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The impact of transformation plasticity on the electron beam welding of thick-section ferritic steel components

Anastasia N. Vasileiou [a,*], Michael C. Smith [a], Jeyaganesh Balakrishnan [b], John A. Francis [a], Cory J. Hamelin [c]

[a] The University of Manchester, School of Mechanical, Aerospace and Civil Engineering, Sackville Street, Manchester M13 9PL, UK
[b] NAMRC, University of Sheffield, Brunel Way, Rotherham S60 5WG, UK
[c] ANSTO, Institute of Materials Engineering, New Illawarra Road, Lucas Heights, NSW 2234, Australia

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ABSTRACT

Welding is an important process used during the construction and maintenance of nuclear reactor components. Welding results in residual stresses, distortions and microstructural changes in the joined components, which can have significant and deleterious effects on their in-service performance. It is thus crucial for engineers to effectively predict these effects.

Ferritic steels undergo solid-state phase transformations (SSPT) during heating and cooling, thus making welding simulation challenging. The strains associated with SSPTs can also cause transformation-induced plasticity. The significance of transformation plasticity for single-pass, autogenous welding of a thick component is the subject of this paper.

Electron beam (EB) welding was the technique chosen to weld 30-mm thick ferritic steel plates using a single pass. The welded plates were instrumented with thermocouple arrays, to capture the far-field and near-field thermal transients on the top and bottom surfaces during welding and the cooling down process. Welding distortions were subsequently measured using laser profilometry. Distributions of the developed residual stresses were measured using the neutron diffraction (ND) method.

Numerical finite element analysis (FEA) was used to simulate the welding process. After calibrating the thermal solution using thermocouple data, mechanical analysis was conducted using three different approaches: (i) taking account of anisothermal SSPT kinetics with transformation plasticity; (ii) taking account of anisothermal SSPT kinetics without transformation plasticity; and (iii) assuming isothermal SSPT kinetics. The predicted residual stresses and structural distortions are compared to the experimental data, thus assessing the influence of different SSPT phenomena.

1. Introduction

SA508 steel is a ferritic, low alloy steel commonly used in nuclear components with SA508 Gr.3 being mainly used in Pressurized Water Reactors (PWR). The methods currently being used to weld these components are based on arc welding processes such as manual metal arc (MMA) welding, submerged arc welding (SAW) and gas tungsten arc welding (GTAW). Traditional arc welding, even in the case of narrow groove (NG) arc welding, involves multiple passes as well as the addition of filler metal. Electron beam (EB) welding, on the other hand, is autogenous and can be a single pass process. EB welding performed under vacuum is called Reduced Pressure Electron Beam (RPEB) welding, which has the advantage of no oxidation (Duffy, 2014). A single pass process can lead to significantly higher productivity, since multiple days of welding could be replaced by a several-hour long procedure.

Ferritic steels experience solid-state phase transformations (SSPTs) which have strains associated with them and, if these strains occur in localised regions within the material, they will lead to the generation of residual stresses. For example, a volumetric component of the transformation strain arises due to differences in the atomic packing density of various phases in the steel (Francis et al., 2007). SSPTs may also take place via different mechanisms on heating to those that apply on cooling, since diffusion-based mechanisms are sluggish at lower temperatures. Weld modelling for the prediction of weld residual stresses (WRS) has proved to be challenging due to the complex nature of these phenomena. Five components of strain, as proposed by Sjöström (1985), should be taken into consideration to describe SSPT:

* Corresponding author.
E-mail address: anastasia.vasileiou@manchester.ac.uk (A.N. Vasileiou).

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$$\varepsilon = \varepsilon^e + \varepsilon^p + \varepsilon^{th} + \varepsilon^{tr} + \varepsilon^{tp} \quad (1)$$

The strain components comprise the elastic strain (ε^e), the plastic strain (ε^p), the thermal strain (ε^{th}), the metallurgical transformation strain (ε^{tr}) and the transformation-induced plasticity (ε^{tp}). The last two components of strain, ε^{tr} and ε^{tp}, are created during SSPT.

Transformation plasticity (TP) can be produced via two mechanisms: the first one is numerically described by the Greenwood and Johnson model (Greenwood and Johnson, 1965), and the second one by the Magee model (Magee, 1966). Recent state-of-the-art publications in weld modelling use algorithms that consider both mechanisms. Such models are not yet extensively validated for different welding processes. It is furthermore reported that the details of any implementation of SSPT kinetics can significantly affect the accuracy of the model. However, the impact of transformation plasticity is not clearly confirmed (Hamelin et al., 2014).

The present work focuses on comparing different modelling approaches concerning TP, using a well-characterised benchmark study: a single-pass, autogenous EB ferritic weld. WRS results are compared with experimental data from neutron diffraction (ND) measurements.

2. Experiment

2.1. Base materials and design of welding specimens

The base material consisted of SA508 ferritic steel, Grade 3, Class 1, having the chemical composition shown in Table 1. The dimensions of the final welded plates were 300 × 200 × 30 mm. Square edge grooves were machined from each plate to produce square-butt welds. The weld preparation drawings for the 30-mm thick plates are shown in Fig. 1.

Table 1
Nominal composition of SA508 Grade 3 Class 1 steel (wt.%).

C	Si	Cr	Co	Mn	Ni	Mo	Fe
0.16	0.27	0.23	0.004	1.43	0.77	0.52	Bal.

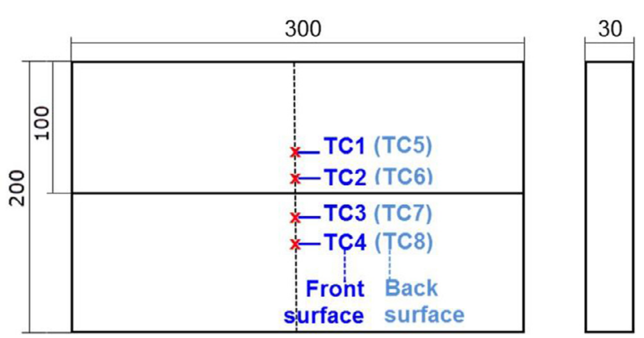

Fig. 1. Dimensions of the RPEB weld (30-mm thick specimen) and thermocouple locations.

2.2. Welding process

The welds were produced by TWI Cambridge, UK and were witnessed by University of Manchester staff. The plates were welded in the 2G-position, as shown in Fig. 2, in a reduced-pressure vacuum chamber. A voltage of 150 kV and a current of 90 mA were used. The pre-heating temperature was 100 °C.

The experiment was repeated twice, thus producing two identical benchmark samples. The reason for producing the second weld was to produce specimens for the measurement of the stress-free lattice parameter, a_0, in subsequent neutron diffraction (ND) residual stress measurements. It also allowed the consistency of the welding procedure to be confirmed.

2.3. Instrumentation

The welded plates were instrumented with thermocouples (TC) to acquire the thermal transients induced due to the RPEB process. The thermocouple arrays were proposed based on numerical analysis. The array consisted of 8 TCs: four on the front surface (Fig. 2a) and four on the back surface (Fig. 2b). On each surface the TCs were placed symmetrically, at distances of 7 mm and 15 mm from the centreline of the weld. TC measurements are essential in order to validate the finite element thermal transient predictions. The sampling rate was 10 Hz.

2.4. Macrograph and non-destructive evaluation of RPEB welds

The welds were radiographed to demonstrate that they were free of significant defects, according to the acceptance criteria in ASME IX:2013. A typical weld macrograph is shown in Fig. 3. The average width of the fusion zone is 3.4 mm. The heat affected zone (HAZ) extends to 4.25 mm from either side of the weld centreline. The fusion zone and HAZ consisted of a mixed bainitic and martensitic structure, while the parent material is a tempered bainitic structure.

2.5. Neutron diffraction measurements

For the Neutron diffraction (ND) experiment, a time of flight neutron source at the UK-ISIS facility was employed to measure the residual stresses in the longitudinal (L), transverse (T) and normal (N) directions. In the Engin-X instrument, two strain components were measured at once and the third component was measured by rotating the weld specimen by 90°. A nominal gauge

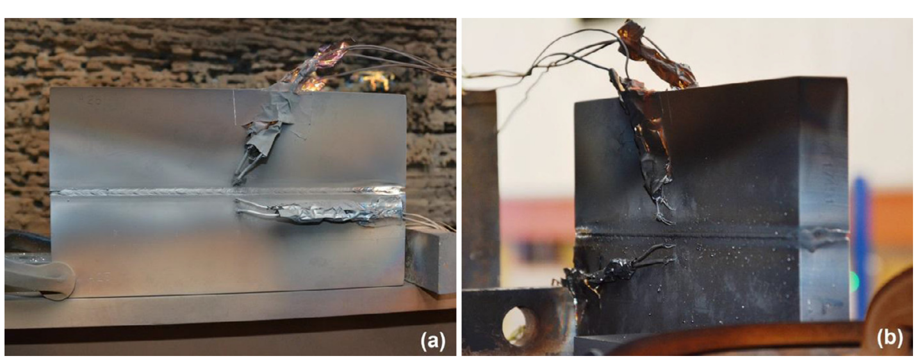

Fig. 2. RPEB 30-mm thick single-pass weld specimen instrumented with thermocouples, after welding: (a) front surface; and (b) back surface.