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Code characterisation of weld residual stress levels and the problem of innate scatter

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Abstract

Economic and safe management of operating nuclear power plant is increasingly dependent upon structural integrity assessments for pressure vessels and piping. The residual stress distribution assumed in defect assessments for welded joints often have a deciding influence on the analysis outcome. Guidance on characterising conservative levels of weld residual stress can be found in structural integrity codes and procedures such as R6, API 579 and BS7910. There is an increasing need to develop more realistic and reliable residual stress distributions that will deliver more accurate integrity assessments. However, future development of such distributions will have to deal convincingly with what is often termed the ''innate scatter'' of weld residual stresses. This paper first identifies and illustrates some of the origins of apparent innate scatter. The stability of the welding process is examined. The importance of transient weld bead starts/stops and the lay-up of passes in multi-pass welds are demonstrated. Uncertainties associated with two commonly used residual stress measurement techniques are reviewed and simple quantitative studies used to reveal the role of measurement gauge length and, more significantly, errors in spatial location on the level of measured residual stress. The final part of this paper surveys how structural integrity codes and procedures currently characterise welding residual stresses for defect-assessment purposes and discusses the development of more realistic residual stress profiles based on statistical treatment of scatter and uncertainties.

Keywords: Stainless steel; Finite element; Residual stress; Deep hole; Neutron diffraction; Contour method; R6 procedure; Fracture assessment

1. Introduction

Economic and safe management of operating nuclear power plant is increasingly dependent on the outcome of structural integrity assessments for pressure vessels and piping. The UK nuclear industry uses assessment methods defined in design codes and procedures; for example the R5 high-temperature procedure [1], the R6 defect-assessment procedure [2], British Standard guide BS7910 [3] for assessing the acceptability of flaws in metallic structures, ASME Boiler and Pressure Vessel design code [4] and the American Petroleum Institute fitness-for-service Recommended Practice API 579 [5].

The magnitude and distribution of residual stress assumed in structural analysis calculations often has a deciding influence on the integrity assessment outcome [6]. All the above procedures simplify the three-dimensional (3-D) residual stress field at a welded joint by choosing an idealised one-dimensional stress distribution along a line through the wall thickness. This residual stress profile is assumed to apply uniformly across the full width of the crack face in defect assessments. Guidance in the codes on what residual stress profiles to use ranges from simplistic assumptions (uniform stress of mean yield strength magnitude) and bounding profiles defined by polynomials to the more realistic distributions that have been introduced recently into procedure R6.

Quantifying with high certainty the magnitude and distribution of residual stress in a welded joint is a challenging task. Historically, point measurements of residual stress in welded structures have exhibited a wide degree of scatter and from this general observation it has been inferred that weldment residual stresses are highly variable. With the advent of new residual stress measurement mapping techniques [7] and the capability to perform

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3-D moving heat source finite element (FE) weld residual stress simulations [8], it is timely to review the origins of apparent "innate scatter" of residual stress levels in weldments.

This paper discusses how the welding process and the influence of weld pass lay-up can affect the residual stress field at welded joints. Uncertainties associated with two common residual stress measurement techniques, neutron diffraction [9] and deep-hole drilling [10], are reviewed and simple quantitative studies used to reveal the significance of measurement gauge length and positioning errors on the level of measured residual stress. The paper then surveys how structural integrity codes and procedures currently characterise welding residual stresses for defect assessment purposes and outlines the prospects for developing more realistic residual stress profiles.

2. Weldment examples

Measurements and FE predictions of residual stress for three weldments are used in the present paper to illustrate some of the problems associated with characterising internal stress fields. The geometry, materials, welding process and fabrication details for these weldments are summarised here.

2.1. Bead-on-plate weldment

A simple bead-on-plate weldment design (Figs. 1a and b) has been adopted by Task Group 1 of the European NET project as a benchmark for parallel round robins covering 3-D weld residual stress simulation and residual stress measurement. Some measurements and predictions have been published [8,11,12] and a full review of the project phase 1 results prepared [13] for future publication. Four nominally identical base plates were machined to the design shown in Fig. 1a from a single piece of solution heat-treated AISI Type 316L austenitic stainless steel plate for the measurement round robin. The base plates were then re-solution heat treated in air (soaked for 45 min at 1050 °C and furnace cooled) to eliminate machining residual stresses. A single weld bead was deposited along the centre-line of each plate using an automated tungsten inert gas (TIG) process with a welding advance rate of 2.27 mm/s (with no weaving) and an average weld heat input of 0.633 kJ/mm. There was a short dwell between striking the arc and commencing the traverse at the start end. Monotonic tensile properties of the base-plate material were measured over a range of temperatures up to 900 °C and a set of properties derived for weld simulation purposes.

2.2. Three bead-on-plate weldment

At present, 3-D multi-pass repair weld residual stress simulations generally model each weld pass as a single continuous weld bead. In reality the length of typical manual metal arc (MMA) repair welds often necessitates the use of multiple weld beads for any individual pass. The effect on the final residual stress state of depositing multiple weld beads, in series, instead of a single bead has been investigated in moving heat source weld bead-on-plate residual stress simulation studies [15].

The general weldment design and material properties used in the residual stress simulations were based on those for a single weld bead weld test specimen [14] fabricated for the EC co-funded ENPOWER research project. The base-plate geometry was extended to a length of 300 mm (see Fig. 2) allowing the deposition of either three weld beads each 60 mm long or a single bead 180 mm long. A weld heat input of 0.7 kJ/mm with an advance rate of 3.1 mm/s was modelled. Full details of the weld simulation studies and results are described in [15].

2.3. Pipe girth weld repairs

A repaired pipe specimen was manufactured from two ex-service power station steam headers, made from AISI Type 316 H stainless steel [16]. The 432 mm outer diameter headers were bore-machined to an average wall thickness of 19.6 mm and solution heat treated (for 1 h at 1050 °C followed by air cooling) to remove any remnant residual stresses. The 1% proof stress of the heat-treated header material was measured to be 272 MPa. The headers were then butt-welded together using a MMA procedure typical of that employed for steam raising pipe welds. A rectangular slot, 90 mm long

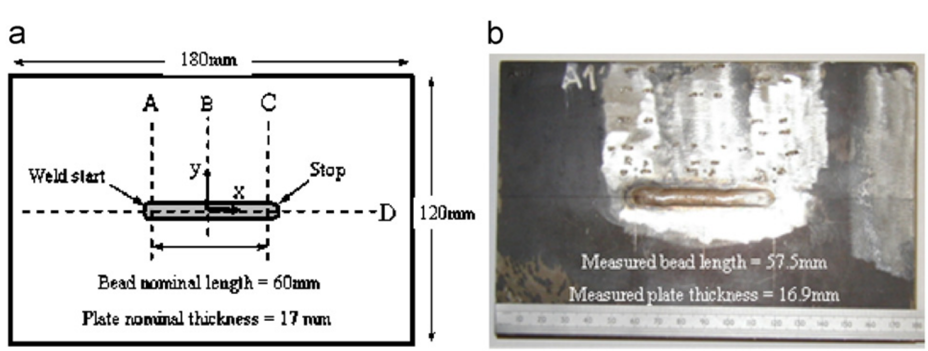

Fig. 1. (a) Sketch of NET bead-on-plate weld design, (b) photograph of specimen A11.