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Evaluating the influence of residual stresses and surface damage on fatigue life of nickel superalloys

R.M.N. Fleury *, D. Nowell

Department of Engineering Science, University of Oxford, Parks Road, OX1 3PJ Oxford, UK

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A B S T R A C T

The effect of surface damage, such as dents caused due to the low velocity impact of hard blunt objects, on the fatigue life of mechanical components are investigated in this paper. A two-dimensional dislocation density approach is used to obtain the stress intensity factors of a crack propagating under dents. Both the contributions of the geometrical stress concentrator (notch), due to the presence of the dent, and the residual stress field, generated during the impact, on the stress intensity factor of the crack are obtained. A short crack growth model is then used to predict the fatigue life of nickel superalloys in the presence of two dent depths. The effect of the residual stress field has been shown to be the main contributor to the difference observed in predicted fatigue life between the two dent depths analysed.

1. Introduction

The effect of handling and service surface damage on the fatigue life of components of gas-turbines has increasingly been the focus of research by aero-engine manufacturers. Surface anomalies on engine parts may occur during manufacturing and maintenance due to low velocity impacts by hard objects, e.g. tool dropping or one part striking another during transport. Typically, these impacts cause dents and scratches on the surface of gas-turbine components. Current evaluation methods of the effect of dents and scratches on aero-engine components service lives follow a very conservative approach of assuming the damage as a propagating crack. This approach takes into account neither the residual stress field generated near the damage nor the time that it takes for the crack to initiate at the stress concentrator. This conservative approach implies a lower accuracy in predicting the fatigue life of components and higher cost associated with maintenance of aero-engines throughout their service life.

Mall et al. [1], when investigating the effect of foreign object damage (FOD) on Ti alloys, found that three main issues affect the fatigue life of components in the presence of surface dents: (i) the geometrical stress concentration under the 'notch' (i.e. dent); (ii) the residual stress field created during the impact; and (iii) the micro-structural changes due to the deformation. Although FOD occur due to much higher impact velocity events, most aspects of FOD are also true for handling surface damage. Using a potential drop technique, experiments undertaken by Groudin et al. [2] have shown that compressive residual stresses due to the impact of objects significantly slow down crack growth in dented and scratched specimens. A similar study was carried out by Doremus et al. [3] using Inconel 718 specimens. They have shown that the initiation life in dented specimens, which had sharp internal corners, reduces once the residual stresses are removed, whereas scratches show the opposite effect.

Finite element models have been used to simulate various impact problems and the residual stresses caused by them. Boyce et al. [4] investigated the residual stress due to the impact of a spherical projectile on Ti alloys. They suggested that impact events of low impact velocities (<200 m/s) can be modelled using a quasi-static approach. Doremus et al. [3] also used a quasi-static model to simulate scratch and sharp dent damage. Higher velocity events such as FOD have been modelled by explicit finite element code [5]. Duó et al. [6] have used laboratory and synchrotron X-ray diffraction (XRD) to measure the residual stresses caused by FOD and validate the explicit finite element code. Comparison between FE models and XRD residual stress measurements can also be found in [7,8]. More recently, a model was developed to predict low impact velocity blunt damage in Nickel superalloys [9]. The model was validated by comparing the geometry of the dent and the residual stress under the dent by laboratory XRD.

Several authors have investigated the impact of FOD on low and high cycle fatigue crack growth [10–12]. Particularly, Nowell et al. [13] and Oakley and Nowell [14] investigated the impact of FOD on

* Corresponding author.
E-mail address: rodolfo.fleury@eng.ox.ac.uk (R.M.N. Fleury).

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fatigue life of turbine blades using a dislocation density method [15,16]. In this paper, we use the FE model validated in [9] to obtain the geometry and residual stress field around blunt dents of different depths. Then, a dislocation density approach is used to obtain the stress intensity factors of a crack propagating under the dents, and in the presence of the residual stress field. Fatigue life predictions are carried out by using the calculated stress intensity factors together with short and long crack propagation laws.

2. Numerical simulation of damage

2.1. Finite element model

The dents and their respective residual stress field generated due to the impact of a hardened steel blunt indenter on RR1000 Nickel superalloy specimens were modelled using an explicit FE solver in LS-DYNA. The model used in this paper is the same model used to simulate the experimental damage introduced on fatigue specimens in [9]. The FE model geometry and boundary conditions are given in Fig. 1, where symmetry was exploited. The profile of the blunt indenter is generated by two perpendicular surfaces of curvature $R_1 = 12.55$ mm and $R_2 = 1.00$ mm. The springs simulate the compliance of the rig and their stiffness is the only calibrated parameter in the model. The calibration was carried out by choosing the appropriate spring stiffness in order to obtain similar rebound velocity as measured experimentally [9]. The optimal value of the calibrated spring stiffness for the impact velocity range analysed is $k = 3 \times 10^3$ N/m. The impact velocity was chosen as to obtain dents of 5 and 10 thou depth ($\sim$ 127 and 254 μm) according to the calibration.

The nickel superalloy elasto-plastic properties were provided by our industrial collaborator. The room temperature true strain true stress material data was implemented in LS-DYNA as piecewise linear elastic–plastic Material 24.[1] A purely elastic model was assumed to the hardened steel indenter and an elastic perfectly plastic material model was used to simulate the deformation of the supporting brass bar behind the specimen. The material properties used for the brass block are: $E = 97$ GPa, $\nu = 0.31$ and $\sigma_Y = 150$ MPa. Linear hexagonal elements with reduced integration were used with a final mesh size near the centre of the notch of $h_e = 0.05$ mm. A stiffness based hourglass energy was added to the elements in order to avoid hourglass modes of deformation. The hourglass energy was kept below 10% of the total energy in order to reduce its impact in the final deformation of the dent.

2.2. Residual stress and dent geometry

The residual stress field generated under the dent during the impact of the striker was obtained by the FE model in LS-DYNA. The dynamic analysis of the impact of the indenter did not include any damping and, hence, a ‘springback’ static analysis was carried out at the end of the dynamic step in order to obtain the residual stresses in unloaded equilibrium. A typical field distribution of the stress component σ_{xx} under the dent is displayed in Fig. 2a. Note that the fatigue load direction is also along the x-direction. A significant compressive zone may be observed under the dent, while the root of the dent is under tensile stress. It is clear from the results in Fig. 2 that whilst the tensile stress under the root will accelerate crack initiation and growth, the compressive zone will slow down the crack propagation. Note that the dent geometry behaves like a notch causing a geometrical stress concentration,

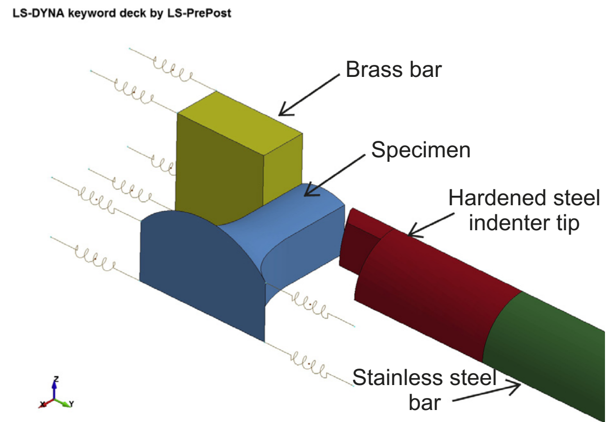

Fig. 1. Model geometry and boundary conditions used in the LS-DYNA explicit FE code.

which will accelerate the crack growth. The geometrical effect of the notch and the compressive residual stress will have an opposite competing effect on the crack propagation and under certain conditions crack arrest may be observed.

The stress under the centre of the dent along the depth, y, measured from the root of the dent is shown in Fig. 2b for dent depths of 5 and 10 thou. The main difference in stress profile under the dent between the two dent depths is the extent of the compressive zone, although the 5 thou dent residual stress profile also show higher compressive stresses under the dent. These results have been validated by comparison with residual stresses measured by laboratory XRD [9]. The results displayed in Fig. 2b will be used in Section 3.3 in order to calculate the stress intensity factors of a crack propagating in the presence of the residual stress field predicted by the FE model.

The geometry of the dent is also relevant in the calculation of the stress intensity factor of a crack propagating under a notch. Three parameters characterise the ‘notch’ (i.e. dent) created due to the impact: (i) the depth of the notch; (ii) the radius of the notch root; and (iii) the notch angle (Fig. 3). The notch depth, d, is the deepest point of the dent. The notch angle is 2θ and from the FE results it was found that $\theta \simeq 65^\circ$ for all dent depths. The value of the notch root radius is $\rho = 1.3$ xmm, which was measured from the FE results. This is slightly higher than the radius $R_2 = 1.1$ mm of the indenter. An important parameter necessary for the stress intensity factor analysis due to the notch is the ratio ρ/d. These were found to be $\rho/d = 10.2$ for the 5 thou dent and $\rho/d = 5.1$ for the 10 thou one.

3. Stress intensity factor calculation

3.1. Dislocation density method

The input for the crack growth rate model given in Eq. (9) is the stress intensity range at the crack tip. A dislocation density approach is used for the calculation of the stress intensity factor of a crack propagating under a notch (i.e. dent). This approach is for two-dimensional problems. However, although the geometry of the dent is not two-dimensional, at the centre of the notch plane-strain approximation may be used with little loss of accuracy. The approach was first formulated by [15,16] for two-dimensional cracks and slots. It has also been applied to notches due to FOD [13]. The approach uses dislocations, i.e. displacements discontinuities, to simulate the stress free boundaries of the notch and the crack. The stress components σ_{ij} due to a dislocation at an arbitrary point (x_d, y_d) is given by

[1] Due to the confidentiality agreement between the University of Oxford and Rolls-Royce plc we are unable to provide the exact elastic-plastic material data of the RR1000 alloy used in this analysis.