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Numerical modelling of the fatigue crack shape evolution in a shot-peened steam turbine material

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ABSTRACT

In this study, the short crack initiation and growth behaviour in a notched sample under low-cycle fatigue (LCF) was investigated in a low-pressure steam turbine material. Different crack initiation mechanisms and crack shape evolution processes were experimentally observed in samples subjected to different surface treatments: polished, T0 (industrially applied shot peening process) and T1 (a less intense shot peening process). To better understand the effects of shot peening on fatigue, a 3D finite element (FE) model was developed to investigate the interaction between crack growth and the effects induced by shot peening. Firstly, residual stress redistribution caused by both mechanical loading and the presence of a crack was numerically investigated. This model was also used to successfully predict the differences in crack shape evolution between varying surface conditions, and quantified the retardation of short crack growth behaviour resulting from shot peening. Finally, the 3D model introduced in this study was compared with a previously developed 2D model with plane strain assumptions to demonstrate the limitation of the 2D model in simulating the crack growth behaviour, and to emphasise the importance of taking the 3D crack shape into account when evaluating the short crack growth behaviour.

1. Introduction

Shot peening is an effective surface treatment method used to improve the fatigue resistance of metallic components, particularly in regions with stress concentration features, such as the fir tree interface in steam turbine systems [1–3]. During the shot peening process, the surface of the workpiece is bombarded by a stream of small spherical shots at high velocities acting as tiny peening hammers, producing inhomogeneous plastic deformation near the surface. This process typically induces increased surface roughness, strain hardening and compressive residual stresses (CRS) within the surface layer [4]. Many investigations have focused on the effect of shot peening on fatigue behaviour in different material systems such as steel [1,3,5–7], aluminium [8–13], titanium [8], magnesium [8,14,15] alloys and nickel-based superalloys [16,17]. It can be generally concluded that the roughened surface after the peening treatment may accelerate crack initiation [8], on the other hand, the CRS and strain hardening effects can compensate for this by deferring the short crack onset and propagation process [5,9,10,14,18]. Recent reviews [19,20] have detailed at some length the effects of shot peening on fatigue by discussing the interaction between the shot peening induced effects (i.e. surface roughness, CRS and strain hardening) and service conditions. Although the effects of shot peening on fatigue have been well documented, it is still unclear how to accurately quantify the benefits of shot peening in prolonging fatigue life, which impedes the development of a less conservative lifing approach exploiting the benefits of shot peening but with sufficient safety margins.

Many researchers have systematically studied the residual stress relaxation behaviour in shot-peened specimens during fatigue loading both experimentally and numerically [2,6,7,11,15,16,21–23]. It was found that the residual stress distribution generally reached a stabilised state after a logarithmic relaxation process during fatigue loading. Most studies have related the improvement in fatigue life by shot peening to the extent of the remaining CRS field after residual stress relaxation, and tried to predict the fatigue life utilising some stress- or strain-based approaches without explicitly considering the crack initiation and propagation behaviour [6,7,24,25]. These approaches have been demonstrated to be effective and efficient, particularly in the high-cycle fatigue (HCF) regime. However, in the low-cycle fatigue (LCF) regime where the relief of CRS is typically more significant, the competition between the effects of surface defects (introduced by shot peening or the manufacturing process) and CRS on short crack growth becomes more pronounced

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[18,26–30]. This leads to diminished benefits of shot peening in improving fatigue life, compared with the HCF regime. Sometimes shot peening may further lead to a degraded fatigue life due to the dominant effects of surface defects on accelerating crack initiation and early propagation [27–30]. Hence, in the LCF regime, the stress- and strain-based approaches may result in non-conservative life prediction, which is unacceptable [24]. Under such circumstances, in addition to understanding the mechanism of the retarded short crack growth realised by shot peening, quantifying this retardation is a prerequisite before developing appropriate lifing methodologies.

To date, most of the quantitative studies on short crack growth behaviour influenced by shot peening (or other surface treatments resulting in CRS, such as laser shock peening) have relied on analytical [12,13] and finite element (FE) [17,31,32] modelling. According to these analyses, the CRS-induced crack closure, which reduces the effective stress intensity factor (SIF) range, ΔK_{eff}, has been deemed as the main factor leading to the delayed short crack growth behaviour. However, the effects of shot peening on crack shape have rarely been considered in previous work, due to the lack of reliable quantitative experimental data describing crack propagation in the bulk of the material to support relevant modelling work. Therefore, most studies assumed a constant crack shape during crack growth [13] or simulated through-thickness cracks as a simplification of the reality [17,32].

He et al. [18,33] recently reported a significant discrepancy between the short crack shape evolution in polished and shot-peened notched samples made of a 9–12% Cr steel (a steam turbine material). This discrepancy was closely related to the shot peening process and the microstructure of the material. This implied the necessity of taking the crack shape effects into account when evaluating the influence exerted by shot peening on short crack growth. Hence, the current study utilised a 3D FE model containing a semi-elliptical crack to investigate how shot peening affects crack shape evolution, and how significant it is in life assessment. Both the crack size and crack shape evolution have been reasonably well predicted based on the modelling results. The FE model applied in this study was developed from a previous FE model which has been demonstrated to be effective in simulating residual stress relaxation [22]. The same material as He et al. [18,33] has been selected and the reported experimental data have been used as validation of the present modelling work. The current work is also relevant due to the relatively few investigations focusing on steam turbine materials subjected to shot peening compared with other material systems [1–3].

Table 1
Monotonic tensile properties of FV448.

$\sigma_{0.2}$ /MPa	σ_{UTS} /MPa	Strain (%) at failure	E/MPa	ν
806 ± 6	987 ± 9	12 ± 3	201.3E + 03	0.3

2. Experiments

2.1. Material and specimen

The material under investigation is FV448, a 9–12% Cr tempered martensitic steel which is representative of the type of material used in low-pressure turbine blades. This material is typically austenitised at 1150 °C, oil quenched, tempered at 650 °C and then air cooled. The main monotonic tensile properties of the materials are shown in Table 1. The other mechanical properties, microstructure and composition of this material have been detailed in [21]. In this study, a U-notched specimen (stress concentration factor, K_t = 1.58) representing the fir tree root geometry of a turbine blade has been used. The dimensions of this specimen are shown in Fig. 1.

Samples to be shot peened were all ground to achieve an initial surface roughness of R_a < 0.8 μm, meeting the industrial machined component (and pre-peen) specification. Some ground samples were polished to remove the grinding marks and the associated residual stress field, with a surface finish of ±1 μm. Both ground and polished samples were used in the baseline tests as a comparison with the shot-peened condition. Two shot peening treatments were investigated in this study. MI230R 13A 200% (intensity: 13 A, coverage: 200%, shot diameter: 0.58 mm), labelled as T0, was chosen as the baseline shot peening treatment since it was industrially applied to steam turbine blades. Another process, MI110R 04A 200% (intensity: 4 A, coverage: 200%, shot diameter: 0.28 mm), labelled as T1, was considered as a comparison. All the shot peening treatments were carried out by Metal Improvement Company, Derby Division.

Experimental residual stress measurements were carried out at the notch root using X-ray diffraction (XRD), accompanied by incremental layer removal via an electro-polishing process to obtain the stress profile into the depth. Details regarding this measurement have been elaborated in [3,22] so are not repeated here. The residual stress distributions caused by the T0 and T1 process at the notch root are shown in Fig. 2, illustrating that the T0 process results in a greater and deeper compressive residual stress layer than the T1 process. In addition, the plastic strain caused by shot peening has been measured using an electron back-scatter diffraction (EBSD) based approach [21]. The results are shown in Fig. 3, illustrating more significant strain hardening effects caused by the T0 process than the T1 process.

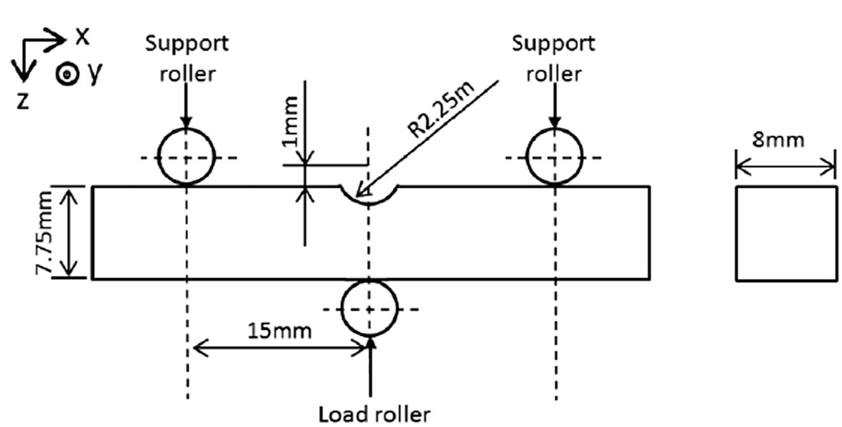

Fig. 1. Dimensions of the U-notched specimen.