OPTIMIZING STRUCTURAL INTEGRITY THROUGH RELIABLE RESIDUAL STRESS MEASUREMENT

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ABSTRACT

The determination of accurate reliable residual stresses is critical to many fields of structural integrity. Neutron stress measurement is a non-destructive technique that uniquely provides insights into stress fields deep within engineering components and structures. As such, it has become an increasingly important tool within engineering leading to improved manufacturing processes to reduce stress and distortion as well as to the definition of more precise lifing procedures. Furthermore, it is often the only means of measuring the stress state within engineering components and structures under conditions (temperature, stress, etc.) representative of those experienced in service. This paper describes recent advances in the utility of the technique through examples of residual stresses both beneficial and departmental to structural integrity.

KEYWORDS

Residual Stress, Structural Integrity, Neutron Diffraction, Stress Measurement

INTRODUCTION

Residual stresses exist in many manufactured components as a consequence of the thermal or mechanical processing. Local plastic deformation of a material will produce a residual stress variation; as will rapid cooling from elevated temperatures, where the materials yield strength is usually significantly lower than at room temperature. To many engineers, residual and applied stresses are separate entities. Applied loads and the stresses they cause are usually well understood, but the comparatively "unseen" residual stress state can often be extremely problematic. Whilst applied stresses can usually be easily estimated by a combinations of calculations and measurements, residual stresses are far more difficult to determine.

Historically, surface and near surface measurements could be made using semi-destructive techniques such as X-ray diffraction and hole drilling [1]. Full thickness measurements could also be made on simple geometries using various destructive sectioning methods [1]. The sparsity in reliable residual stress data has led to most design standards taking a conservative view of residual stress with upper bound yield values often being assumed. This is a reasonable approach if the structure can be assumed to be 'defect-free' at start of life. Under these conditions it may also be reasonable to derive a 'safe life' based on crack initiation procedures. However, damage tolerance based structural integrity remnant life assessments are now virtually mandatory in both the aerospace and nuclear power industries and such methodologies are increasingly used for any situation where safety is paramount. The principles of such an approach are shown in Figure 1. As the kinetics of defect growth can be strongly influenced by residual stresses a detailed knowledge of the variation in the residual stress tensor is required for such 'fitness for purpose' structural integrity assessments.

Neutron stress measurement is a non-destructive technique that has the unique ability to determine the full 3D stress tensor deep within engineering components and structures under conditions (temperature, stress, atmosphere, etc.) representative of those which might be experienced in service. As such, it has become an increasingly important tool within engineering leading to improved manufacturing processes to reduce stress and distortion as well as to the definition of more precise structural integrity lifing procedures. The technique was first developed 1970s [2] and started to gain popularity with the realisation of instrumentation specifically designed to measure residual stress [3]. This has engendered considerable industrial interest in the technique and has resulted in substantial further investment on both sides of the Atlantic. 20 million US$ is currently being invested by the UK/US alone to produce state of the art neutron stress measurement diffractometers at ISIS in the UK [4], ILL in Grenoble, France, and in the US at Los Alamos [5] and Oak Ridge. Complimentary developments are also underway both in Europe, Australia and Japan.

The purpose of this paper is to publicise the opportunities provided by recent advances in residual stress measurement by neutron diffraction using structural integrity based examples of both deleterious and beneficial residual stress fields.

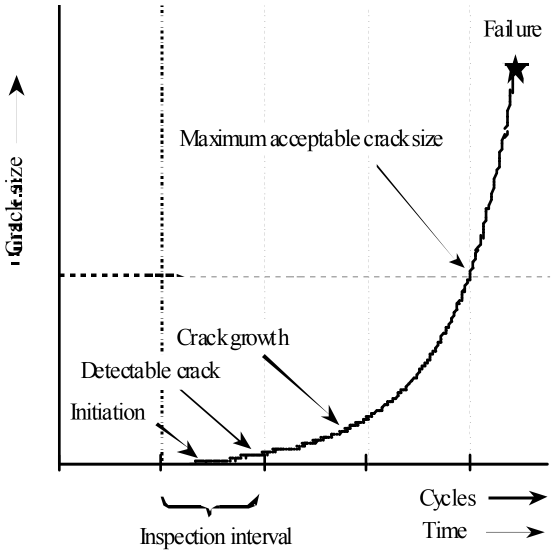

Figure 1 Damage Tolerence based life assessment

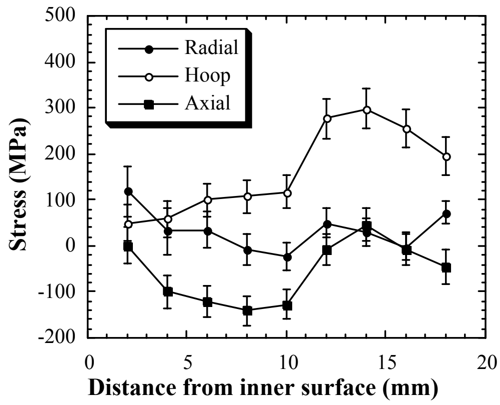

Figure 2 Residual stresses in weld HAZ

Structural assessment of Reheat cracking in Austenitic welds

Tensile weld residual stresses generally have an adverse effect on component life. When detailed structural integrity assessments are performed by industry, upper bound weld residual stress distributions from published compendia [5] are generally used. However, for safety-related plant it is sometimes vital to thoroughly understand the complete residual stress field and how it influences crack initiation, crack growth and fracture processes. For example, the principal stress magnitude and multi-axial stress-state are important factors affecting reheat crack initiation in stainless steel power plant operating at high temperatures. This cracking mechanism is caused predominately by the relaxation of welding residual stress, and therefore can initiate during service if creep temperatures prevail. To predict the kinetics of creep damage leading to reheat cracking, it is essential to know the full residual stress tensor, because tri-axial stresses can substantially affect creep relaxation, void growth and the creep ductility of the material [6].

FE methods are increasingly used to calculate residual stress distributions in multi-pass fusion welds by simulating both the thermal and mechanical response of the materials [7]. They have the advantage of providing a detailed map of the full residual stress tensor. But residual stress modelling is inherently more complex than conventional stress analysis and many approximations have to be made. So it is very important to independently validate predicted residual stress results and understand their limitations, before use in safety-critical structural integrity assessments. As an example, neutron diffraction measurements of residual stress and strain in the heat affected zone (HAZ) of a stainless steel pipe girth are described and compared to axi-symmetric FE weld residual stress simulations [8].

The welded test component studied was fabricated from two 316L austenitic stainless steel pipes. Following machining, the pipe was solution heat treated for one hour at 1050˚C with an air cool. The pipes were welded together using a Tungsten Inert Gas (TIG) root pass and a typical Manual Metal Arc (MMA) procedure. Neutron diffraction is now a well established technique for sub-surface strain measurements in metallic components. The change in the inter-planar distance in a crystalline material owing to any stress is determined in this technique by the observation of the change in position of diffraction peaks [2]. The present set of measurements was performed on the ENGIN spectrometer [3] which is based at the pulsed neutron source, ISIS, of the Rutherford Appleton Laboratory, UK

Through thickness measurements were performed across the tube. The hoop and radial measurements were performed with the pipe placed vertically whilst axial measurements were performed with the pipe placed horizontally on a support block. The measurement positions were determined by first aligning the specimen with the help of the telescopes and then confirming the precise location using the intensity of the diffracted beam as the gauge volume enters the specimen. The incident neutron beam was collimated to 3 x 3 mm. The focal width of the radial detection collimators used was 1.7 mm. The stress-free lattice parameter used in this work was obtained form the average of several measurements at different points through the thickness of a block (50 mm x 60 mm) cut from one end of the tube.

The ENGIN spectrometer uses the time of flight technique for the measurement of strain. Analysis of the resulting time of flight spectrum produces a lattice parameter a, which is obtained by fitting all the detectable peaks using the Rietveld refinement technique. The strain in the material is then given by: $\varepsilon=\Delta a/a_0$ where Δa is the lattice parameter shift, and a_0 is the stress-free lattice parameter. It has been shown that the strain calculated from a Rietveld refinement is a good approximation to the engineering strain in the component [9]. The stress is then calculated using Hookes Law thus :

$$\sigma_{ij}=\frac{E}{1+\nu}\ \varepsilon_{ij}+\frac{\nu E}{(1+\nu)(1-2\nu)}\ \delta_{ij}\,\varepsilon_{kk} \qquad (2)$$

where k is a dummy suffix summing over all k (*i.e.*, $\sigma_{kk}=\sigma_{11}+\sigma_{22}+\sigma_{33}$); E is Young's modulus; ν, Poisson's ratio; and δ, Kronecker's delta function.

Strain measurements were performed at the original girth weld heat affected zone (HAZ) 10.5 mm away from the weld centre-line. The full stress tensor was calculated for all the measured points, assuming that the hoop, axial and radial directions were the principal stress axes. The through-thickness variation of residual stress in the girth weld HAZ is given in figure 4 . The hoop stress profile peaks at 6 mm below the outer surface with a maximum value of 299 MPa (1% proof stress of base metal). The axial stresses in the HAZ exhibit a sine wave distribution (compressive towards the inner surface and tensile towards the outer), with a small compressive membrane stress equal to about –55 MPa. The radial stresses are generally low.

A numerical weld simulation was performed independently by British Energy (formerly Nuclear Electric) [8] using the ABAQUS finite element code to predict the residual stress field in the test component girth weld, that is prior to introduction of the repair. This involved a thermal calculation to predict the multi-pass weld temperature history at any point in the model, followed by a sequential non-linear mechanical analysis using thermal and mechanical properties for type 316 stainless steel up to its melting temperature. The axi-symmetric finite element model used provided a good representation of the test component geometry, weld preparation and weld bead lay-up.

The measured through-wall residual stresses at the ‘original’ girth weld are compared with finite element predictions in figure 3, both at the weld centre-line and in the HAZ. The predicted HAZ stresses at the –10.5 mm position are most relevant as these correspond to the last capping pass, where the neutron measurements were made. Predicted stresses from the +10.5 mm side are shown to illustrate the asymmetry arising from weld pass sequence effects. Overall, the correspondence between measured and predicted stress is impressive, particularly in the weld where a_0 errors arising from anisotropy and chemistry effects might be expected to distort the measured results.

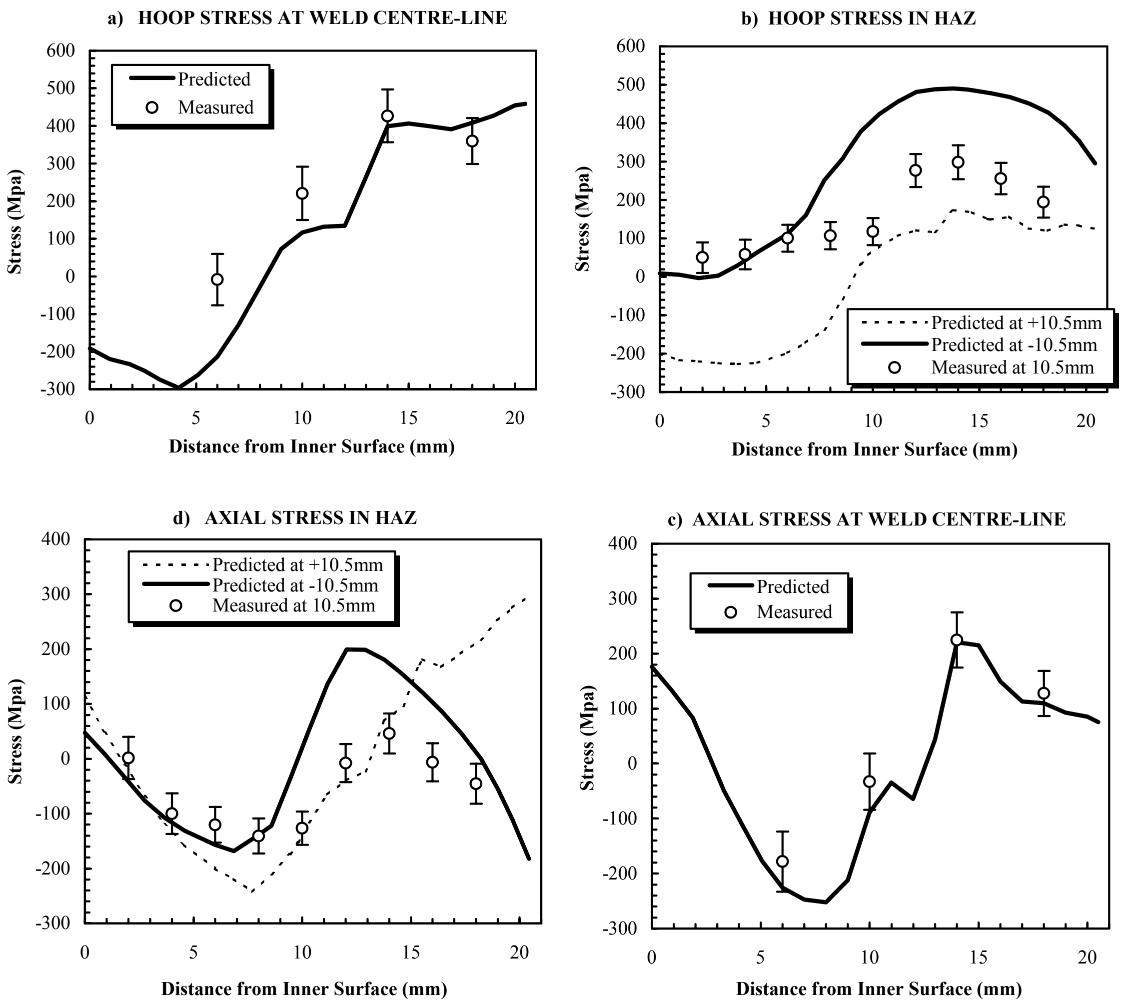

Figure 3: Comparison of measured and predicted residual stress in the HAZ of the 'original' girth weld

Both the measured and predicted hoop stresses demonstrate the same through-wall profile in both the weld fusion zone and HAZ; that is, exhibiting a peak at about 6 mm below the outer surface and a falling trend towards the inner surface. This characteristic profile is a global effect caused by the hoop contractions of outer weld passes applying a tourniquet compressive load on earlier passes. In the HAZ, it is evident that the predicted hoop stresses exceed those measured, particularly towards the outer surface. This conservative predictive feature has been observed in other weld analyses using similar modelling techniques and is the subject of on-going development work. The agreement between measured and predicted axial stress profiles is equally good (see figure 3). The measured profile in the HAZ shows the same sine wave characteristic predicted by the finite element model below the last capping pass.

In addition to validating the FE model, these results provide direct evidence of the residual stress profiles present in 19m thick Austenitic tube butt welds and have been used to aid assessment of the likelihood of reheat cracking occurring in specific in-service nuclear power plant welds [6].

Fatigue assessment of Cold Expanded Holes

The cold expansion of holes in metallic aircraft structures can considerably improve the fatigue life of fastener joints. Probably the most successful cold expansion process used is that developed by Fatigue Technology Inc., Seattle, USA (FTI). This process involves placing a longitudinally-split sleeve within the hole and then drawing an oversized tapered mandrel through the assembly so that the material undergoes permanent plastic deformation around the hole. Upon removal of the mandrel, owing to the spring-back of the surrounding elastic material, a self-equilibrating residual stress field is produced. In an annular region adjacent to the hole the residual stress field is compressive and results in improved fatigue behaviour.

At present, the benefits of cold expansion are not built in to the damage tolerant design of aircraft although their presence clearly impacts on the fatigue performance of the structure. In order for the crack growth life of cold expanded holes to be accurately determined adequate knowledge of both the original residual stress filed and how it is changed by the fatigue loading must be available. The usual way to account for the effect of residual stresses on crack propagation is invoke superposition so that an effective stress intensity factor can be defined as $K_{eff} = K_{appl} + K_{res}$. For a given residual stress distribution K_{res} can be found either using an integration method or using a weight function approach.

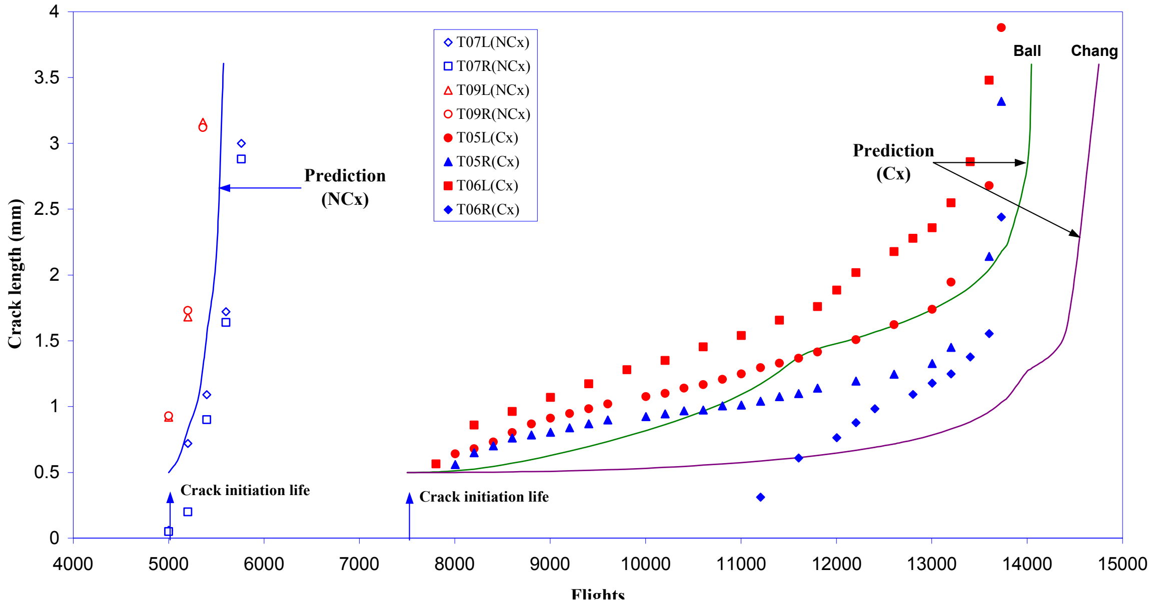

Figure 4. Measured and simulated fatigue crack growth using two different residual stress models.

One critical factor is whether the beneficial residual stress distribution imparted by the cold expansion process is changed by the applied loading. This can be particularly important for tactical aircraft which may be subjected to significant under and overloads in their flight load spectra. Under these conditions it can be difficult to predict both the local fatigue crack growth rate and the life of cold expanded holes subject to spectrum loading. This is illustrated by Figure 4 which shows attempts by Gaerke et al. [10] to predict crack growth from open (NCx) and cold expanded (Cx) 6mm holes in an 2024 aluminium alloy specimen subjected to the FALSTAFF load spectra [11]. This is a standard flight-by flight loading sequence meant to represent the stresses on the wing surface near the fuselage in a tactical aircraft. What is clear is that the two closed form solutions for the residual stresses around a cold expanded hole given by Ball and Lowry and Chang produce significantly different crack growth rate predictions. To investigate load interaction affects the effect of a 30KN under-load on the residual stresses surrounding a 6.25mm cold expanded hole in a 300 x 40 x 5 mm 7050 aluminium alloy plate have been determined using neutron diffraction [12,13].

Such an experiment is particularly suited to neutron diffraction as the technique is completely non-destructive. Thus the residual stresses were measured in the same specimen both after cold expansion and subsequent to the application of the compressive 30KN under-load. Measurements were performed on the ENGIN diffractometer as described earlier using a gauge volume of 2 x 2 x 1.5 mm^3. Hoop, transverse and radial strains were determined, from which the associated stresses were calculated. The stress-free value, a_0, was obtained by measuring a point 100 mm away from the hole. Stresses were then calculated using Hooke's Law (eqn. 2) assuming that the measured directions were the principal stress axes.

Figure 5 illustrates the effect of the 30 KN compressive underload on the hoop residual stress distribution at the mid-thickness of the plate. It can be seen that there are two distinct changes to the residual stress field. The magnitude of the maximum compressive residual stress has reduced in the area near to the hole from around –400 MPa to around –300 MPa, and the depth of this compressive zone has increased from 1 mm to 1.8 mm. Such a change is likely to have a substantial effect on the driving force for crack growth and illustrates the difficulties of producing damage tolerant fatigue life predictions in such circumstances.

These results show the potential benefits of neutron diffraction stress measurement for structural integrity determination through its unique ability to measure the stress tensor deep inside components and structures.

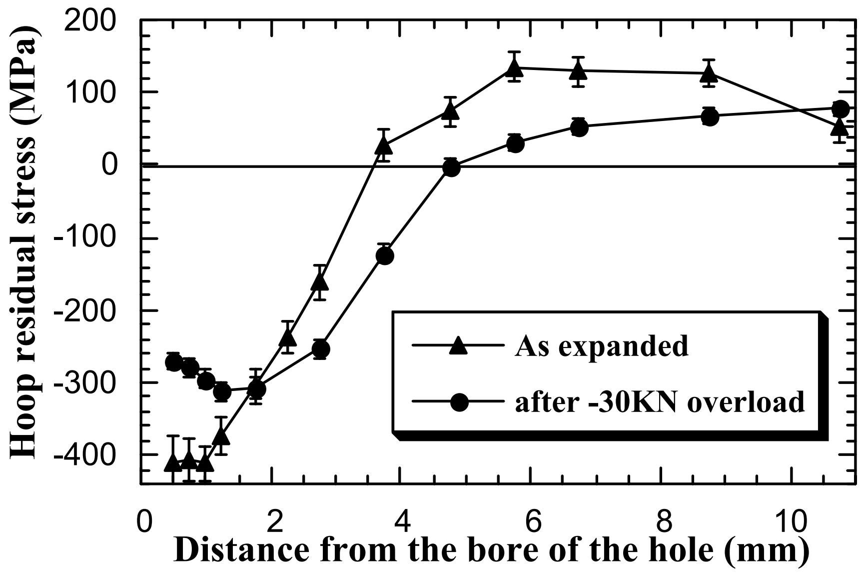

Figure 5. Hoop residual stresses at a 7050 cold expanded fastener hole before and after a –30 kN under-load.

The future

The future is bright for neutron diffraction stress measurement. There is significant investment in new instrumentation world-wide and the technique is constantly evolving to become more accessible for novice users. There will be a substantial growth in the user base and this growth provides a substantial opportunity for researchers and engineers involved in damage tolerance based structural integrity. One of the purposes of this paper is to publicise the power of the technique so that a vibrant engineering user community is waiting to use coming instrumentation when it comes on stream over the next few years.

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