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Numerical simulation of a three-pass TIG welding using finite element method with validation from measurements

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ABSTRACT

Structural integrity assessment of welded joints requires characterising the residual stresses generated during the process. Although measurements can provide a quantitative estimation of the residual stresses, a reliable numerical model offers greater advantages in terms of cost, time and versatility. A validated model can be used to optimise the measurement procedure and thereby aiding in further refinement of the model itself. In the current work, a three-pass tungsten-inert gas welding in an austenitic stainless-steel plate is simulated using a three-dimensional sequentially coupled thermo-mechanical analysis for the purpose of predicting the transient thermal profiles and the final residual stresses as a part of NeT programme. Block-dumped heat transfer analysis was conducted with element activation and deactivation to represent the physical deposition of the weld beads for each pass, followed by a mechanical analysis to predict the stresses. Incremental deep-hole drilling and neutron diffraction techniques at ILL and HZB facilities in Grenoble and Berlin respectively, were employed to measure the residual stresses through the thickness of the sample plate at the center. The predicted thermal history and the residual stresses are verified with the measured thermocouple recordings and the stresses respectively.

1. Introduction

The European Network on Neutron Techniques Standardization for Structural Integrity (NeT) was established in 2002 to develop experimental and numerical techniques and standards for reliable characterisation of residual stresses in structural welds [1]. It involves partners from 35 organisations ranging from industrial, academic and research facilities from countries in Europe and beyond. Each problem is undertaken through round robins on measurement and modelling activities and subsequent interpretation of results by a dedicated Task Group (TG). Task Group 4 was established in 2007 to develop a three-pass slot weld benchmark made from Type 316 L stainless steel. The specimen geometry is selected such that it is representative of weld repairs employed in engineering applications. The multi-pass welding serves as an increase in complexity over single-pass welds (TG1) through the generation of a complex 3D residual stress distribution.

The TG4 has launched parallel measurements and simulation round robins for comparison and standardization of measurement and simulation protocols for residual stress characterising in complex weldments. As a part of the round robin research, 3D finite element (FE) simulation using ABAQUS v6.12 code was conducted to predict residual stresses from the welding process along with measurements using incremental deep hole drilling and neutron diffraction techniques on the sample weldment to characterise residual stresses. The predicted transient thermal profile and the residual stresses were compared with the measured values in order to validate the FE model and predictions. Apart from this, the results from the FE model and measurements were used in round robin comparisons with predictions and measurements from other partners in the TG [2,3]. The current paper presents the details about the samples including preparation, various batches, welding process, the numerical modelling and measurement procedures on samples from various batches and discusses the results from predictions and measurements, drawing conclusions.

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2. Sample details

The NeTTG4 specimen was a 3-pass slot weld in AISI 316 L austenitic steel, made using the TIG welding process [1,4]. The dimensions of the plate were 194 mm × 150 mm x 18 mm, while the slot was 80 mm long and 6 mm deep. Twelve identical specimens with slots were machined from a large blank of 316 L stainless steel. Ten of the twelve specimens were set aside for characterisation purposes including creation of weld macrographs, specimen destruction for contour method and deep hole drilling measurements. The remaining two were used for trial welding and fine tuning of welding parameters. Out of the ten specimens, one plate was set aside for manufacturing the weld pad. The remaining nine plates had slots machined in them. The schematic of the plate with the slot dimensions is given in Fig. 1. The plates were then subjected to solution heat treatment, to reduce any residual stresses introduced through machining, by heating up to 1050 °C at a rate of 5 °C min^{-1}, holding at this temperature for 45 min, cooled down in the furnace up to 300 °C and then air cooled to room temperature.

From the nine plates, one was reserved to characterise any residual stresses in the plates prior to welding. Another plate was reserved for thermocouple instrumentation at the University of South Brittany leaving seven plates for to be welded. Prior to welding, five thermocouples were spot-welded to the welded side mid-length position of the weld, but offset from the weld centreline. The thermocouple locations are shown in Fig. 2. This was done for two specimens. On the third specimen both strain gauges and thermocouples were applied as shown in the back face in Fig. 2. The remaining four specimens had no special instrumentation applied. The reason for seven plates was to circulate four plates for neutron and synchrotron X-ray diffraction based round robin residual stress measurements and two specimens for destructive stress measurement methods such as contour method, slitting and hole drilling, leaving one specimen for detailed metallography and extraction of d_0 specimens.

The plates were TIG welded using argon as the shielding gas and had an approximate heat input of 1.5–1.8 $kJmm^{-1}$. The welding was performed at Rolls Royce, Derby. Three weld passes were made into the slot, with each pass depositing the filler material directly on top of the predecessor, to fill the slot. The specimens were lightly clamped in a vice. The travel speed was 76.2 mm min^{-1}. The interpass temperatures for pass 2 and pass 3 are about 50–60 °C. The filler wire used was AWS A5.9-93 (ER316L) with a diameter of 0.9 mm. The chemical composition of the filler material is tabulated in Table 1. A tungsten electrode of approximately 3.2 mm in diameter was used in the welding process. The specimen fabrication, preparation and subsequent welding was performed strictly adhering to the manufacturing protocol written specifically for the TG4 problem [4].

Later an additional batch of six specimens were manufactured by TWI, Cambridge, for further characterisation including repeated contour and slitting measurements, additional neutron diffraction and over-core strain relief measurement. The additional six samples were notionally identical to the first set of twelve samples in the sense that the sample preparation prior to the welding process and the actual welding parameters were maintained the same. However, there were slight variations in the welding pass lengths and the measures implemented to overcome the underfill at the weld start end.

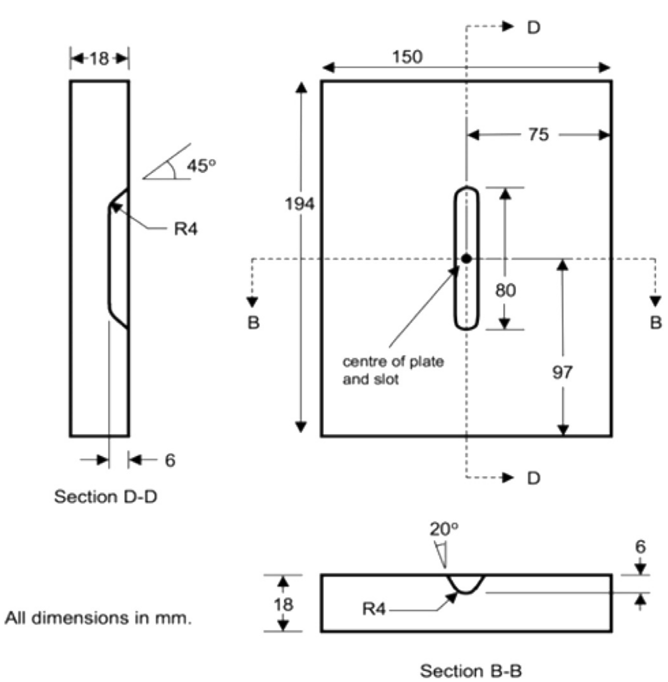

Fig. 1. Schematic representation of TG4 sample [1,4].

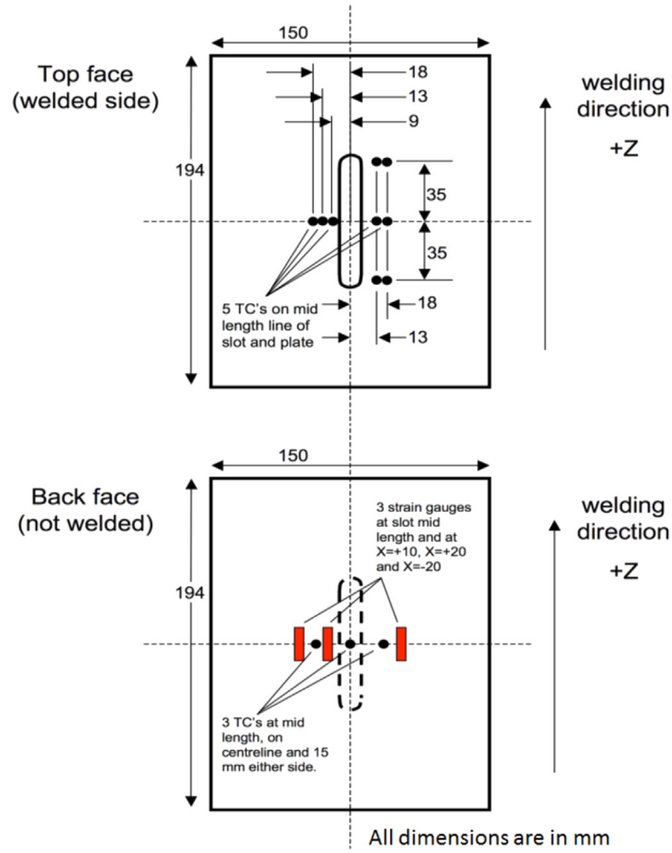

Fig. 2. Schematic of the thermocouple location on the TG4 sample [1,4].

Table 1
Chemical composition of the base plate made of AISI Type 316 L stainless steel (% wt.).

Element	C	Mn	Si	P	S	Cr	Ni	Mo	Cu
316 L	0.03	2.0	0.5	0.025	0.01	18.0	12.5	2.70	0.3

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