High cycle fatigue prediction of metallic shot peened parts based on a reliability approach

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Abstract This paper presents a probabilistic approach to predict high cycle fatigue HCF behaviour of shot peened parts based on the multi-axial HCF criterion of Crossland. The modifications induced by shot peening in the first outer layers of the treated parts were taken into account. They are classified into four categories: (i) the compressive residual stresses, (ii) the surface work-hardening; (iii) the geometrical irregularities and (iv) the surface integrity. The reliability of the HCF resistance was calculated by using the Strength-Load method with Monte Carlo simulation, by taking into account the dispersions of: (i) the Crossland criterion material characteristics, (ii) the shot peened surface conditions and (iii) the applied loading parameters are taken into account. An application has been carried out on shot peened ductile steel SAE 3415 allowing, in a first hand, the validation of the applicability of the proposed model, and in a second hand, the implementation of interesting engineering iso-Probabilistic Crossland Diagrams (PCD).

1 INTRODUCTION

Shot peening is an established mechanical surface treatment used, generally, to enhance fatigue life of metallic components. This treatment leads to induce generally both favourable effects (i): compressive residual stresses, which have little effect on crack nucleation, but can drastically retard crack propagation stage, (ii) metallurgical modifications in the superficial layers, leading in the majority of cases to induce favourable surface work hardening which allows delaying the crack nucleation stage. However, in few cases of extremely hard materials, unfavourable surface softening is observed, as well as phase transformation or decarburizing. In the cases where the shot peening parameters are not well optimised, two unfavourable effects can be induced: (i) micro geometrical surface imperfections and (ii) superficial defects, such as: small micro cracks, overlaps, scales. In order to take into account the initial favourable and unfavourable shot peening surface conditions on the HCF behaviour, deterministic approaches have been proposed by Deperrois *et al.* and Fathallah *et al.* They are mainly based on multiaxial HCF criteria. The applications of the proposed approach show a good agreement with the experimental investigations. Unfortunately, scatterings around the surface properties, which are often very large and significant on the HCF behaviour, were not taken into account. These dispersions can have different origins: (i) the material structure (grain size, texture, defects, multi-phases, etc.) ; (ii) the surface finishing conditions (shot peening conditions, cutting, burnishing, *etc.*) ; and (iii) the used experimental investigating techniques (X-ray diffraction analysis technique, micro-hardness measurement, *etc.*). Consequently, a relevant approach including a HCF probabilistic analysis is then naturally required, in order to increase the confidence level of the HCF prediction of shot peened components. In this work, the proposed HCF reliability prediction is carried out by taking into account the materials, the loading and all the shot peening surface condition parameters with their accuracies. This approach allows, firstly, better evaluation and quantification of the effect of the different input data dispersions relative to both experimental and physical origins, and secondly, the analyse of the quality and the confidence level of the HCF reliability prediction of shot peened parts. The computation of the HCF reliability of shot peened parts submitted to random loading was carried out by using the "Strength-Load" reliability method with Monte Carlo simulation. This approach has been applied to the different shot peened affected layers. As a result, interesting shot peened PCD curves were obtained for different surface conditions. These PCDs are very useful for engineers to quantify the HCF reliability influence of the surface treatment conditions and to have high reliable safe predictive design of shot peened parts.

2 BACKGROUND

2.1 Shot peening high cycle fatigue criterion

An approach has been developed by Fathallah *et al.* to predict the HCF behaviour of shot peened parts. It is based on the global approach and critical plane HCF criteria such as Sines, Crossland and Dang Van. It has the advantage to take into account the modifications induced on the peened surface, which are classified into four categories: (i) the compressive residual stresses, (ii) the surface work-hardening; (iii) the geometrical irregularities and (iv) the surface integrity.

2.1.1 Review of the Crossland Criterion

The Crossland criterion is defined by the limitation of an equivalent stress σ_{eq} expressed by a linear relationship between $\sqrt{J_{2,a}}$ and P_{max}. The HCF resistance is defined for a specified number of cycles and a given probability (generally, 10^7 cycles and 50% probability). It is expressed by the following inequality:

$$\sigma_{eq} = \sqrt{J_{2,a}} + \alpha_c P_{\max} \le \beta_c \qquad (1)$$

Where, $\sqrt{J_{2,a}}$ is obtained by a double maximisation.

$$\sqrt{J_{2,a}} = \frac{1}{2\sqrt{2}} \max_{t_i \in T} \left\{ \max_{t_j \in T} \sqrt{((\underline{\underline{S}}(t_i) - \underline{\underline{S}}(t_j) : (\underline{\underline{S}}(t_i) - \underline{\underline{S}}(t_j))} \right\} \qquad (2)$$

$$\text{And } P_{max} = \frac{1}{3} \max_{t \in T} \left[tr\left(\underline{\underline{\sigma}}(t) \right) \right] \qquad (3)$$

α_C and β_C are generally identified by a fully reversed torsion test (i.e. $\sqrt{J_{2,a}} = t_{-1}$; $P_{max} = 0$) and a fully reversed bending test (i.e. $\sqrt{J_{2,a}} = f_{-1}/\sqrt{3}$; $P_{max} = f_{-1}/3$). They are expressed as follow:

$$\alpha_C = 3\frac{t_{-1}}{f_{-1}} - \sqrt{3} \qquad (4)$$

$$\text{And } \beta_c = t_{-1} \qquad (5)$$

Two principle cases are identified: (i) a safe prediction ($\sigma_{eq} = \sqrt{J_{2,a}} + \alpha_c P_{\max} \le \beta_c$) and (ii) a failure case ($\sigma_{eq} = \sqrt{J_{2,a}} + \alpha_c P_{\max} > \beta_c$).

2.1.2 Accounting for the compressive residual stresses effect

It is well observed that the shot peening residual stress relaxation is constituted by two principle steps: (i) a first stage called quasi-static or elastic shake down step (after the first cycles), mainly due to plastic deformation redistribution in the affected layers followed by an elastic stabilization. And, (ii) a second stage of a slow relaxation due, principally, to the evolution of the mechanical properties under the cyclic loading (cyclic softening or hardening of the affected layers). It is well established that the superposition of the applied loading $\underline{\underline{\sigma}}_{app}(t,z)$ to the stabilized residual stresses $\underline{\underline{\sigma}}_R^*(z)$ is possible after the first phase of residual stresses relaxation. So, the shot peening maximum hydrostatic pressure P_{max}^{peened} used in Crossland criterion after the first stage of relaxation is given by the following expression:

$$P_{max}^{peened}(z) = \frac{1}{3} \max_{t \in T} tr\left[\underline{\underline{\sigma}}_{app}(t,z) + \underline{\underline{\sigma}}_R^*(z) \right] \qquad (6)$$

2.1.3 Accounting for the metallurgical effect

The shot peening metallurgical modification is characterised by an increase of the density of dislocations in the first affected layers (plastic deformations), which is qualitatively correlated to the X-ray diffraction such as

Full Width at Half Maximum peak ($FWHM$). In order to take into account this effect in the HCF prediction of shot peened parts, it has been assumed that, only, the HCF Crossland parameter β_C is changing in-depth of the affected layers. The α_C parameter is supposed to be constant because, it remains small between 0.1 and 0.3 for the majority of metals. In addition, the hydrostatic pressure remains, for the majority of cases, with low magnitude. The β_C parameter, which is generally, identified by the fully reversed torsion fatigue limit t_{-1} (Eq. 5) is assumed to be a function of the density distribution of the dislocations, according to the theory of plasticity. Deperrois proposed a general relationship giving the change of β_C with the in-depth profile of the $FWHM$:

$$\beta_C(z) = K\,[FWHM(z)]^n \tag{7}$$

For the shot peened parts, the induced plastic deformations have more influence on the fatigue strength in the case of high work-hardening metals (the coefficient n is higher) than in the case of low work-softening material (the coefficient n is lower). Fathallah *et al.* have assumed that n constant is the hardening coefficient, deduced from the work- hardening law using the expression of Holloman: $\sigma = K\,\varepsilon_p^n$.

2.1.4 Accounting for the micro geometrical surface irregularities effect

To characterise the effect of the shot peening micro-geometrical imperfections, Fathallah *et al.* consider, only, the second order defects which are the waviness. A typical indentation geometrical defect is considered in the unfavourable zone. It is a spherical indentation having the used shot radius (depending on the shot peening coverage percentage) and a penetration depth equal to the mean waviness depth W_t , defined as the maximum peak-to-valley according to the standard ISO 4287. The effect of the local stress concentration around this representative indentation is, then, evaluated by means of numerical simulations using the finite element method. Finally, the applied stress tensor $\underline{\underline{\sigma}}_{app}(t,z)$ is replaced by $\underline{\underline{\sigma}}_{app}^{SI}(t,z)$ taking into account the effect of the shot peening second order imperfections.

2.1.5 Accounting for the surface defects effect

Fathallah *et al.* use the damage variable D , proposed by Lemaître and Chaboche, to take into account the superficial shot peening defects. The previous experimental investigations show a very superficial shot peening damage uniformly distributed at the surface. The superficial scalar damage variable (i.e. for z=0), denoted D_S , is supposed to be homogenous and isotropic (does not depend on the direction). The effective cyclic stress tensor, at zero z-coordinate, is given by the following relationship:

$$\underline{\underline{\tilde{\sigma}}}(t, z=0) = \frac{1}{(1-D_S)}\,\underline{\underline{\sigma}}(t, z=0) \tag{8}$$

The effect of the unfavourable superficial damage results in a reduction of the constant β_C of the Crossland fatigue criterion by the factor $(1-D_S)$. The application of Crossland criterion at the first shot peened surface layer is finally expressed as follows:

$$\sqrt{J_{2,a}}\,(z=0) + \alpha_C\,P_{max}(z=0) \le (1-D_S)\,\beta_C(z=0) \tag{9}$$

2.1.6 Accounting for the surface defects effect

The shot peening effects are then integrated in the multi-axial HCF criterion of Crossland for the different affected superficial layers. The criterion will have the following expression:

$$\sigma_{eq}^{peened}(z) \le \beta_C^{peened}(z) \tag{10}$$

$\sigma_{eq}^{peened}(z)$ is computed by taking into account the compressive residual stress effect and the influence of the second order geometrical irregularities. It is expressed by the following expression:

$$\sigma_{eq}^{peened}(z) = \sqrt{J_{2,a}}^{peened} + \alpha_{c0} P_{max}^{peened} \quad (11)$$

Where $\sqrt{J_{2,a}}^{peened}$ and P_{max}^{peened} are respectively the amplitude of the shear stress and the maximum hydrostatic pressure of the total loading tensor $\underline{\underline{\sigma}}_t(t,z)$ due to shot peening, which is then expressed as follows:

$$\underline{\underline{\sigma}}_t(t,z) = \underline{\underline{\sigma}}_{app}^{SI}(t,z) + \underline{\underline{\sigma}}_R^*(z) \quad (12)$$

β_C^{peened} is computed with taking into account the effect of : (i) the metallurgical modification (work hardening or work softening) represented by the in-depth profile of the *FWHM* of the shot peened material *FWHM(z)* and (ii) the surface integrity represented by the superficial damage variable D_S .

It is a z-depth function expressed as follow:

$$\begin{cases} \beta_C^{peened}(0) = \beta_C \left(\dfrac{FWHM(z=0)}{FWHM_0} \right)^n (1 - D_S) \; ; for \; z = 0 \\ \beta_C^{peened}(z) = \beta_C \left(\dfrac{FWHM(z)}{FWHM_0} \right)^n \; ; for \; z > 0. \end{cases} \quad (13) \text{ and } (14)$$

2.2 HCF Probabilistic approach

A probabilistic approach has been proposed by Ben Sghaier *et al.* to predict the HCF reliability of metallic components. It is based on Crossland criterion, and takes into account the dispersions due to the applied loading and the material parameters. The approach consists to modify the Crossland criterion as follows: (i) the representative loading point has been transformed into a dispersed surface in the HCF diagram, generated by N random sampling of applied loading gives a bell shaped curve, (ii) the HCF threshold line has been transformed into a dispersion zone characterised by a beam of lines, corresponding to the different cases obtained from a random sampling of N values of t_{-1} and f_{-1} , according to their probability density function (PDF). The reliability has been computed by using the "Strength-Load", with FORM approach. The application of this method is physically consistent with the experimental observations, and leads to have more reliable HCF predictions. However the implementation of this method is difficult.

3 SHOT PEENING HCF PROBABILISTIC APPROACH

3.1 Methodology

In our study, the material, the loading and the surface condition parameters with their corresponding dispersions are taken into account in the computing of the reliability:

(i) The material dispersion is characterised by the accuracies of the two fatigue limits (generally t_{-1} and f_{-1}) used to identify the Crossland criterion parameters α_C and β_C . It is well accepted that experimental investigations lead to have normally distributed fatigue limits. To simulate this dispersion, we proceed, then, by a normal random sampling of t_{-1} and f_{-1} leading to a sample of the parameters α_C and β_C . The use of all these combinations gives a beam of Crossland limit lines. This transforms the HCF diagram into three zones: a zone of absolute safety, a zone of absolute failure and an intermediate zone of probable failure. Physical condition between t_{-1} and f_{-1} can exists, such as proposed by Papadopoulos *et al.* for the case of hard and mild metals.

(ii) The proposed approach can be carried out for different distributions and dispersion levels of the applied loading amplitudes. In this work, two cases are studied: normal and Log-normal distributions. Their dispersions are simulated by a random sampling leading to obtain a loading surface dispersion in the Crossland diagram.

(iii) Also, the dispersions of the surface conditions parameters can have different types of distributions. As shown in the § 2.1.6, the residual stress and the surface imperfections effects are taken into account in the expression of $\sigma_{eq}^{peened}(z)$. Also, the metallurgical modification and the superficial damage effects are integrated in the expression of $\beta_C^{peened}(z)$. Subsequently, their dispersions will be introduced in both surfaces dispersion of the loading and of the material parameters.

In this work the capability to take into account the influence of the range and the statistical distribution of the different surface condition parameters has been tested by means of complementary calculations.

3.2 Computation of the reliability

The reliability is computed by using the "Strength-Load" method, using the approximate method of Monte Carlo simulation. The strength function is here the HCF threshold beam of lines taking into account the effect of the metallurgical and the surface defects effects. The load function is the loading dispersed zone due to the effect of residual stress and surface geometrical imperfections.

3.3 The Monte Carlo simulation method

To compute the reliability one considers a vector $\{X\}$ of random variables representing uncertain structural quantities such as materials, loading and surface condition parameters which are physically independents. Let x_i be an element of the random vector $\{X\}$, with a probability density function (PDF) $f_{\{x_i\}}(\{X\})$. A performance function G, separating the security and the failure fields is written as follows:

$$G(x_i)=S(x_i)-L(x_i) \tag{15}$$

Where, S is the strength function and L is the load function. The probability of failure P_f is expressed as follows:

$$P_f = \int_{G(x_i)<0} f_{\{X\}}(\{x_i\})\, dx_1 .....dx_n = Pr(L(x_i) > S(x_i)) = Pr(G(x_i) < 0) \tag{16}$$

In that case, if the inequality $G(x_i) > 0$ is verified, this indicates a structural safety condition. In the opposite case, if $G(x_i) < 0$, this means a failure of such a structure. $G(x_i) = 0$ represents the limit state function.

Let $I(x_i)$ denotes an indicator failure function, where:

$$I(x_i) = \begin{cases} 1 & if\ G(x_i) < 0 \\ 0 & if\ G(x_i) \geq 0 \end{cases} \tag{17}$$

$$P_f = \int_{D_f} I(x_i) f_{\{X\}}(\{x_i\})\, dx_1 .....dx_n \tag{18}$$

Where D_f is the failure space defined by $G(x_i) < 0$. By introducing $I(x_i)$ in Eq. 18, P_f becomes the expectation value of $I(x_i) : E[I(x_i)]$. Using several random sampling, the Monte Carlo method aims to simulate a high number of load and strength values according to their PDF which are not necessary normally distributed. Let N be the total number of simulation events, for the N computed value of $G(x_i)$, we assume that the failure events frequency where $G(x_i) < 0$ extend towards the failure probability P_f when $N \to +\infty$:

$$P_f = \lim_{N\to+\infty} \frac{Number\ of\ failure\ events\ (G(xi) < 0)}{N} \tag{19}$$

Such a procedure presents the interest of simplicity, whereas it needs a high number of iterative calculations and its convergence speed is very low and it is proportional to $\sqrt{N}$. For a given coefficient of variation of P_f equal to 0.1 the number of Monte Carlo simulations needed is about 100/ P_f . The reliability, R is given by the following relationship:

$$R=1-P_f \tag{20}$$

4 SHOT PEENING ISO-PROBABILISTIC CROSSLAND DIAGRAMS

Interesting shot peening PCD can be determined by application of this proposed approach. For a given case of random loading, dispersed material and surface condition parameters, the PCDs are obtained by using repetitive computations corresponding to various loadings. The principles steps of computation are: (i) determining the uncertainty zone due the Crossland material parameters dispersions (Eqs. 4, 5, 13 and 14), (ii) computing the reliabilities for different loading path by increasing incrementally the mean loading tensors, by using (Eqs. 10, 19 and 20), (iii) recording the different Crossland representative center points corresponding to the mean tensor loadings at the target reliability values and (iv) finally fitting the iso-reliability recorded center points. Those PCD are very helpful to study the influence of the shot peening surface modifications on the HCF reliability of the treated components. They can be used to optimise and to design such structures.

5 APPLICATIONS

In order to validate the proposed approach, we use available results from work of Fathallah *et al.* of an experimental investigations carried out on a ductile steel (SAE type 3415), corresponding to fully reversed torsion and bending fatigue limits of t_{-1} =93MPa, and f_{-1} =146.6MPa, respectively. The samples were obtained with three surface finishing conditions: (i) as machined, (ii) standard shot peening parameters using 100% coverage, (iii) and a severe shot peening parameters with 1000% coverage (high exposure time). The initial surface properties were characterised, near the notched zone of the used fatigue specimen, which is 120° large V-shaped and with a 4mm root radius. The residual stresses and the $FWHM$ profiles were analysed by X-ray diffraction method. In this work, we assume that the residual stresses in the notch root are quite comparable to those obtained in the plane surface. The surface roughness and defects were also observed and examined. Notched specimens were submitted to three points bending fatigue tests, by applying a stress ratio: $R_\sigma = 0.1$.

The fatigue limits were obtained for each surface condition. The results show an enhancement of the HCF behaviour for the standard shot penning condition (100% coverage) and a degradation for the case of the severe condition of 1000% coverage. The application of the Crossland criterion for the case of shot penned parts at the outer and in deeper layers of the notched root of fatigue samples, where the crack initiations have been observed, has been developed in work of Fathallah *et al.*. It leads to the following inequalities:

$$\text{For } z=0,\ \frac{1}{\sqrt{3}} K_t^{xx}(0)\sigma_{xx}^{a}(0) + \frac{\alpha_{C0}}{3}\left[K_t^{xx}(0)\left(\sigma_{xx}^{a}(0)+\sigma_{xx}^{m}(0)\right)+\sigma_{Rxx}(0)+\sigma_{Ryy}(0)\right] \leq (1-D_S)\beta_{C0}\left(\frac{FWHM(z=0)}{FWHM_0}\right)^{0,056} \tag{21}$$

$$\text{For } z>0,\ \frac{1}{\sqrt{3}} K_t^{xx}(z)\sigma_{xx}^{a}(z) + \frac{\alpha_{C0}}{3}\left[K_t^{xx}(z)\left(\sigma_{xx}^{a}(z)+\sigma_{xx}^{m}(z)\right)+\sigma_{Rxx}(z)+\sigma_{Ryy}(z)\right] \leq \beta_{C0}\left(\frac{FWHM(z)}{FWHM_0}\right)^{0,056} \tag{22}$$

In this work, applications of the proposed model were carried out as follow: (i) a first one to evaluate and to analyse the effects of the induced shot peening surface modifications on the HCF reliability and (ii) a second one, to determine several reliability PCDs corresponding to different surface finishing conditions, in order to characterise the HCF reliability behaviour of the peened and unpeened affected layers.

Also, in order to test the capability of the proposed model to take into account the influence of the deviation amplitude level and the type of the statistical distribution (Log Normal and Normal laws), complementary calculations have been carried out.

5.1 Application 1: Effect of shot peening surface properties on HCF reliability

The model has been applied at the first surface layers $(z=0)$, of the three used finishing conditions, where the crack initiation sites have been observed. To evaluate the influence of the shot peening effect on the HCF reliability, we use the critical loading corresponding to the fatigue limit obtained experimentally, for the untreated surface condition. It is defined as follows: ($\sigma_{xx}^{a}(0)$=131.85 MPa, $\sigma_{xx}^{m}(0)$=161.85MPa). Their Cov values were deduced from the experimental scattering results ($Cov\sigma_{xx}^{a}(0)=Cov\sigma_{xx}^{m}(0)$=3%). In this work, the Cov values of the studied material fatigue limits t_{-1} and f_{-1} are taken equal to 1%. The X-ray analysed residual stresses, the $FWHM$ values, the $K_{t}^{xx}(z)$ profile and the D_{S} value, taken from the previous investigation work of Fathallah *et al.* are reported in the present paper. The Cov values of the residual stress and the $FWHM$ values have been deduced from the experimental scatterings. However, the Cov values of $K_{t}^{xx}(z)$ and D_{S} are taken equal to 1%. Following the § 4, the needed sampling size of Monte Carlo simulation (N), used to compute the reliability is taken equal to 10^{4}. Figure 1 shows the material and the loading dispersions zones in the Crossland diagram for the unpeened case at zero-depth. The obtained reliability value is $(R(z=0)=51.97\%)$. The shot peening HCF reliability ($R^{peen}(z=0)$) at the surface layer is computed for the 100% and 1000% coverage shot peened parts. They are determined for three cases: (i) without taking into accounts the superficial defects effect, (ii) without taking into account the superficial defects and the surface imperfections effects and (iii) with taking into account all the shot peening effects. All the computed reliabilities are reported in table I.

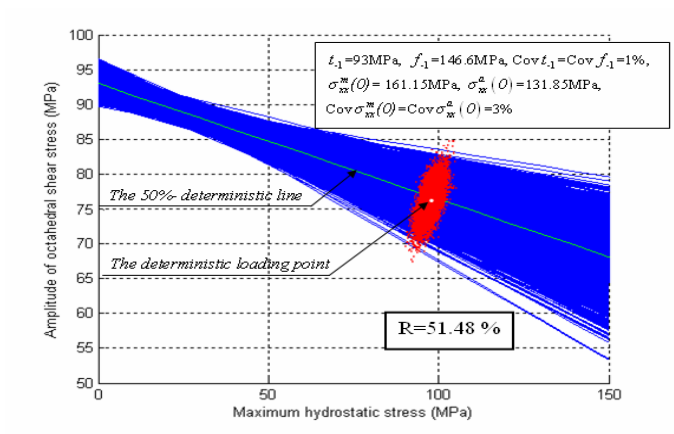


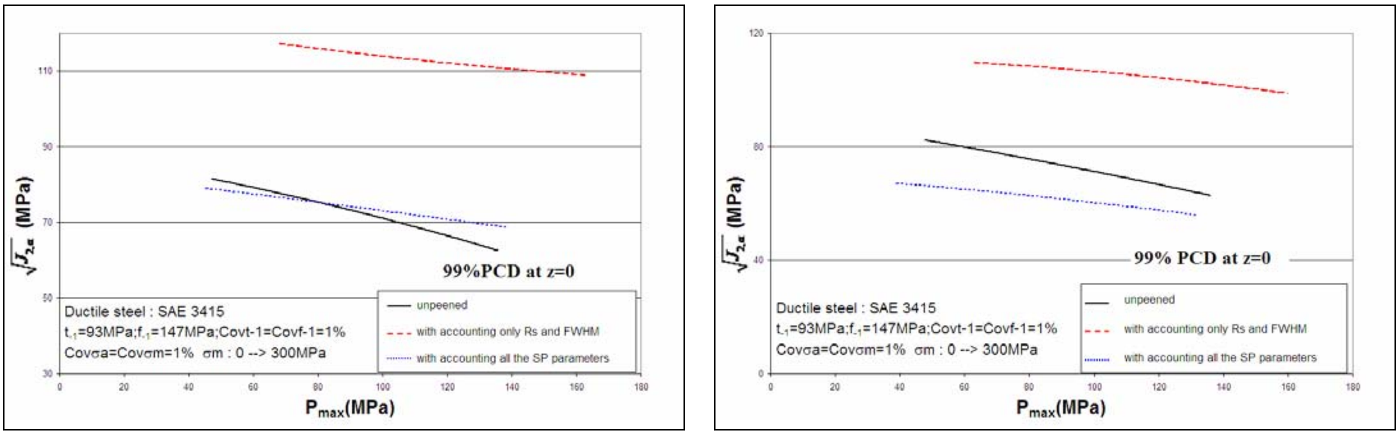
Figure 1. Reliability evaluation (unpeened case).

Table I. Reliability at the first surface layer for the three surface finishing conditions (part submitted to the untreated critical loading).

Surface finishing condition		**Reliability (%)**
As machined		51.48
Shot peening with 100% coverage	without taking into account superficial defects and surface imperfections effects	100
	without taking into account superficial defects effect	99.69
	with taking into account all the shot peening effects	90.64
Shot peening with 1000% coverage	without taking into account superficial defects and surface imperfections effects	100
	without taking into account superficial defects effect	82.56
	with taking into account all the shot peening effects	0.05

5.2 Application 1: Effect of shot peening surface properties on HCF reliability

In this application, we propose to determine zero-depth PCDs, corresponding to the first surface layer $(z = 0)$ of the two shot peening conditions of 100% and 1000% coverage are represented in figures 2.a-b. They are obtained for three cases: (i) the unpeened surface condition and (ii) the shot peened conditions, with accounting only the residual stresses and the work hardening effects and (iii) the shot peened conditions with accounting all the shot peening effect parameters. The PCDs were determined for a range of mean longitudinal stress $\sigma_{xx}^{m}(z)$ situated between 0 and 300MPa.



(a) (b)

Figure 2. The zero-depth 99%-reliability PCD of the two shot peening conditions: (a) 100% and (b) 1000% coverages.

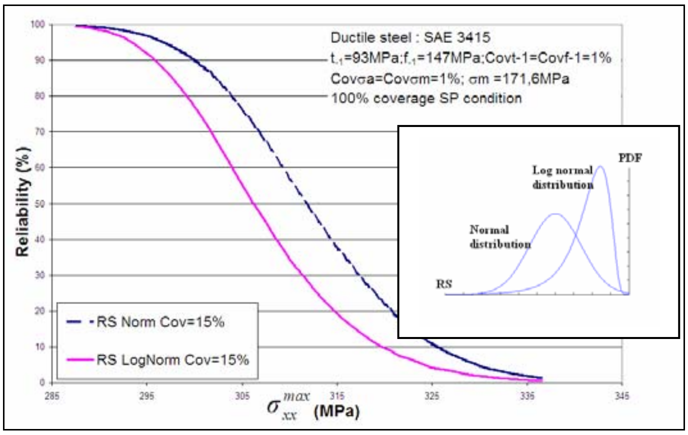
6 DISCUSSION

(i) The first application, carried out for the unpeened experimental fatigue limit loading, shows the applicability of the proposed approach. The computed HCF reliability is 51.97% (figure 1). It is quite equal to the expected value of 50%, which is the probability corresponding to the experimental fatigue test. However, the difference is not significant, and it can be explained by: (i) the induced experimental scatterings, (ii) the statistical method of determining the fatigue limit, and (iii) the adopted hypothesis, particularly the normality of the scattering distributions.

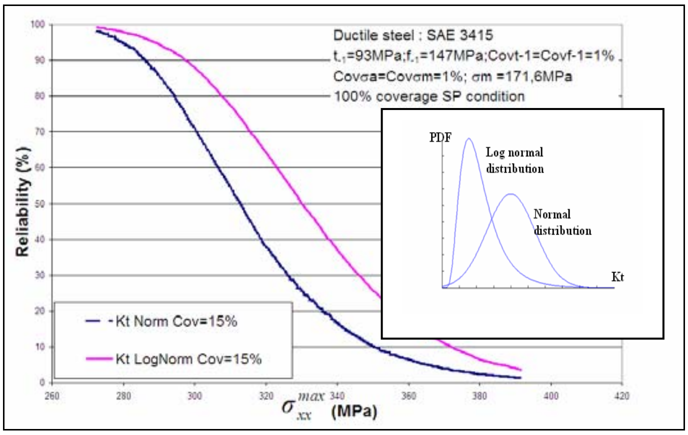
(ii) When all the shot peening effect parameters are taken into account (table I), we observe that the zero-depth 100% coverage shot peening HCF reliability increases from 51,97% to 90,64 % and it decreases from 51,97% to 0,05% for the case of 1000% coverage shot peening. These results are physically consistent with the previous experimental investigations in the work of Fathallah *et al.* whereas, the results obtained when taking into account only the beneficial effects (the compressive residual stresses and the *FWHM* (table I), the model leads to non pertinent and dangerous predictions. Hence, it appears necessary to consider all the peening effects, in order to predict correctly the HCF reliability of the shot peened parts. Moreover, we observe that the model permits to predict and to evaluate the detrimental effects of the superficial defects and micro geometrical imperfections. It is observed, in this case, that the superficial damage is a significant parameter leading to the 1000% coverage degradation of HCF behaviour (table I). A complete sensitivity analysis study can be developed by using for instance the design of experiments method.

(iii) Figures 2.a,b show that for the two shot peening surface conditions, that PCDs obtained by taking into account the two beneficial effects of residual stresses and surface work hardening, are located higher than the those obtained by taking into account all the shot peening parameters: the favourable and the unfavourable effects. This can be used also, to characterise qualitatively the effect of the different shot peening surface modifications.

(iv) Figures 3.a,b illustrate the plotted curves of the computed reliability with the maximal applied stress σ_{xx}^{max}, obtained for the 100% coverage case and by using normal and Log normal PDF surface condition parameters for the favourable effect of the compressive residual stress and the unfavourable effect of the surface imperfection effect, taken within the same range of dispersion. For the favourable case, it is observed that the normal distribution of the residual stress value is more reliable than the Log normal distribution. This is in good agreement with the physical observation, indeed the case of log normal leads to have an absolute mean value of the compressive residual stress less than the normal one's. This observation is also, confirmed in the unfavourable effect case of the surface imperfection, characterised by Kt, where it has been observed that the Log normal distribution is more reliable than the normal distribution. This observation shows clearly the capability of the probabilistic model to take into account correctly the statistical distribution of the input parameters.



(a)



(b)

Figure 3. Reliability-Load curves for the 100% coverage shot peening condition for normal and log normal distributions: (a) CovRs=15%, (b) CovKt=15%.

7 CONCLUSION

In the present work, a probabilistic approach has been developed to evaluate the shot peening HCF reliability. The multiaxial HCF criterion of Crossland has been used by taking into account the: (i) favourable effects of the compressive residual stresses and surface work hardening, and (ii) the unfavourable effects of the superficial damage and micro-geometrical surface irregularities. The reliability has been determined by using the "Strength-Load" method and computed by the numerical Monte Carlo simulation. The dispersions of the material, the loading and the surface conditions have been taken into account. The proposed approach leads to evaluate the reliability and to obtain PCDs corresponding to different surface finishing conditions. A good agreement with the experimental observations has been observed. The capability of the proposed model to take into account, the dispersion ranges and probabilistic laws of the input parameters, has been verified. This approach leads to improve the deterministic shot peening fatigue behaviour analysis by taking into account material and loading dispersions which have a very significant effect on the fatigue behaviour and are rarely taken into account in previous works. Also, this approach leads to compare different shot peening surface conditions and leads to analyse the HCF reliability of each affected layer. The analysis can be carried out for different reliability levels. This improved HCF approach adds a supplementary confidence level to the fatigue behaviour and it can be used as an interesting method for engineering design leading to a more secured HCF behaviour of shot peened parts.

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