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Residual stress measurement of a 316l stainless steel bead-on-plate specimen utilising the contour method

M. Turski*, L. Edwards

The Open University, Walton Hall, Milton Keynes MK6 7AA, UK

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ABSTRACT

This paper describes the mapping of transverse residual stresses within a single bead-on-plate round robin test specimen. The purpose of these measurements was to quantify the magnitude and shape of the residual stress field arising from a single weld bead laid down on an austenitic stainless steel plate. Measurements were made through the thickness of the specimen using the contour method. The contour method is a new destructive, stress relaxation method allowing the full field residual stress to be measured. Results from these measurements show transverse tensile residual stresses over 150 MPa below the plate surface along the length of the weld bead with peak stresses of up to 210 MPa close to the weld stop position. Finally, as these measurements are insensitive to local microstructure variations within the specimen (i.e. texture or variations in lattice parameter), they are useful in helping to validate diffraction based residual stress measurements made within this round robin measurement program.

1. Introduction

Arc welding processes involve the deposition of molten filler metal and the localised input of intense heat. Consequently, the surrounding parent material and weld metal undergo complex thermo-mechanical processes involving elastic, plastic, creep and viscous deformation. These can result in the development of substantial residual stresses within the structure, which can be particularly detrimental to the service life of components operating at elevated temperatures and pressures. For this reason it is important that the magnitude and spatial extent of these residual stresses can be determined and predicted as part of a structural integrity assessment programme. However, successful predictions of such stresses through FE (finite element) model simulations of residual stress generation through welding is particularly challenging due to the inherent complexity of the welding process. Consequently it is important that residual stress measurements are available to validate these simulations.

A simple single bead-on-plate test specimen design has been adopted as part of the European NET project as a benchmark for parallel round robins covering 3D FE weld residual stress simulations and residual stress measurements. Such a specimen was chosen as a single bead of limited length would introduce a strongly varying 3-dimensional residual stress field that had similar characteristics to a repair weld typically found in plant components. Through comparisons between results from the round robin weld residual stress simulations and residual stress measurements both the process of residual stress measurement and prediction could be further developed and standardised.

This paper outlines the measurement of transverse residual stresses within the bead-on-plate weld specimen using the contour method. The contour method is a relatively new technique first proposed by Prime [1]. This method is based on Bueckner's superposition principle, where a specimen containing residual stresses is cut into two parts and the resulting relaxed surface contour is measured. The measured surface contour is then forced back to its original shape using finite element methods, producing the original residual stress field. This procedure allows the full field residual stress normal to the cut to be measured along the cut plane. The method has since been used to determine the residual stresses in a variety of welds for several materials [1–4].

2. Weld bead-on-plate specimens

Four nominally identical $180 \times 120 \times 17$ mm base-plates were machined from a $600 \times 150 \times 50$ mm solution heat treated 316L austenitic stainless steel plate. The base-plates were re-solution heat treated in air 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 under closely controlled and recorded conditions [5]. There was a dwell of approximately one second between striking the arc and commencing the traverse at the start of the weld. The welding

* Corresponding author.
E-mail address: mark.turski@magnesium-elektron.com (M. Turski).

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advance rate was 2.27 mm/s with an average weld heat input of 0.63 KJ/mm.

The residual stress measurements reported here were undertaken on specimen A1.1. Fig. 1 shows a schematic representation of the plate after welding including the position of the single cut along line A–B required for the contour measurement. The measured bead length for the specimen A1.1 was 57.5 mm, with the weld start and stop positions located at −30 and 27.5 mm from the centre of the plate (see Fig. 2).

3. Contour measurement

The contour method is a relatively new relaxation technique for residual stress evaluation, and has the potential to measure a full cross-sectional profile of residual stresses in a relatively cheap and time-efficient manner [1]. It is simple in use, although destructive, and the equipment required is widely available in many workshops and laboratories. The method has found a number of applications [2,6] including welds [2–4]. The concept of the contour method is derived from Bueckner's elastic superposition principle [7]. The method itself involves four steps: specimen cut, contour measurement, data reduction and finite element analysis.

The contour method was applied to the weld bead-on-plate specimen A1.1 to map the distribution of transverse residual stress on a longitudinal (i.e. parallel to the weld bead) cross-section located at mid-width of the weld bead (see Fig. 1).

3.1. Specimen cutting

As with other relaxation methods [8], it is assumed that cutting process relaxes the residual stresses elastically and does not induce any stresses into the material. Additionally, the ideal cutting process would generate a perfectly straight cut, without any further removal of material from the cut surfaces. Wire electro-discharge machining (EDM) is thought to come closest to these conditions.

For this measurement the specimen was cut by wire electric-discharge machining with a 0.1 mm diameter brass wire, using 'skim cut' settings, along the line labelled as A–B on Fig. 1. During cutting, the plate was constrained firmly by clamps, either side of the cut, to prevent movement of the plate as the residual stress within the plate was relaxed. Fig. 3 shows a photograph of specimen A1.1 after cutting.

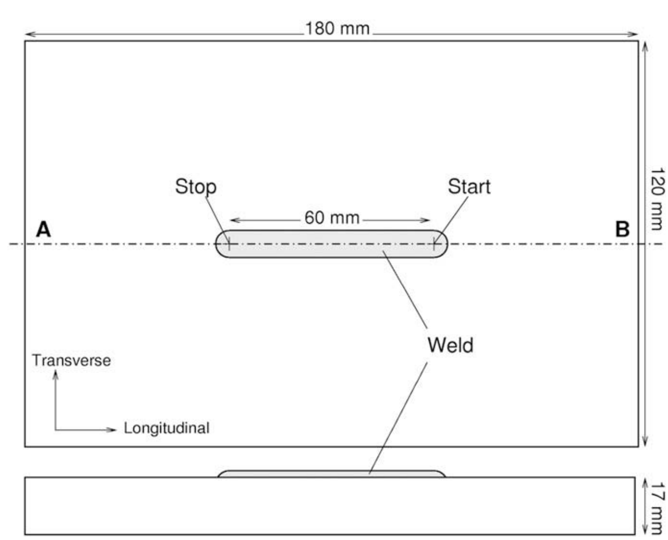

Fig. 1. Nominal dimensions of bead-on-plate specimen.

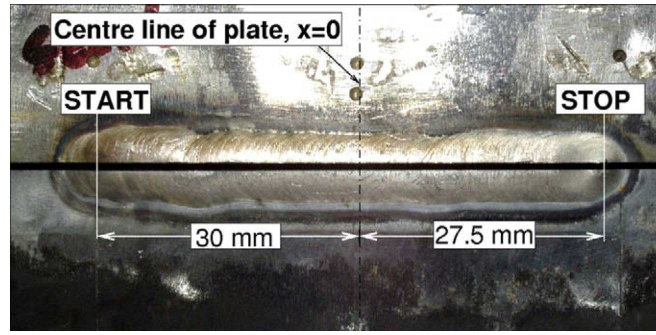

Fig. 2. Detail of the single weld bead, showing the weld start and stop positions with respect to the centre of the plate. Note this image was taken after the plate was sectioned for the contour measurement.

3.2. Measurement of surface contour

Following the cut, both cut surfaces were measured using a Mitutoyo Crysta Plus 574 co-ordinate measuring machine (CMM), equipped with a 2 mm diameter ruby-tipped Renishaw PH10M touch trigger probe. This allowed the out-of-plane displacement contour formed by the release of the residual stress to be measured. The CMM machine has a resolution of 0.1 μm, with a reported measurement accuracy of 4.9 μm over a 500 mm distance perpendicular to the measurement. However, precision is more relevant for this application because of the small measurement range and the need for only relative, rather than absolute measurements. Experimental measurements carried out on an EDM cut surface indicate a precision of ±0.6 μm.

Each cut surface was sampled with a measurement point spacing of 0.5 × 0.5 mm, resulting in ∼13,000 measurement points for each surface. The contour measurement plane for each surface was also defined at this stage; this was achieved by fitting a plane to 4 individual measurements, each measurement being made 5 × 5 mm in from each corner of the cut surface.

After measurement of the surface contour the cut surface was polished and etched to produce a macrograph showing the fusion boundary of the weld bead (see Section 4).

3.3. Data processing

After surface contour measurement, the contours of both cut-sides were averaged point-by-point correspondingly. This averaging step is essential as it allows the effect of shear stresses and

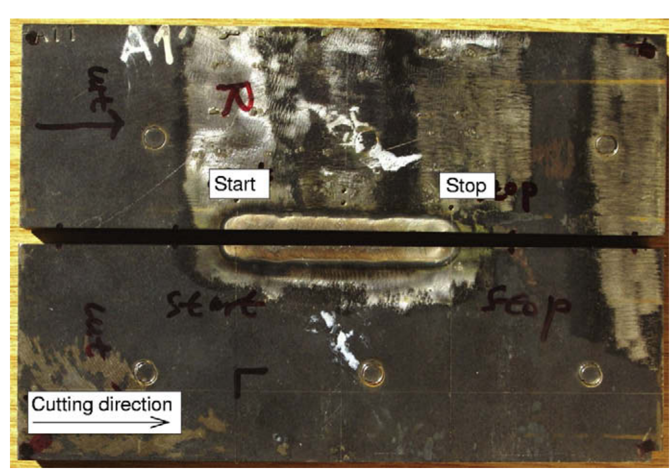

Fig. 3. Bead-on-plate specimen after contour measurement cut.