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In-situ neutron diffraction measurement of stress redistribution in a dissimilar joint during heat treatment

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ABSTRACT

Neutron diffraction is routinely used to monitor stress redistribution before and after heat treatment in dissimilar joints. However there remains a paucity of information concerning the evolution of strain throughout the process of heat treatment itself. Due to different mechanical properties between opposing sides, a competitive strain redistribution process occurs. Consequently, a novel in-situ measurement approach has been developed: strains at multiple points in a dissimilar joint have been measured during heat treatment. Thus, the described work elucidates areas within the thermal cycle in which competitive strain redistribution occurs, and where high residual stresses remain, following PWHT. The method may be used to characterise comparable material combinations, with a view to optimising the thermal cycles, and ultimately, the structural integrity of dissimilar joints.

1. Introduction

Generally, the heat-affected zone (HAZ) of arc welds is associated with regions of concentrated, high, residual stress, which is created during cooling after welding. Together with HAZ microstructural changes during welding, high residual stress can result in unexpected failure and is, therefore, an important consideration in the assessment of welded structures [1,2].

Within subsea oil and gas systems, dissimilar welds are commonly used to facilitate the joining of two alloys with different material properties. In one such scenario, a low alloy steel (LAS) forging is welded to a leaner pipeline steel (such as API 5L grade X65). Postweld heat treatment (PWHT) of the forging is required to temper the hard HAZ that forms upon cooling from welding. Similar PWHT of the X65 material is undesirable. To avoid subjecting the X65 to PWHT the forging can be welded using a 'buttering' technique, which provides intermediate layers of a suitable material (such as AWS A5.14 ERNiCrMo-3, 'Alloy 625') that can be heat-treated in factory conditions. Subsequently, the HAZ of the field closure weld, that completes the assembly, lies wholly within the heat-treated buttering and, thus, no further heat treatment is necessary.

When installed, the structures are protected with aluminium based sacrificial anodes, which safeguard the neighbouring ferritic production components from corrosion. The majority of joints with forgings of this type have provided satisfactory service; however several joints have cracked at the dissimilar interface between the LAS forging and the heat-treated buttering [3,4]. Failure of this kind has been attributed to hydrogen ingress, as cathodic protection can provide a source of hydrogen that can embrittle susceptible microstructures.

Industry standard heat treatments for AISI 8630M LAS to Alloy 625 butterings are typically within the range of 5–10 h at 650–675 °C, with air cooling. As a result of carbon diffusion from the relatively higher carbon forging into the buttering during PWHT, carbides form within a narrow, planar-solidified band in the weld metal [5–7]. These chromium-based M_7C_3 precipitates have been considered to play a critical role in the embrittlement of the joints, when subject to cathodic protection (CP) [6]. A compromise may be necessary in which PWHTs should be sufficient to temper the HAZ and relax residual stress without forming embrittling phases, as combinations of high stress, susceptible microstructure and hydrogen level should be avoided to prevent hydrogen cracking.

For dissimilar joints, in addition to strain from local thermal contraction, strains arise from differences in the coefficients of thermal expansion between the forging and the weld. During cooling from welding temperatures, these strains cause deformation of the joint region and set up residual elastic stresses. The subsequent PWHT redistributes the residual stress; however it is

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not yet clear how residual stress evolves in the dissimilar joint during welding and subsequent PWHT.

Dissimilar LAS-Alloy 625 joints have previously been the subject of ex-situ residual stress experiments using neutron diffraction (ND). For example, Sotoudeh et al. measured the stress profiles of a number of joints subject to different PWHT conditions [8], creating a stress profile up to 50 mm from the dissimilar interface. Skouras et al. [9] compared deep hole drilling to ND measurements of residual stress. In both cases, the authors encountered problems with weak diffraction, probably due to material thickness and strong texture effects.

In light of these observations, this paper aims to answer the following questions:

(1) Is it possible to monitor dissimilar joint strain evolution in-situ, during heat treatment?
(2) What fusion zone microstructures are present in the 8630M-Alloy 625 joint at room temperature and during PWHT?

2. Experiments

2.1. General procedure

The primary objective of this work was to use ND to quantify competitive strain evolution in a dissimilar joint during heat treatment. Monitoring multiple points is, however, further complicated by the multiphase nature of the sample. Secondary to this, ex-situ measurements were carried out to measure residual stress relaxation before and after heating. The heat treatment parameters were selected to be comparable to industry standard PWHTs. Heating was applied using controllable, electric, heating blankets.

In selecting the appropriate sampling times and gauge volumes, the limited PHWT period must be considered. These sampling times must feature a compromise between the number of points that can be measured, during the heat treatment, and an acceptable degree of measurement error. Additional measurement complexity is caused by interfacial regions, in which more than one phase is present within the sampling volume of the neutron beam. The described procedure can be considered an expansion on the in-situ heat treatment method described by Chen et al. [10], in which a single point in a ferritic steel was monitored during PWHT. In the current study, three measurement points were monitored during the heat treatment: the ferritic side, the austenitic side and the, interface region.

In the case of buttered dissimilar welds, in which multiple welding passes are involved, the HAZ experiences a heating transient, as each weld bead is laid. Whilst the HAZ itself does not melt, the melting point is approached, close to the fusion boundary and metallurgical changes may, therefore, be expected. Dissolution and re-precipitation, as well as texture changes, may occur with each successive pass [11]. As a result, thermodynamic modelling was used to predict equilibrium phase changes in the regions within the overall thermal cycle. To assess the extent of mixing in sampling regions expected to be dual-phase, microstructural analysis was carried out using a scanning electron microscope (SEM). Chemical analysis was facilitated by using energy-dispersive X-ray (EDX) spectroscopy in an SEM.

2.2. Materials and sample preparation

An ex-service AISI 8630M LAS forged hub was water-jet machined to create an 'L' shaped component, approximately 250 mm long, in order to contain the deposited weld metal. The hub was MIG welded with Alloy 625 (ERNiCrMo-3) using a 'layering' procedure, i.e. beads deposited in rows parallel to the interface with the substrate. The specified compositions of the joint can be found in Table 1, whilst welding parameters are presented in Table 2.

The welded specimen was electro-discharge (ED) machined to create two 100 mm long plates. Sample thickness is an important consideration when preparing a specimen for strain measurement using ND. By shortening the length of the beam path, the counting times are reduced, meaning the point-to-point measurement resolution can be increased. Typical industry PWHT times are between 5 and 10 h, hence a compromise had to be found. The sample thickness had to be small enough such that the number of points during the hold temperature could be maximised, whilst minimising stress relaxation through the machining operations. With this in mind, the pair of plate samples were further ED machined to $99 \times 100 \times 14\ \text{mm}^3$, with the dissimilar-interface situated in the middle. The width of the sample therefore contained 2–3 weld beads. Maximum stress relaxation due to machining was also likely to be found in the normal direction. A diagram of the dissimilar joint design, welding sequence and the region extracted for ND measurements, is given in Fig. 1.

The main challenge for accurate measurement of stress fields in weldments using ND lies in the accurate determination of strain-free cell parameters [12,13]. For this experiment, stress-free (a_0) sample combs were designed to accommodate a gauge volume of $3 \times 3 \times 3\ \text{mm}^3$ (and hence a diagonal of 4.24 mm). Two, 5 mm deep stress-free combs were created; one with vertical and one with horizontal teeth, allowing for measurement of the three principal stress directions. ED cutting with Ø0.25 mm wire enabled the precise machining of the sample comb with 5 mm wide teeth. Additional teeth were machined in order to allow the a_0 measurement points to be isolated, when clamped in place

Table 1
Specified compositions in weight per cent (wt%) for the parent and weld metal.

Material	C	Mn	Ni	Cr	Mo	Si	Nb	Fe
8630M	0.28–0.33	0.75–0.95	0.70–0.90	0.80–1.00	0.35–0.45	0.15–0.35	-	Bal.
Alloy 625 (ERNiCrMo-3)	0.10 max	0.50 max	> 58.0	20.0–23.0	8.0–10.0	0.50max	3.15–4.15	5.0 max

Table 2
Parameters used in the welding of the 8630M substrate with Alloy 625 consumable.

Pass no.	Wire diameter (mm)	Current (A)	Voltage (V)	Polarity	Wire feed speed (m/min)	Welding speed (m/min)	Heat input (kJ/mm)
1	1	150 ± 15	22 ± 3	DC+pulsed	3.6	0.32 ± 0.05	0.495
$2-n$	1	170 ± 15	24 ± 3	DC+pulsed	4.2	0.35 ± 0.05	0.560