Experimental and Numerical Investigation of Residual Stress Relaxation in Shot-Peened Notch Geometries under Low-Cycle Fatigue

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In service, turbine components are subjected to low-cycle fatigue (LCF) during start-up and shut-down operations, especially at the fir tree root blade-disc connection which has a complex geometry and corresponding high stress concentration. Shot peening generates compressive residual stress and strain hardening which can improve fatigue life [1]. However, prediction of the fatigue life of shot-peened components under LCF is challanging due to difficulties associated with predicting residual stress relaxation, especially in regions of high stress concentration. The current study aims to develop a validated 3-D eigenstrain-based modelling tool to model residual stress relaxation under LCF in shot-peened notch geometries. The residual stress and strain hardening profiles caused by shot peening have been first evaluated by experiments and then incorporated into the finite element (FE) model separately.

The material under investigation is FV448 - a ferritic heat resistant steel representative of those used for steam turbine blades. An industrially applied shot peening treatment (intensity: 13A, coverage: 200%) for steam turbine blades has been applied to U-notched samples (K_t = 1.58) representative of the real fir tree geometry. The LCF behaviour of the shot-peened sample has been evaluated by three-point bend tests with a load ratio R = 0.1 [2].

Residual stress variation with depth at the notch root of shot-peened samples was measured before and after fatigue load cycles, using an X-ray diffraction (XRD) device and an incremental layer removal approach achieved by electropolishing. In addition, an EBSD-based approach [3] has been used to measure the plastic strain caused by shot peening, which was then used to determine the local strain hardening levels in peened samples.

In the FE model, a combined isotropic-kinematic hardening material model has been applied, considering both the monotonic and cyclic mechanical properties of FV448 which have been determined experimentally [2]. The residual stress distribution in peened samples was simulated as an elastic response of the whole component to the predicted misfit strain (i.e. eigenstrain) caused by shot peening [4]. In order to incorporate the effects of strain hardening into the FE model, varying local yield stresses were defined at different depths within the surface layer affected by shot peening. Residual stress relaxation after 1 cycle and 50% life (about 15000 cycles) was then simulated by applying a similar load as in the real experiment to the FE model; the applied nominal strain range $\Delta\varepsilon$ in the loading direction was 0.68%.

The results show that the full residual stress distribution has been accurately modelled in the peened notched sample. The modelling results of residual stress relaxation after cyclic loading ($\Delta\varepsilon$ = 0.68%) match well with experimental data; a 20% relaxation was observed after the first cycle but with no further relaxation during subsequent fatigue cycles.

This study suggests that the hybrid eigenstrain/FE approach is particularly effective in modelling residual stresses in shot-peened components with notch geometry. This approach is helpful in evaluating the benefit of shot peening by effectively predicting residual stress relaxation after fatigue loading.

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