A Verified Assessment Method for Prediction and Management of Stress Relaxation Cracking

JOINT INDUSTRY PROJECT OUTLINE

PROP 304497

Summary

Stress relaxation cracking (SRC) is a potentially catastrophic failure mode of concern across a number of industries, and can occur in stainless steels and nickel alloys, during high temperature service, particularly in thick section welds.

SRC is thought to be mitigated by a high temperature post-weld heat treatment (≥ 900°C), However, recent TWI experience has identified occasions where PWHTs have exacerbated problems rather than prevented them. Furthermore, current test methods for SRC do not reliably replicate in-service conditions and are unreliable, making it difficult to assess SRC risk.

In the proposed project, an approach will be developed, and verified, for reliable prediction of SRC. The approach will provide a solid basis for the identification of risk and where mitigation measures, such as PWHT, are suitable.

The assessment of SRC risk is complex and requires a multi-disciplinary approach. In this project, high temperature material test data will be used in advanced FE models to predict the failure times for in-service scenarios. Validation of the predictions will be achieved through large-scale testing. In this way a thorough, pragmatic, engineering approach for determining the risk of SRC in service will be developed. The approach builds on a large body of work, concerning the assessment of structures in high temperature service, previously undertaken at TWI and a number of other organisations.

TWI Ltd, Granta Park, Great Abington, Cambridge CB21 6AL, United Kingdom. Tel: +44 (0)1223 899000

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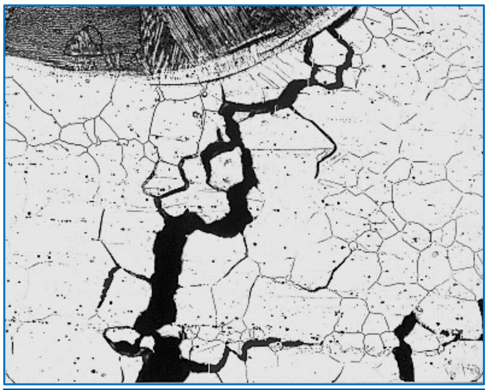
Project Concept

SRC is a failure mode that can occur, over moderate service durations, in stainless steels and nickel alloys, which are essentially solid solution strengthened, but can undergo significant precipitation reactions during elevated temperature exposure. Alloys that are known to have been affected include: 304H, 316H, 321H, 347H, Alloy 800/H/HT and Alloy 617. The SRC phenomenon typically occurs in components that have high levels of residual stress and constraint. More than 50 SRC failures were identified in the chemical process industry over the last couple of decades (Van Wortel, 2007) and it has plagued power plants made from these materials. Catastrophic failures of large components, related to SRC, might have severe cost implications, as well as resultant fatalities.

Although the phenomenon is typically related to in-service relaxation, stress-relief operations after welding, or at the first moments of high temperature service, can lead to similar mechanisms of failure, but are typically termed stress-relief cracking or reheat cracking. Tempered ferritic steels containing additions of chromium, molybdenum and vanadium require particular attention as they are almost always post weld heat treated and tend to show vulnerability during this operation.



Stress relaxation crack in Alloy 800H.

During high temperature service, residual stresses relax resulting in plastic strains. However, the high constraint and multi-axial stress states, present in large welded structures, prevents effective stress relaxation. Furthermore, reduced creep ductility, over certain temperature ranges, can exacerbate the issue.

A high temperature, ~900°C, post-weld heat treatment can be employed to reduce the incidence of SRC (API 942-B, 2017), but material may not be immune to SRC even after such a heat treatment. Current tests for SRC do not satisfactorily replicate the scenario in service, and a more sophisticated approach is therefore required to predict the occurrence of SRC. Appropriate mitigation strategies can then be developed and implemented. High temperature heat treatments are impractical for large vessels and might risk dimensional changes. Construction costs and times will be reduced, if such heat treatments can be safely omitted, or if lower temperature heat treatments can be safely applied.

This project is intended to establish a thorough, validated, engineering approach for the assessment of the risk of SRC in large welded structures. The approach relies on the generation of small-scale test data, in order to provide inputs for the modelling of large-scale structures, with finite element analysis (FEA). Such an approach is widely used for creep and creep-fatigue assessment of structures and is implemented in design codes, R5 (maintained by EDF, formerly British Energy) and RCC-MR. These codes are primarily focused on the nuclear industry and data to support such codes relate, mainly, to parent material or service-aged 304H and 316H (Spindler, 2009), which have particular relevance to advanced gas-cooled reactors (AGR's).

The proposed project aims to build on the approaches outlined in R5, by generating data specific to welds and heat-affected zones (HAZs) in material(s) and at temperatures of interest to the sponsoring consortium. The approach will be validated, using large-scale tests relevant to service conditions. The proposed approach builds on a large body of work already conducted by TWI on the assessment of structures for reheat cracking in the nuclear industry, including efforts to supplement and improve the R5 code.

Objectives

- Develop a robust and validated engineering approach to accurately predict the susceptibility of large-scale structures to SRC;
- Determine appropriate heat treatment requirements to mitigate SRC.

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Benefits

The proposed project will provide a validated approach for assessment of SRC, which will *reduce down-time and reputational damage* associated with in-service failures. The number of costly and unnecessary heat treatments will also be minimised leading to *reduced construction times and lower costs*.

Approach

Overview

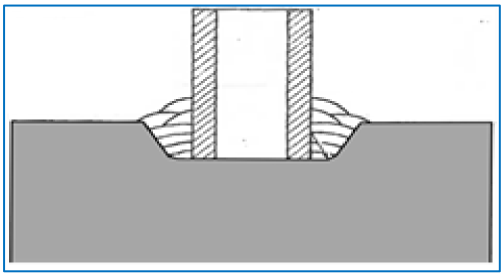
The accurate replication of service-induced SRC, requires a multi-axial stress state, as well as representative weld microstructures. Such a stress state, which is expected in large welded structures, can be replicated with small-scale, circumferentially-notched specimens. By machining the specimen from a weld or simulated HAZ and locating the notch in the appropriate material, the susceptible microstructure can be targeted. Parameters such as strain-to-failure, which will be used to inform FEA models of large-scale structures, can be determined from such small-scale tests. Previous work by Spindler, 2009, for the development of R5, primarily focused on notched tests in service-aged material and not welds, whilst the proposed project aims to expand this approach to welds. The local constraint, resulting from the tip of a stress relaxation crack, can also accelerate creep damage and crack growth. This phenomenon could also be investigated, as part of this project, using fracture toughness testing.

Parameters generated from the small-scale tests, will be used in combination with FEA to predict cracking in verification test pieces. Examples of such test pieces include the Borland test: a cylinder fillet welded onto a base plate, before heating in a furnace, see Figure. A verification test piece could also take the form of a welded component mock-up, to which primary stresses and temperature are applied.

Break down of activities

The project will be broken down into the following activities:

- *Knowledge sharing*: knowledge of failures and recent SRC research activities will be sought and shared between the consortium;
- *Review of specimen design and modelling approaches* used previously
- *Small-scale testing*: a series of un-notched and circumferentially-notched specimens, notched into the HAZ with different acuities, will be produced from welds and stress relaxation tests will be conducted to determine the material characteristics. Circumferentially-notched tests will be undertaken at different temperatures to characterise changes in creep ductility across the temperature range, appropriate to service/heat treatment. This data will be crucial for avoidance of post weld heat treatment cracking.
- *Advanced microstructural assessment*: microstructural characterisation of the as-received and tested materials, using high resolution, advanced, metallographic techniques, will be performed to establish the significance of microstructural features, and link their formation to the fabrication, service and testing history.
- *Welding residual stress modelling*: Welding residual stresses, in the validation structure, will be modeled using FEA, and verified using appropriate residual stress measurement techniques, e.g. contour method and neutron diffraction.



Schematic diagram of the Borland test

- *Damage modelling*: An FEA damage model, incorporating the obtained material data and residual stresses, will be produced to predict failure in validation test structures and small-scale tests;
- *Large-scale testing*: Validation structures will be welded and tested to determine if FEA modelling, with data from small-scale test specimens, can predict the outcome and thus verify the approach.

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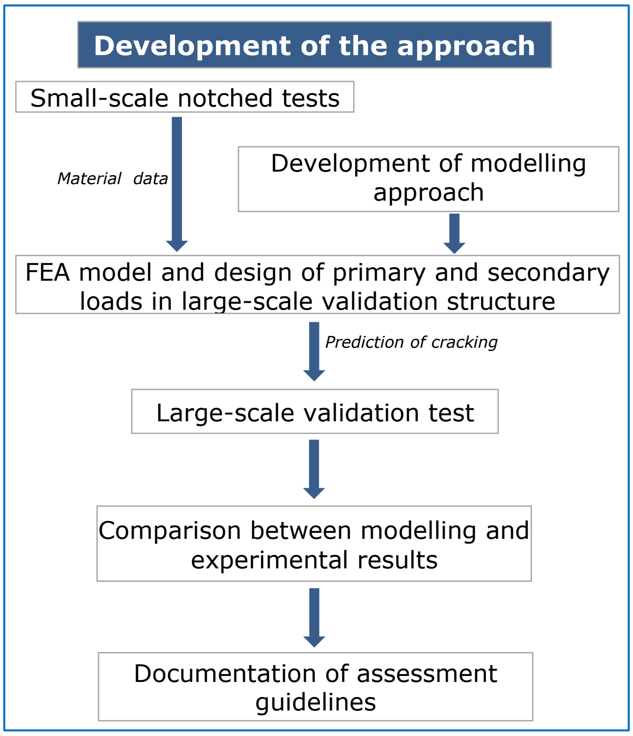
The above activities will validate the concept of using small-scale test data to determine the susceptibility of large-scale structures to SRC and provide a way of diagnosing the risk of the phenomenon for in-service components. The activities are summarised in the flow diagram. Once appropriate data for a particular material have been obtained, a minimum ductility could be specified for cross-weld notched specimens, in order to qualify those welds.

Modelling approaches and specimen design

A number of modelling approaches may be suitable for the purposes described above. R5 implements a ductility exhaustion approach (Spindler 2009), whilst mechanistic models may also be suitable for predicting damage by capturing the processes leading to failure, i.e. plasticity, cavitation. An activity related to this project will therefore be to review creep damage modelling approaches. Several different notched and waisted specimen designs also exist, which will be reviewed to determine the most suitable.



Flow diagram for the validation of the use of small-scale test data to predict SRC in large-scale structures.

Deliverables

A verified and documented method for assessment of the likelihood of SRC in structures. Documentation of heat treatments required to avoid SRC in the investigated materials.

Price and Duration

The overall price for the work is £360,000 (excluding VAT), which requires £60,000 per sponsor, assuming six sponsors. The duration of the project is anticipated to be three years. The scope of the project will be scaled to the budget obtained.

References

API 942-B, 2017: 'Material, fabrication and repair considerations for austenitic alloys subject to embrittlement and cracking in high temperature 565°C to 760°C (1050°F to 1400°F) refinery service', American Petroleum Institute.

Spindler M W and Smith M C, 2009: 'The effect of multiaxial states of stress on creep failure of Type 316h under displacement control', in ASME 2009 Pressure Vessels and Piping Conference, January 2009, pp. 817-823, American Society of Mechanical Engineers.

Van Wortel, 2007: 'Control of relaxation cracking in austenitic high temperature components', in: Minutes of EFC WP15 Corrosion in Refinery Industry, 26 April 2007.

Further Information

For questions or further information please contact **Imran Bhamji** or **Kasra Sotoudeh**:

Email: Imran.bhamji@twi.co.uk, kasra.sotoudeh@twi.co.uk