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Applications of Residual Stress in Combatting Fatigue and Fracture

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Abstract

Residual stresses have a significant impact on the propensity for engineering components and structures to undergo fatigue and fracture, with either a positive (life enhancing) or negative (life reducing) 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 stresses. Accurate life prediction relies on accurate experimental assessment of residual stresses, often combined with simulation using advanced numerical analysis techniques, that must be calibrated against real service data and this implies a necessity for ongoing condition monitoring. The present paper will outline some industrial applications where detailed knowledge of residual stress is advantageous in assessing their influence on fatigue and fracture performance, and hence assists in combatting failure. It will also draw attention to some examples of failures of expensive structures where residual stresses played a role and consider the design and/or fabrication measures that would have led to an amelioration of the level of residual stress and hence prolonged life.

Keywords: residual stresses; steam turbine blade and disc; friction taper hydro-pillar processing; weld repair; cracking

1. Introduction

As noted in a number of recent papers, e.g. Withers (2007), James et al. (2007), James (2001), residual stresses have a significant impact on the propensity for engineering components and structures to undergo fatigue and fracture, with either a positive (life enhancing) or negative (life reducing) 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

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stresses. The high level of residual stress induced during most manufacturing operations is often not fully realized by engineering designers (see for example, residual stresses induced during hot [Hidveghy et al. (2003)] and cold [De Giorgi (2011)] rolling), with surface modification and welding techniques being particularly influential in determining fatigue and fracture performance. An additional complexity with predicting the influence of residual stresses on components or structures arises from their potential modification during stress cycling 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 can lead to expensive blade failures [Nwby et al. (2014)]. 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 (1981) and Guagliano (2011) have both provided interesting reviews of its chronological development.

Nomenclature

ILL	Institut Laue-Langevin, Grenoble, France
ESRF	European Synchrotron Radiation Facility, Grenoble, France
PWHT	Post-weld heat treatment
FTHP	Friction taper hydro-pillar processing
HAZ	Heat-affected zone of a weld
SCC	Stress–corrosion cracking
EDM	Electro-discharge machining

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 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 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 Suresh (1988), where the phenomenon can be useful in pre-cracking of standard fracture toughness specimens, e.g. James et al (1990). Fatigue crack growth under compression-compression loading has been analyzed by Vasudevan and Sadananda (2011) while Lenets (1997) has considered environmentally-assisted compression fatigue of metallic materials [Lenets (1997)]. Examples of this mechanism in action, leading to failure of aircraft landing gear struts and other components, have been reported.

Predicting fatigue performance in the presence of residual stress fields remains complex, particularly for welded structures, although documents such as BS 7910:2013 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 (section 7.1.8.3) in an enclosed furnace with temperature ranges between 550ºC to 620ºC. 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 welded structures. Stacey et al. (2000) 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.

Accurate life prediction relies on accurate experimental assessment of residual stresses, often combined with simulation using advanced numerical analysis techniques. In recent years, very significant advances have been made in our ability to perform full-field measurements of residual stresses using sophisticated 3D synchrotron X-ray and neutron diffraction techniques, along with 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-