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Residual stress measurements in a ferritic steel/In625 superalloy dissimilar metal weldment using neutron diffraction and deep-hole drilling

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This paper reports the use of non-invasive and semi-invasive techniques to measure the residual stresses in a large dissimilar weldment. This took the form of a butt weld between two sections of a P92 steel pipe, joined using an In625 welding consumable. Residual stress measurements have been carried out on the 30 mm thick welded pipe using the deep-hole drilling technique to characterise the through wall section residual stress distribution for the weld metal, HAZ and parent material. In addition, neutron diffraction measurements have been carried out within the weld zone. Diffraction patterns presented a high intensity and sharp peaks for the base P92 steel material. However measurements in the weld superalloy material were proven problematic as very weak diffraction patterns were observed. A thorough examination of the weld material suggested that the likely cause of this phenomenon was texture in the weld material created during the solidification phase of the welding procedure. This paper discusses the challenges in the execution and interpretation of the neutron diffraction results and demonstrates that realistic measurements of residual stresses can be achieved, in complex dissimilar metal weldments.

1. Introduction

Weldments in safety critical plants are subject to structural integrity assessments where residual stresses may play a key part [1,2]. In the case of engineering components operating at elevated temperature, the presence of tensile residual stresses can increase the likelihood of time dependent failure by acting as a driving force for the initiation and growth of cracks. There is a need to be able to measure the residual stresses arising from such a joining technique. Dissimilar welds are often used in service without heat treatment which means a knowledge of residual stress is even more important. Residual stress measurements provide both an improved understanding of the magnitude and origins of residual stresses in these complex dissimilar metal weldments as well as an improved basis for undertaking integrity assessments.

Residual stresses are those stresses not required for an engineering component to maintain its equilibrium with the environment [3]. Previous studies [4–6] have shown that residual stresses can have beneficial or detrimental effects. In all cases, knowledge of primary and residual stresses needs to be known when assessing the integrity of a structure [7]. Residual stresses are categorised based on the length scale over which they equilibrate [3]. Macro-stresses, Type I, vary over large distances and over several grain in a polycrystalline material. Meso-stresses, Type II, vary over the dimensions of individual grains. Stresses that fall below the Type II length scale, that are contained within individual grains are classed as Type III micro-stresses and usually arise due to dislocation stress fields or coherency at interfaces within the microstructure. Type I macro-stresses provide the principal elastic stored energy to give a driving force for damage creation and evolution. Types II and III stresses may also provide a contribution to specific parameters.

A wide range of techniques is available for measuring stresses over different length scales. These techniques range from non-invasive to invasive and are capable of measuring stresses from the macro-scale down to the micro-scale. Examples of non-invasive techniques are X-ray diffraction and neutron diffraction [8]. In semi-invasive methods, analysis requires only small quantities of material to be removed, allowing further testing on the component. Examples of semi-invasive methods include center hole drilling [9], slotting [10] and the Sachs method [11]. Lastly, fully invasive measurement techniques involve the removal of large quantities of

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material and measurement of stress relaxation. Falling in this category are methods such as the Rosenthal and Norton method and the crack compliance method [10,12]. Normally non-invasive methods may become invasive by additional experimental or sample constraints. For example, large samples may need sectioning to fit them into laboratory measurement facilities or very thick specimens may need windows cutting to permit the passage of neutron or X-ray beams.

Both material removal and diffraction techniques can be characterised based on their gauge volume V_0 [3,8]. Residual measurement techniques employ a wide range of gauge volumes thus, recording different stress types. It becomes evident that it is important to consider the measurement gauge volume V_0 over which a certain type of stress equilibrates. If a given sampling gauge volume V is much greater than a given stress type volume, that is $V_0^{\mathrm{I}}, V_0^{\mathrm{II}}$ or V_0^{III}, then the associated stress type will not be recorded. Material removal techniques, such as the deep-hole drilling technique, centre hole drilling, contour method and crack compliance remove macroscopically sized regions where $V_{\mathrm{gauge}} \gg V_0^{\mathrm{II}}, V_0^{\mathrm{III}}$. Type I and Type II residual stresses have length scales that equilibrate over volumes $V_0^{\mathrm{II}}, V_0^{\mathrm{III}}$ thus, only Type I stresses can be recorded when using these methods. Depending on the chosen gauge volume, diffraction techniques such as conventional X-rays, synchrotron and neutron diffraction can be used to measure all residual stress length scales.

Previous studies [13,14] have successfully assessed the presence of residual stresses in similar metal welds by both measurements and modelling. However for dissimilar weldments the magnitude and distribution of the residual stresses for the as-welded condition have not been investigated rigorously. These weldments have a complex microstructure. In addition, diffusion effects between the weldment and parent material should be taken into account. These phenomena are of increased importance as dissimilar weldments are often used in service in the as-welded condition so there is little opportunity to mitigate the build up of significant residual stress. Usually, a dissimilar weld material, such as In625, is used in power plant pipelines to connect pipes made of different steels, such as joining martensitic to austenitic steel.

In this work, residual stress distributions in a P92/In625 welded pipe have been obtained using neutron diffraction and deep-hole drilling techniques. The neutron diffraction measurements were undertaken using the ENGIN-X instrument at the ISIS neutron source at the Rutherford Appleton Laboratory, UK. The deep-hole drilling measurements were carried out at the University of Bristol residual stress Laboratory, UK. Measurements have been made at the parent, heat affected and weld regions of the pipe, to establish a comprehensive distribution of the residual stresses.

2. Experiment

2.1. Weld fabrication

The dimensions of the P92 pipe used in the measurements are shown in Fig. 1. The chemical composition of the P92 steel pipe provided by the manufacturer is presented in Table 1. The welding process started by pre-heating the pipe to a temperature between 100 °C and 150 °C for the execution of the root run which was performed with a welding consumable of In82 superalloy. On completing the root run the pipe was heated to a temperature between 200 °C and 250 °C, which was maintained until the manual metal arc (MMA) weld was completed. The weld consumable was specified as 4 mm diameter In625 with a typical weld composition as shown in Table 2. Mechanical properties provided by the University of Nottingham [15] for the P92 steel and the In625 superalloy are presented in Tables 3 and 4.

A complete weld of 36passes, illustrated in Fig. 2, was achieved by laying weld beads from the bottom of the weld preparation to the outside of the pipe. Weld beads were laid one after another rather than continuously. After each bead was completed the pipe was rotated through 45° before the next bead was started. These start/stop positions were marked on the pipe as the welding proceeded. At the outside surface of the pipe there are five capping runs. These capping runs extend above the original pipe surface by approximately 3 mm and beyond the extent of the weld preparation by approximately 3 mm on each side. On completion of the welding, the pipe was air cooled to room temperature.

2.2. Microstructural evaluation

A macro specimen containing the weld, heat affected and parent regions was extracted using electro discharge wire cutting in order to evaluate the hardness profile and grain size. Vickers hardness measurements were conducted along the extracted cross-section using a load of 30 kg (HV30). The macro specimen was subsequently polished and electro-etched using ortho-phosphoric acid (70 ml H_3PO_4 + 30 ml distilled water) at 4 V for 5 s.

2.3. Deep-hole drilling method (DHD)

The DHD technique falls into the semi-invasive measuring category [16]. The method is divided into four different procedural steps. Prior to the execution of step 1, stress free bushes are attached to the front and back of the specimen to act as a reference. Step 1 involves gun-drilling a through thickness reference hole. In step 2 the reference hole diameter is measured using an air probe at

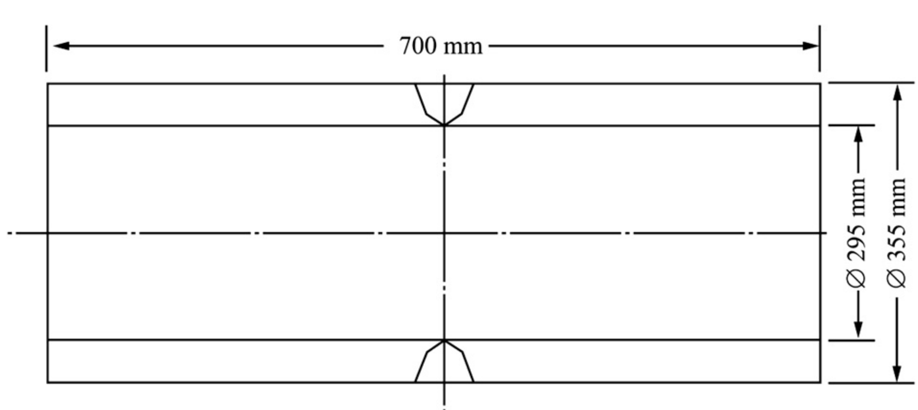

Fig. 1. Overall pipe dimensions.