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Corrosion Fatigue of Low Carbon Steel under Compressive Residual Stress Field

Volodymyr Okorokov[a,*], Marta Morgantini[a], Yevgen Gorash[a], Tugrul Comlekci[b], Donald Mackenzie[a] and Ralph van Rijswick[c]

[a]*University of Strathclyde, 99 George St, Glasgow, G1 1RD, UK*
[b] *University of the West of Scotland, High Street, Paisley, PA1 2BE, UK*
[c]*Weir Minerals, Venlo, 5928 PH, NL*

Abstract

This paper presents experimental investigation and numerical modeling of the effect of compressive residual stress on the corrosion fatigue life of a low carbon steel. A fatigue life test methodology based on double notched tensile test specimens is proposed. A new plasticity model is proposed for accurate simulation of compressive residual stress and calibrated to experimental stress-strain curves obtained for low carbon steel. The proposed model is implemented as a user-material in the ANSYS Workbench Finite Element Analysis program and utilized in plastic analysis and fatigue assessment. Corrosion fatigue test results are discussed and compared to numerical predictions.

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Keywords: Corrosion fatigue; Autofrettage; Crack arrest; Compressive residual stress; Cyclic plasticity

1. Introduction

Corrosion fatigue failure is a fundamental design consideration in industries where plant and structures are subject to cyclic loading in a corrosive environment. In many applications, this is addressed through manufacture in corrosion resistant base materials, such as stainless steels, or incorporating barrier linings or coatings to protect the

* Corresponding author. Tel.: +44-787-427-54-42;
E-mail address: volodymyr.okorokov@strath.ac.uk

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base material from corrosive attack. However, these approaches are not always appropriate for cost or technical reasons. In such cases, an alternative approach may be to enhance resistance to corrosion fatigue failure by inducing compressive residual stress in highly loaded regions of the structure.

Residual stress methods such as shot peening, low plasticity burnishing, laser peening, deep rolling and autofrettage are used in a variety of industries to improve fatigue life. The motivation for the work presented here is to develop greater understanding of the autofrettage process in pump applications but it is also relevant to use of other residual stress methods in other applications.

Autofrettage is used to improve fatigue performance of pressure retaining structures, such as pressure vessel, gun barrels and pump fluid ends. Compressive residual stress is established by initially subjecting the component to an internal pressure great enough to cause plastic deformation in highly loaded regions. This reduces the local mean stress in these regions under operating conditions [1-5], increasing crack initiation time and fatigue life. The compressive stress field may also arrest growth of the crack after initiation [6, 7].

The effect of autofrettage residual stress on corrosion fatigue behavior *per se* has not previously been reported in the literature to a notable extent. Cyclic loading of carbon steel in a corrosive environment is widely known to significantly reduce the number of cycles to failure compared to a non-corrosive environment. Further, the material does not exhibit the fatigue (or endurance) limit behavior observed in tests in dry air. This paper presents an experimental investigation of the effect of residual stress on fatigue life of a carbon steel in a corrosive environment.

Experimental investigation of the fatigue life of autofrettaged components in pressure test rigs, as in [8], requires access to specialist facilities. This type of testing is relatively expensive and appropriate as a final step in designing a new pressure component. Here, a simpler and less expensive experimental method is proposed, based on tensile tests of double notched square cross-section specimens. A residual stress field is induced in the specimen prior to fatigue testing by initially loading the specimen so as to cause plastic deformation in the notch region, such that a compressive residual stress field is established upon subsequently unloading to zero axial force. The experimental results are simulated and analyzed in terms of a proposed new plasticity material model and the theory of critical distance [9].

2. Modelling Compressive Residual Stress

The autofrettage residual stress field arises from plastic deformation of the component during initial loading beyond first yield and subsequent unloading. Accurate prediction of the residual stress field therefore requires a mathematical material model of the plastic deformation that incorporates the material cyclic plasticity response.

2.1. Cyclic Plasticity Testing

The material considered in the investigation is a general purpose low carbon steel with nominal yield stress 260 MPa and Tensile Strength 500 MPa. Monotonic and cyclic stress strain curves for the material were obtained through tensile testing of rectangular test specimens of total length 140 mm, gauge length 25 mm, grip section width 20 mm, gauge section width 12 mm and thickness 6 mm. The tests were conducted on a 250 kN INSTRON servo-hydraulic testing machine under strain control, with a total strain rate of $5E^{-4}$ s^{-1} for both monotonic and cyclic loading. Strain was measured using a 10 mm gauge length extensometer.

The cyclic plastic behaviour of the material for non-zero mean strain is shown in Figure 1. The results exhibit important cyclic plasticity phenomena such as the Bauschinger effect, cyclic mean stress relaxation and elastic property degradation with accumulation of plastic strain. This behaviour is of specific relevance to autofrettage as it captures a realistic material response similar to that experienced in application of the autofrettage process.