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Residual stresses in condition monitoring and repair of thermal power generation components

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ABSTRACT

Residual stresses have a significant impact on fatigue and fracture of engineering components and structures, with an effect that is largely dependent on the sign of the residual stress relative to that of the applied stress, i.e. on whether they add to, or subtract from, the applied stress. The present paper will emphasise the importance of detailed knowledge of residual stresses to applications in thermal power generation. The context of the examples is condition monitoring and repair procedures where assessment of the influence of residual stress fields is important to both fatigue and fracture performance, and to certification of the repair procedure itself. The main conclusion in the paper is that the innovative use of solid-state friction taper hydro-pillar processes can offer additional capability in condition monitoring of through-thickness creep damage in thermal power plant, as well as provide cost-effective local repair of creep or fatigue damage in, for example, thick-walled steam pipe and blade-disc attachment holes.

1. Introduction

Residual stresses have a significant impact on the fatigue and fracture performance of engineering components and structures. Their effect can be either positive (life enhancing) or negative (life reducing) and this is largely dependent on whether the residual stress adds to, or subtracts from, the applied stress. Several useful reviews of residual stress and their effects are given in Refs. [1–3]. It is also the case that the high level of residual stress induced during most manufacturing operations may be overlooked by engineering designers (see for example, data on the residual stress level induced during hot [4] and cold [5] rolling). Surface modification techniques and welding are particularly influential in determining fatigue and fracture performance and, in the case of welding, also create geometric discontinuities that provide additional points of stress concentration. There are interesting possibilities in designing alloys that can reduce weld-induced residual stress through phase transformation. This was illustrated in a paper by Bhadeshia [6] who emphasised the important role that metallurgical phase transformations and associated shape changes play in affecting the development of residual stresses. He outlined the design of alloys such that the deformation caused by bainite and martensite transformations eliminates residual stress, leading to extraordinary improvements in the fatigue life of constrained structural assemblies. It is clearly highly beneficial to optimally design welding fabrication in terms of both process parameters, e.g. heat input, preheat and interpass temperatures, as well as in metallurgical terms through consideration of filler metal alloy content, cooling rate and post-weld heat treatment (PWHT).

Further complexity in life prediction arises from the modification of residual stress during cyclic loading and there is no definitive guidance available to assist with predicting this effect. A classic example of this aspect of stress modification during fatigue cycling is the relaxation of shot peening stresses in the fir tree root region of steam turbine blades during service, which could lead to blade failures in low pressure steam turbines. Other work reported by some of the present authors [7] details the work done in characterising residual stresses and fatigue life prediction for the last stage blades in the low pressure turbines of a 600 MW turbo-generator set. The residual stress field in the fir tree blade attachment region was measured on new unpeened and peened blades, and on ex-service blades using high energy synchrotron X-ray diffraction. Fig. 1 shows such a 23 kg last stage blade mounted on the stage of the ID15A instrument at the ESRF in France, for bi-axial measurements of the residual stress.

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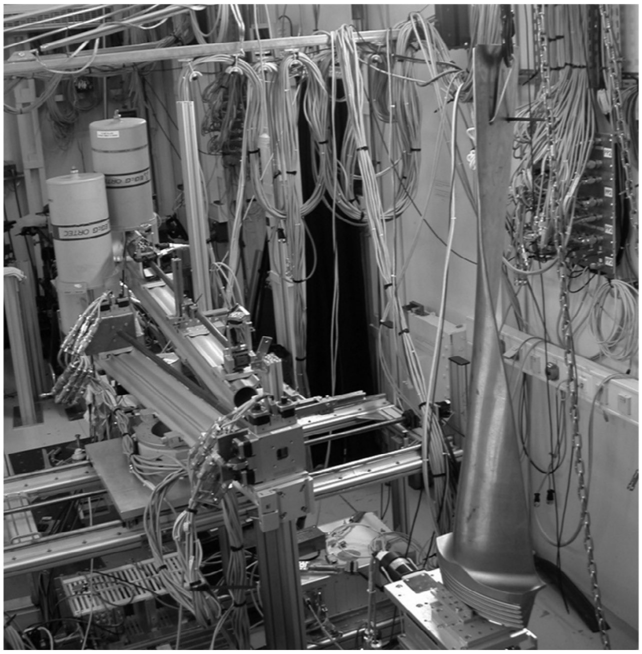

Fig. 1. Bi-axial measurement of residual stresses in a 23 kg 12CrNiMo martensitic steel turbine blade.

Shot peening has been used for many years as a means of combatting fatigue failure via mechanical pre-stressing of the surface of engineering parts; Cary [8] and Guagliano [9] have both provided interesting reviews of its chronological development. Tensile residual stresses are usually the most detrimental in general service, and, in the presence of a macroscopic notch, they can also lead to fatigue crack initiation and growth during compression-compression fatigue. In these cases, the notch root region undergoes plastic deformation during the compressive part of the fatigue loading and develops a tensile residual stress field during the unloading part of the fatigue cycle. The superimposed compression fatigue loading then leads to tensile fatigue cycling in the cyclic plastic zone. An example of a situation where tensile residual stress associated with compression fatigue of a notch can lead to fatigue crack growth is that of hard materials [10], where the phenomenon can be useful in pre-cracking of standard fracture toughness specimens, e.g. [11]. Fatigue crack growth under compression-compression loading has been analysed by Vasudevan and Sadananda [12] while Lenets has considered environmentally-assisted compression fatigue of metallic materials [13]. Examples of this mechanism in action, leading to failure of aircraft landing gear struts and other components, have been reported [14].

Predicting fatigue performance in the presence of residual stress fields remains complex, particularly for welded structures, although documents such as BS 7910:2013 [12] now provide generalized guidance on residual stress profiles in as-welded joints (annex Q) and on the likely values of residual stress in structures subject to post-weld heat treatment (see Section 7.1.8.3) in an enclosed furnace with temperature ranges between 550 °C and 620 °C. The guidance further notes, however, that where local post-weld heat treatment is carried out no general recommendations can be given and conservative assumptions should be made; this would be the usual case for any large structure that contains welds (either from fabrication or from repair processes). Stacey et al. [15] have discussed the incorporation of residual stress assessment procedures into the EU SINTAP defect assessment procedure and note that the SINTAP procedure is built on the guidance contained in BS 7910 and the CEGB R6 procedures. SINTAP is an acronym for Structural Integrity Assessment Procedures, a project funded by the European Community whose aim was to develop a unified procedure for European Industry that covered structural integrity assessment of structures and components.

It is the premise of this paper that accurate life prediction relies on detailed experimental assessment of residual stresses, often combined with simulation using numerical analysis techniques, e.g. Ref. [7]. In recent years, very significant advances have been made in the ability to perform full-field measurements of residual stresses via sophisticated 3D synchrotron X-ray and neutron diffraction techniques, using automated stages that allow precise location of measurement points, coupled with software-driven data analysis. At certain facilities, including the Institut Laue-Langevin (ILL) and the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, it is also possible to apply fatigue loading in-situ on a beamline whilst making residual stress measurements. For critical engineering applications, 3D residual stresses can then be measured at points of local stress concentration and used to calibrate detailed finite element models of complex welded (or other) structures, and hence to produce estimates of fatigue life under the loading conditions of interest. These nondestructive techniques along with other destructive techniques for measuring residual stress are outlined by Withers [1] in a review paper.

It can be posited that structural life prediction under cyclic loading is probabilistic in nature, at least in part, because each weld in a structure comprises an individual 'system' whose behaviour is influenced by material, metallurgy, loading, environment, manufacture and fabrication. A significant part of this variation arises from the differences in residual stresses that exist between nominally similar welds and structural geometries (or even rolled members), resulting from relatively minor variations in these factors. Thus structural life prediction essentially deals with the analysis of a 'system of systems' and further advances in accuracy of life prediction, or in the treatment of residual stress issues, may require the incorporation of new systems analysis tools into our prediction methodologies. The analysis of 'systems of systems' is an emerging discipline and the methodology for defining, abstracting, modelling, and analysing 'system of systems' problems is still incomplete. Nonetheless, as we move towards 'smart' structures with embedded sensors for condition monitoring, concepts relevant to the analysis of 'systems of systems' and networks of 'things' (which is one type of distributed system) are likely to become more relevant to life prediction for complex structures. Work is currently ongoing to define the characteristics of 'systems of systems' and a very interesting discussion on the concept of the Network of 'Things' is provided by Voas in a free US National Institute of Standards and Technology document [16]. The document sets out, in the context of "systems with large amounts of data, scalability concerns, heterogeneity concerns, temporal concerns, and elements of unknown pedigree with possible nefarious intent" the underlying foundation science to explore the reliability and security of networks of 'things'. Whilst not directly transferable to a structural 'system of systems' it points the way to new concepts in thinking about systems analysis, which is an integral part of the complexity involved in ensuring structural reliability.

Condition monitoring in service is required as an integral part of a fracture mechanics-based life assessment for complex structures that supports run-repair-replace decisions. In thermal power generation, there are stringent requirements stipulated for repair processes on, for example, boilers, pipework and pressure vessels. Part of the certification procedure for new repair techniques and their incorporation into codes and standards involves an assessment of the residual stresses induced during repair and their potential alleviation through post-weld heat treatment (PWHT). The overall intention in the repair process is to deliver the component back

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