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A fracture mechanics based approach to predict fatigue life of scratch damaged shot peened components

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Abstract

Shot peening is a surface treatment widely used in industry in order to extend service life of a large number of components. Recent experimental studies demonstrated that if a scratch of certain size is created over the shot peened surface then the benefit can be reduced or even completely eliminated. Almost no work was published regarding modelling or predicting the fatigue behaviour of the scratch damage over shot peening.

This work presents a methodology to predict the fatigue life and non-propagating cracks of scratch damaged shot peened components. The finite element method was used to determine the actual strain at surface and fracture mechanics parameters calculated from cracks emerged on the residual stress profile. The total fatigue life is obtained by adding initiation life, which is calculated by the strain-life model, with crack propagation life determined using \( \frac{da}{dN} \) curves. A good agreement was found between the numerical predictions and experimental results, showing that this method is quite reliable for predicting both fatigue life and non-propagating cracks of scratch damaged shot peened components.

Keywords: shot peening; scratch damage; finite element method; fracture Mechanics; strain life; non-propagating cracks.

Nomenclature

\( a_0 \) El Haddad \textit{et al.} constant

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Shot peening is one of the most effective and popular surface treatments used in industry to improve fatigue properties of components. The benefit is created by the impact of a large number of hard, usually spherical shot, onto the surface of a component that causes local plasticity, resulting in a cold worked surface with a compressive stress field which has advantages in reducing the likelihood of crack formation and fatigue crack growth. This layer is only of some hundreds of microns depth, but enough to be quite effective. It is almost unanimously accepted that the principal benefit of shot peening in fatigue is created by the compressive stress field at the surface and a less evident effect of cold work, which has advantages in reducing/stopping microcrack propagation [1-3].

Some concern arises if the treated surface is damaged in some way, for example by a scratch. Recent experimental work demonstrated that if a scratch is created over the treated surface the benefit may be reduced or vanish completely, depending on scratch size, [2]. Little work has been published about the simulation of a scratch in a compressive residual stress field like that induced by shot peening. Benedetti et al [4] recently proposed an approach based on the stress field state and on the characterization of the fatigue properties of the material in different metallurgical states, however this method provides only an estimate of the fatigue life and does not give information about crack propagation. Recently the authors proposed a method to assess the fatigue life of shot peening surfaces [5], based on fracture mechanics and finite element analysis with residual stress which provided excellent results for surfaces without damage. The same methodology will be applied to damaged surfaces in order to fatigue model and understanding better the influence of scratches in the shot peened surface.

2. Fatigue life prediction model

The model proposed divides the fatigue failure process of scratch damaged shot peened components into three regimes, similar to the Cameron and Smith [6] approach for notched components but with some changes to include shot peening. For the first regime, i.e. crack initiation the strain life method modified by Smith et al. [7] to include mean stress is proposed. The strain is calculated from finite element analysis of the component considering the residual stress due to shot peening and the scratch geometry. Fatigue life during crack propagation is calculated by integrating the Paris law between a crack size as defined by the El Haddad et al. constant [8] up to the critical limit of the material. For short cracks $J$ integral solutions are calculated close to the scratch root using non linear finite element model accounting for the effect of the residual stress induced by shot peening and crack closure effects. In order to use Paris law, $J$ integral solutions are converted to $K$ solutions assuming plain strain. $K$ solutions for long cracks are used without the effect of shot peening or scratch. The transition crack length, between short and long crack propagation, is determined when the $K$ solutions are equal, as proposed by Dowling [9].
3. Specimen studied

Several specimens were tested at high temperature (650°C) in the conditions as-machined and shot peened (110H 6-8A 100%) in order to determine the effect of shot peening on fatigue life. The specimen, fig. 1 (a), is representative of a critical region of a gas turbine aero engine compressor disc. In some specimens scratches were created artificially after shot peening, in one side, at the root of the stress feature using an NC milling machine. The scratch was 3 mm long and 50 μm or 100 μm deep as represented in fig. 1 (b) and (c) (the critical cross section of the specimen has dimensions 11x5.08=55.88mm²). The elastic stress concentration factor is \( K_t = 1.33 \) (curvature radius of 4.5mm) for the plain surface, \( K_t = 3.98 \) for the 50μm scratch depth and \( K_t = 5.03 \) for the 50μm scratch depth, [2].

The material of the specimens is a nickel base superalloy developed using a powder metallurgy technique, whose commercial name is RR1000. Material properties can be found in [10, 11].

The residual stresses were measured, by X-Ray diffraction combined with electrolytic polishing to assess in depth values. The compressive residual stress after thermal exposition at 650°C during 100h is about 135MPa at surface, the peak value is at 40μm from surface with 875MPa and vanishes at about 130μm from surface. The residual stress profile can be found in [12].

Specimens were fatigue tested in a servo-hydraulic testing machine, in load control, with a trapezoidal waveform 1-1-1-1s and load ratio of R=0.1. Loads were selected so that failure could occur in the range of 1000 to 100000 cycles. More details about experimental setup can be found in [12].

Coffin-Manson parameters, necessary for strain life evaluation, were obtained by the least squares method from the results published by Zhan [13], who tested five specimens in low cycle conditions similar to the ones used in this work. Paris law parameters, necessary for crack propagation analysis, were obtained from the experimental results carried out to the specimens tested in the as-machined condition [2]. All parameters can be found in [14].

4. Finite element models

The abovementioned specimens were modeled using the finite element code ABAQUS©. The aim of this study was to obtain parameters to be used for fatigue life assessment. Two bi-dimensional models of part of the geometry (due to symmetry conditions) were built, fig. 1 (a) and fig. 2. Both models are non-linear with biquadratic plain strain elements (CPE8) which can include both as machined and shot
peened superficial conditions. For the first model the objective was to determine the strain at surface for 
both surface conditions and with the scratches, fig. 2(b). The second model includes a very small crack in 
which integral solutions were taken for several crack sizes (from 0.01mm to 0.5mm depth) emerged in 
the notch root. As this is a 2D model the crack shape is assumed to be a through crack in thickness. A 
master-slave surface was defined in the crack faces to prevent overlapping when the crack closes.

![Fig. 2. (a) 2D FE element model; (b) mesh in the critical section with scratches created to assess strain and stress; (c) crack with 500 μm depth in the root of a scratch with 50 μm depth](image)

The Chaboche model (time independent kinematic hardening) was used to define the cyclic material 
behavior whose parameters are published on [15]. In order to simulate residual stress due to shot peening 
a thermal gradient was introduced with the same profile as the residual stress measured experimentally [5, 
14]. This method was successfully applied before by Cook et al. [16]. This model does not include the 
effect of strain hardening at the surface or of surface roughness due to shot peening.

5. Finite element results

Fig. 3 presents some results from finite element analysis. The parameters for the strain life model are 
represented in fig. 3 (a). Strain range is coincident for both shot peened and as machined conditions. The 
effect of shot peening is only noticed in the mean stress. However at the surface only a small difference is 
noticed for the geometry without scratch (strain life model only considers strain at surface).

The effective value of the stress intensity factor, calculated from integral solutions assuming plain 
strain conditions, is plotted in fig. 3 (b). The effect of shot peening is clearly evident where residuals are 
higher in compression. For the geometries with scratch the curve follows exactly the values obtained for 
those without damage, being noticed a very small (almost negligible) influence of the scratch root. This 
figure also represents the values of $a_0 = 0.0171\text{mm}$ and an estimative of $\Delta K_{th} = 6.6 \text{MPa}\sqrt{\text{m}}$ for this 
material [14].

![Fig. 3. FEM results for the geometry without scratch, 50μm and 100μm scratch depth for a maximum nominal stress of 900MPa (a) strain range and mean stress; (b) effective stress intensity factor range against crack size](image)
6. Fatigue life predictions

Total fatigue life predictions were made according to the procedure given in 2. As proposed, initiation life is calculated using the strain life method corrected to account for mean stress. Propagation in the compressive region affected by shot peening is assessed by integrating the Paris law with the stress intensity factor solutions provided in fig. 3 (b). For long cracks (\(a \geq 0.5\, \text{mm}\)), where the influence of the scratch and shot peening is negligible, fatigue life was calculated by integrating the Paris Law with \(K\) solutions for the specimen geometry that can be found in [14]. Table 1 shows the fatigue life predictions and fig. 4 compares the predicted values with experimental results [2].

Table 1. Fatigue life predictions

<table>
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<tr>
<th>Surf.</th>
<th>Sc. Depth [(\mu\text{m})]</th>
<th>Max. Stress [MPa]</th>
<th>Crack Init. (a_0) 0.3mm [cycles]</th>
<th>(a_0) 0.3mm [cycles]</th>
<th>(K_{\text{mer}}) [cycles]</th>
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Fig. 4. Numerical predictions against experimental results

7. Discussion

Analyzing the results of tab. 1, and according to this model, the shot peening effect is quite effective in shot crack propagation (having almost one order of magnitude increase in fatigue life) and has almost no influence on crack initiation. In fact, cyclic relaxation almost eliminates the shot peening effect at surface, fig. 3 (a). This is in agreement with some workers statements [3, 17] and others which argue that the superior resistance of shot peened components to fatigue is due to the ability of the residual stress in stopping microcrack propagation and less in preventing fatigue crack initiation. It can be seem from fig. 4 that there is a good match between the numerical results and the experimental observations. Even for shot peening, predicted life is extremely well fitted. The maximum deviation is for the geometry with 50\(\mu\text{m}\) scratch where the expected fatigue life ranges from one half to the double of that experimentally obtained, which is acceptable for fatigue results.

The model proposed by Cláudio et al. [5] also allows predicting the load for crack arrest by determining the load at which \(\Delta K_{\text{eff}} \leq \Delta K_{\text{th}}\) at \(a_0\) length from results of fig. 3(b). Several specimens, that were fatigue tested, did not fail even after a large number of cycles non-propagation cracks being found with 15\(\mu\text{m}\) depth (i.e. close to \(a_0=17.1\mu\text{m}\)), [12] which confirms the validity of the model proposed. In fact, the calculated load for crack arrest (which can be found in [14]) fits very well the experimental results, making this an appropriated model to predict crack initiation, propagation, crack arrest and fatigue life.
8. Conclusions

Fatigue life was successfully predicted for the specimens studied, both shot peened and scratched using only properties taken from plain specimens such as: material parameters, LCF results, crack propagation data, and information about the residual stress profile due to shot peening.

Numerical simulations accurately predicted crack arrest for scratch damaged shot peened specimens.

The model proposed, by adding the fatigue life in crack initiation with early crack propagation and crack propagation provides a detailed understanding of the fatigue crack growth in shot peened components, being in agreement with many workers statements and experimental results.

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