquin equation whose parameters are in section 3. The Goodman criterion was used to correct for mean stress effects.

In Table 1, the first column of fatigue results refers to the "Hot spot method", in which the stress used to calculate fatigue life was taken exactly at the surface. The next five columns refer to the line method. The quantity $a_0 = 0.0171$ mm is the El Haddad *et al.* constant [29], which is determined using fatigue parameters for RR1000 at 650ºC. $2a_0$ is the distance from the scratch tip to average the stress profile according to the line method. As a_0 is a parameter calculated from linear elastic parameters (assuming low plasticity), fatigue life was also determined calculating the mean stress at a critical distance of 0.1 and 0.2 mm in order to check if results led to better predictions. A weight function, $\varphi(x)$ imilar to the one used by Lanning *et al.*[30], was applied to give more relevance to the stress at the scratch root when compared with the interior positions. The weight function used is given by equation (5).

$$\varphi(x) = \left(1 - \frac{x}{x_{ef}}\right)^m \tag{4}$$

where x_{ef} is the critical distance.

The exponent m used was $m=1$. For bigger values of m, fatigue life prediction does not change significantly.

In the last column of Table 1, fatigue life predictions are presents considering the SFI (Stress field intensity method) model, which is based on the local elastic-plastic stress profile. The major difficulty when applying this method is to find the critical distance by observing the stress profile. For higher loads or when residual stress is considered, the stress profile does not behave as expected, since the definition of the critical distance is not quite accurate. It should be noted that the calculated fatigue life is strongly dependent on the value obtained for the critical distance.

The results of Table 1, allow concluding that the greater is the distance to average stress from the surface, the greater is the life predicted. Stress levels near the surface are very high resulting in lower life predictions. The use of a weight function, $\varphi(x)$, to give more relevance to the stress values at the surface does not significantly change the obtained results.

Fatigue life predictions made by the strain life method are in Table 2. The strain-life curve was obtained from previous LCF tests whose parameters are in section 3. The values of strain range and mean stress were taken at the surface from FE results. The expression proposed by SWT (Smith, Watson and Topper method) [38] was used to account for mean stress effects. The predicted life for the specimens without shot peening is about ½ of the experimental results, which is not a bad result taking in account fatigue results. However the predicted life for the shot peening condition is much lower than expected.

Table 1 – Fatigue life predictions by the stress life approach.

SP	CSA Stress [MPa]	Experimental [Cycles]	Life Predicted [Cycles]							
			Hot spot stress	Critical distance line method					SFI
				$2a_0$	0.1mm	0.1mm + $\varphi(x)$	0.2mm	0.2mm + $\varphi(x)$	
NO	800	59193	17407	18009	19499	18831	21762	20346	22738
NO	850	29393	11739	12132	13102	12667	14577	13654	16197
NO	900	15191	8058	8317	8958	8671	9932	9323	11425
NO	950	8137	5578	5749	6170	5981	6811	6410	8423
NO	1000	4500	3963	4076	4356	4230	4781	4515	6201
NO	1050	2562	2886	2961	3149	3065	3433	3256	4687
YES	1000	105249	5030	13356	15851	16146	8686	11722	41599
YES	1050	39976	3532	8297	9693	9837	5805	7493	21172
YES	1100	15883	2539	5254	6035	6102	3953	4877	11382

Table 2 – Fatigue life predictions by the strain life and strain energy density life approach.

SP	CSA Stress [MPa]	Experimental [Cycles]	Strain Life Approach [cycles]	Strain Energy Density Life Approach				
				x_{ef} [mm]	Life Predicted [Cycles]			
					x_{ef} (from LCF test)	x_{ef} (from Washer specimen NoSP)	$0..x_{ef}$ (from LCF test)	$0..x_{ef}$ (from Washer specimen NoSP)
NO	800	59193	26473	0.425	17396	52833	8500	53678
NO	850	29393	12466	0.478	6992	25267	5133	26770
NO	900	15191	6674	0.535	4484	12191	3621	12728
NO	950	8137	3962	0.674	3624	7510	2783	6011
NO	1000	4500	2613	0.758	2498	2454	2233	2763
NO	1050	2562	1865	0.852	2122	1326	1867	1309
YES	1000	105249	3633	0.244	1689	483	7089	43584
YES	1050	39976	2359	0.244	1496	262	3850	14790
YES	1100	15883	1666	0.244	1405	188	2678	5299

Fatigue life predictions for the total strain energy density taken at a distance x_{ef} are identified in Table 2 by "Life at x_{ef}" (from LCF test) where the curve used to relate energy with number of cycles was obtained from LCF tests whose parameters are in section 3. If the curve energy-life is obtained from the experimental results for the washer specimen without shot peening, the life predicted is in the next column identified by "from Washer specimen NoSP". The last two columns refer to a different approach in which the equivalent strain energy was averaged from surface up to the effective distance, such as the SFI model. This method has been used by Lanning, Nicholas et al. [30].

Observing the results obtained when effective strain energy is taken at a distance x_{ef}, life predictions give much lower life than expected. For the shot peening condition results are much worse. However if the equivalent total strain energy density is taken not at x_{ef} but averaged from $0..x_{ef}$, the predicted results are quite close to the experimental ones.

5. DISCUSSION

In section 5 several numerical fatigue life predictions were made, by applying total fatigue life methods. The objective was to numerically obtain fatigue life for the washer specimens experimentally tested in the conditions with and without residual stress due to shot peening. From the literature, no previous work has made predictions of fatigue life for components with high stress concentrations and shot peening under LCF conditions. Some of the methods used for fatigue life evaluation are not appropriate for these conditions. Even so, the most common methods were used to check if any of these can be used to predict life for all the conditions experimentally tested.

The results of fatigue life predictions using the stress life approach are in Table 1. Comparing these results with experimental ones, Figure 8, it is possible to see that the differences are significant, but predictive values are always conservative. Volumetric approaches that consider large distances from the surface (such as the line method or the SFI method) give fatigue lives that are closer to the experimental results. The SFI method is very difficult to apply because the criterion used to determine the critical distance does not work for LCF whether or not residual stress is included. Even when trying to introduce other criterion in order to define the critical distance, there is no way to fit the experimental observations for all situations studied. As seen in Table 1 and Figure 8, the El Haddad *et al.* distance fatigue life predictions are too pessimistic. According to the initial expectation, stress life methods are not appropriate for life prediction under LCF conditions, leading to conservative results.

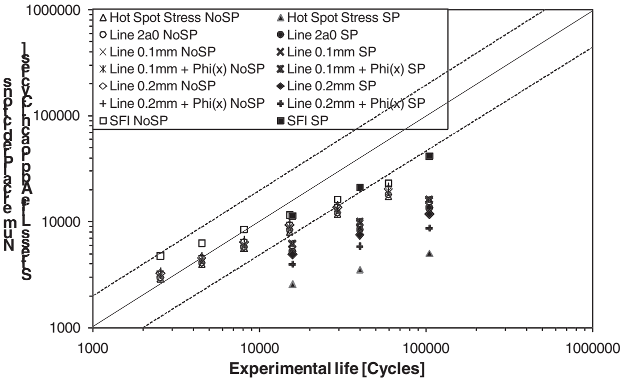

Fig. 8. Experimental results vs numerical predictions of fatigue life calculated by the stress life approach.

The results predicted by the strain life approach, given in Table 2 are also plotted in Figure 9 against the experimental results. Life predicted by this method is always inferior to the experimental observations. For the shot peened condition these results give less than 1/10th of the expected life. The main reason is because strain and stress are taken at the surface where the condition is almost the same (both with and without shot peening). This criterion is frequently used to determine crack initiation because parameters are taken from the surface, where initiation normally occurs. If these results refer to crack initiation, the predicted life may be in agreement with many observations found in the literature. In fact many researchers argue that the principal benefit of shot peening is in the ability to retard or stop microcrack propagation pointing out that residual stress has no influence on initiation [31-33]. From the experimental tests, many specimens did not fail after a large number of cycles. Burgess [34], analysed some of these specimens classified as run-outs and concluded that they had a small crack, in the order of some tens of microns, that arrested, being once again in agreement with the ability of shot peening in retarding or stopping microcrack propagation. As proposed by Cameron and Smith [35], this method can be used together with a crack propagation law for total fatigue life determination purposes.

Bentachfine, Pluvinage *et al.* [36] proposed a method based on the strain energy density to predict fatigue life for both HCF and LCF conditions. This method, seems to be appropriate to determine the fatigue life without shot peening. In Table 2 and Figure 9 are some fatigue life predictions results for the cases studied. By comparing these results with experimental ones, it is possible to find a reasonable good fit when shot peening is not considered. However, numerical predictions for shot peening cases do not give so good results when comparing with the experimental ones. This is because the effective distance obtained by the criterion defined by Bentachfine, Pluvinage *et al.* [36] falls behind the tensile region of initial residual stress. Averaging strain energy, between the surface and the critical distance, (last two columns of Table 2), predictions for the shot peened condition become close to the experimental results. Dingquan *et al* [37], have a similar opinion, saying that residual stress should be averaged over a defined depth in order to evaluate the new fatigue limit. They also maintain that this distance is a material parameter. However, even when changing the critical distance, the results do not improve significantly.

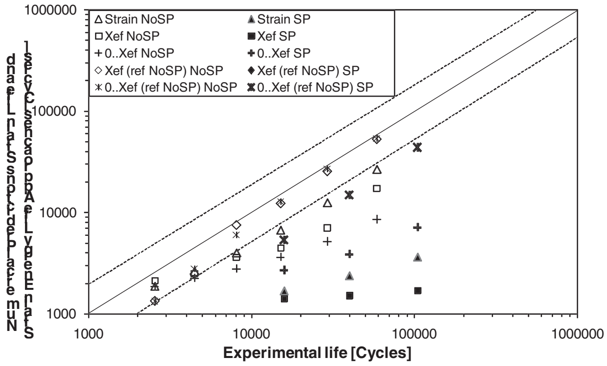

Fig. 9. Experimental results vs numerical predictions of fatigue life calculated by the strain life and strain energy life approaches.

5. CONCLUSIONS

Fatigue life calculated using total fatigue life predictive methods which are normally used for notched geometries, gave conservative results for almost all of the situations herein studied. These were found to be too pessimistic in predicting the shot peening effect. Results are much better if stress or strain energy density is averaged over a critical distance, when shot peening is considered.

The strain life method gave the most conservative results. In this case, fatigue life predictions with and without shot peening is almost the same, which is not in agreement with the experimental results. However this conclusion may be in agreement with many observations from other researchers which argue that shot peening has the ability to retard or stop microcrack propagation instead of avoiding crack initiation. If these affirmations are correct, then this approach could be used in methods like Cameron and Smith method [35] which combine crack initiation with crack propagation predictions.

The strain energy density life prediction approach, according to [36], provides results quite close to the experimental observations for all cases studied without shot peening. However if residual stress is considered, this method does not provide reliable life predictions. The principal limitations are due to the difficulty in defining the critical distance since gradients are extremely high close to the scratch when shot peening is considered.

ACKNOWLEDGEMENTS

The authors would like to thank to RTO/NATO, FCT for funding and ongoing support.

REFERENCES

[1] Byrne, J. and Burgess, A., Surface improvement for structural integrity and life extension. *8as Jornadas de Fractura, UTAD, Vila Real de Trás os Montes, Portugal, (*2002) *Ed. by SPM*.

[2] SPM, Shot peening. *Course about structural failure and cases study "Curso Sobre Ruína de Sistemas e Estudo de Casos"* (2001), SPM.

[3] Torres, M. A. S. and Voorwald, H. J. C., *Int. J. of Fatigue* **24** (2002) 877.

[4] Meo, M. and Vignjevic, R., *Advances in Engineering Software* **34** (2003) 569.

[5] Schiffner K. , Droste C. and Helling, *Computers and Structures* **72** (1999) 329.

[6] Meguid, S. A., Shagal, G. and Stranart, J. C., *J. of Mat. Processing Technology* **92 (**1999) 401.

[7] Meguid, S. A., Shagal, G., Stranart, J. C. and Daly, J., *Finite Elements in Analysis and Design* **31** (1999) 179.

[8] Meguid, S. A., Shagal, G. and Stranart, J. C., *Int.l J. of Impact Eng.* **27** (2002) 119.

[9] Li J.K., Yao, M., Wang, D. and Wang, R., *Fatigue and Fracture of Eng. Mat. and Structures* **15** (1992) 1271.

[10] Y. F. Al-Obaid, *Computers and Structures* **40** 1991 1451.

[11] Lamand, Li L., Barrallier, L., Lalanne, B. and Castex, L., *Fatigue and Fracture of Eng. Mat. and Structures* **24** (2001) 93.

[12] Han, K, Peric D., Crook, A. J. L. and Owen, D. R. J., *Engineering Computations* **17 (**2000) 593.

[13] Han, K, Peric D., Owen, D. R. J. and Yu, J., *Engineering Computations* **17** (2000) 680.

[14] Al-Hassani, S. T. S., *7th International Conference on Shot Peening, Ed. by Prof. A. Nakonieczny, Warsaw, Poland* (1999) 217.

[15] Arif, A. F. M.. *J. of Mat. Processing Technology* **136** (2003) 120.

[16] Sherratt, F., The rational basis of the peening process. *in Shot Peening: Techniques and Applications, EMAS, Ed. by Marsh, K.J.* (1993) 7.

[17] De Los Rios, E. R., Walley, A., Milan, M. T. and Hammersley, G., *Int. J. of Fatigue* **17** (1995) 493.

[18] Li J.K., Yao, M., Wang, D. and Wang, R., *Fatigue and Fracture of Eng. Mat. and Structures* **15** (1992) 1271.

[19] John, R., Larsen, J. M., Buchanan, D. J. and Ashbaugh, N. E., *Fatigue 2002 - Proceedings of the Eighth Int. Fatigue Congress, Stockholm, Sweden* **2** (2002) 1063.

[20] Fathallah, R., Laamouri, A., Sidhom, H. and Breaham, C., *Int. J. of Fatigue* **26** (2004) 1063.

[21] Giuseppe, C. and Taylor, D., *15th European Conference of Fracture*, Stockholm, Sweden (2004) 11.

[22] Cláudio, R. A., Fatigue Behaviour and Structural Integrity of Scratch Damaged Shot Peened Surfaces at Elevated Temperature. PhD Thesis (2005) University of Portsmouth.

[23] Cláudio, R.A., Branco, C.M., Byrne, J., *International Conference on Experimental Mechanics, ICEM13*, (2007) Greece.

[24] Cook, G., Timbrell, C. and Wiehahn, M., Using abaqus to analyse fatigue crack growth under the combined influence of residual stress and cyclic external load. *ABAQUS UK Users Group Conference,* (2002) England.

[25] Cláudio, R.A., Silva, J.M., Branco, C.M: Byrne, J., *"Crack Propagation Behaviour of Shot Peened Components at Elevated Temperature", 10as Jornadas de Fractura* (2006) Univ. do Minho.

[26] Zhao, L. G. , Tong, J., Vermeulen, B. and Byrne, J. *Mechanics of Materials* **33** (2001) 593.

[27] Zhan, Z., *A study of creep-fatigue interaction in a new nickel-based superalloy. PhD Thesis* (2004) University of Portsmouth.

[28] Koh, S. K., *Pressure Vessels and Piping* **79** (2002) 791.

[29] El Haddad, M. H., Topper, T. H. and Smith, K. N., *Engineering Fracture Mechanics* **11** (1979) 573.

[30] Lanning, D. B., Nicholas, T. and Haritos, G. K., *Int. J. of Fatigue* 27 (2005) 45.

[31] Song, P. S. and Wen, C. C., *Eng. Fracture Mechanics* **63** (1999) 295.

[32] Guagliano, M. and Vergani, L., *Eng. Fracture Mech.* **71** (2004) 501.

[33] Zhu X.Y. and Shaw W. J. D. *Fatigu and Fracture of Eng. Mat. and Structures* **18** (1995) 811.

[34] Burgess, A., *Influence of surface damage on the fatigue behaviour of a shot peened nickel base superalloy at elevated temperature. PhD Thesis (2005) University of Portsmouth.*

[35] Cameron, A. D. and Smith, R. A., *Int. J. of Pressure Vessels and Piping* **10** (1982) 205.

[36] Bentachfine, S., Pluvinage, G., Gilbert, J., Azari, Z. and Bouami, D.. *Int. J. of Fatigue* **21** (1999) 421.

[37] Dingquan, Z., Kewei, Xu and Jiawen, He, *Materials Science and Engineering, A* 136 (1991) 79.

[38] Smith, K. N., Watson, P. and Topper, T. H, *J. of Materials* 5 (1970) 767.