International Journal of Solids and Structures 94–95 (2016) 247–253

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Mitigating cutting-induced plasticity in the contour method, part 1: Experimental

F. Hosseinzadeh[a,*], Y. Traore[a], P.J. Bouchard[a], O. Muránsky[b]

[a] The Open University, Materials Engineering, Milton Keynes MK7 6AA, UK
[b] ANSTO, Institute of Materials Engineering, Lucas Heights, NSW, Australia

ARTICLE INFO

Article history:
Received 21 May 2015
Revised 12 November 2015
Available online 10 February 2016

Keywords:
Residual stress
Contour method
Plasticity

ABSTRACT

Application of the contour method for the measurement of weld residual stresses (WRS) is prone to inaccuracy due to plastic deformation resulting from the redistribution of typically high (close to yield) WRS during the cutting process. The current work, seeks ways to mitigate cutting-induced plasticity by controlling stress redistribution through optimisation of the contour cutting configuration. The idea of using a stress-informed fracture mechanics approach to find the optimal cutting configuration is introduced. The level of plasticity associated with different cutting configurations is then assessed, allowing control of the location and magnitude of cutting-induced plasticity to occur during the cutting process. A conventional edge-crack cutting configuration is compared with a proposed double-embedded cutting configuration by measuring the longitudinal WRS in two three-pass slot weld specimens (NeT TG4) produced using identical weld procedures. The experimental results show that a novel double-embedded cutting configuration leads to greater accuracy in WRS measurements relative to conventional edge-crack cutting configurations at the expense of higher levels of plasticity being introduced local to small ligaments.

1. Introduction

Welding is the most widely employed joining technique in the production of engineering structures. However, it typically introduces high tensile residual stresses in the vicinity of the weld, which can adversely affect the performance of the weld structure. If left unmitigated, weld residual stresses (WRS) can add to the operational stresses and exacerbate degradation mechanisms, for example by promoting crack initiation and crack growth leading to potential premature failure (Withers, 2007; Muránsky et al., 2014). It is, therefore, of technological importance to assess the magnitude and spatial distribution of WRS introduced and account for its presence in remaining life calculations and structural integrity safety assessments (Paulo et al., 2014; Citarella et al., 2015; B.M.G. Biritish Energy and and Serco Assurance, 2009).

The European Network on Neutron Techniques Standardisation for Structural Integrity (NeT) is advancing experimental and numerical techniques for characterising WRS in structural welds to a high level of reliability. Several benchmark studies have been examined under the auspices of the NeT framework including: (i) a single-pass finite length weld deposit on a Type 316L stainless steel plate (Task Group 1, TG1) (Smith et al., 2014), (ii) a three-pass slot-weld in a Type 316L stainless steel plate (Task Group 4, TG4) (Muránsky et al., 2012) and (iii) a single-pass autogenous weld along the edge of a thin SA508 ferritic steel beam (Task Group 5, TG5) (Hamelin et al., 2014). The task group studies included (blind) round-robin measurements and simulations of WRS by a number of international participants.

A various "non-destructive"[1] diffraction (neutron, synchrotron) and "destructive"[2] stress-relief (contour, deep hole drilling) measurement techniques were employed by the NeT participants in order to assess their accuracy, sensitivity and repeatability against each other. These independent WRS measurements were then used in the validation process of numerical weld analysis (Smith et al., 2014; Muránsky et al., 2012; Hamelin et al., 2014). Cross-checking of measurement and simulation results also revealed that the conventional contour method produced an inaccurate measurement of WRS. This was attributed to significant plasticity occurring during

* Corresponding author. Tel./fax: 44 19 0885 8839.
E-mail addresses: Foroogh.Hosseinzadeh@open.ac.uk (F. Hosseinzadeh), ondrej.muransky@ansto.gov.au (O. Muránsky).

[1] The original internal residual stress field in the specimen is preserved during the measurement process; however, the extraction of a reference stress-free coupon from this or another specimen is often required.

[2] The original internal residual stress field in the specimen is released during the measurement process, and cannot be remeasured using complementary techniques.

http://dx.doi.org/10.1016/j.ijsolstr.2015.12.034

the contour cutting process (Smith et al., 2014; Dennis et al., 2008; Smith and Smith, 2009) as a result of WRS redistribution.

The current work presents the stress-informed cutting configuration for the contour method (Traore et al., 2011; Hosseinzadeh and Bouchard, 2012) leading to development of a novel double-embedded cutting configuration. The double-embedded cutting configuration is put to the test by measuring the longitudinal (σ_{33}) WRS in one of the NeT TG4 benchmark weld specimens. The recovered WRS are compared with results obtained by the contour method employing conventional edge-crack cutting configuration on another nominally the same NeT TG4 benchmark weld specimen. It is shown that the proposed double-embedded cutting configuration produces a more accurate measurement of WRS than conventional edge-crack cutting configuration. The Part 2 of the current study presents numerical non-linear (elasto-plastic) analysis of the contour cutting process that reveal the distribution of cutting-induced plasticity in the contour method when employing the conventional edge-crack and double-embedded cutting configurations. The numerical analysis shows that the double-embedded cutting configuration provides more accurate measurement of WRS due to effective localisation of the cutting-induced plasticity occurring during the cutting process into narrow regions. These regions of high cutting-induced plasticity can be omitted from the stress back-calculation analysis so the accuracy of the recovered WRS is not compromised.

2. Contour method

The contour method is a stress-relief based measurement technique where the specimen of interest is cut into two parts on a plane of interest (Prime, 2001; Prime and DeWald, 2013), and a 2D map of the original (pre-cutting) residual stress distribution acting normal to the plane is inferred from the deformation of the cut surfaces. The basic steps of the contour method include (i) planar sectioning of the specimen, (ii) cut-surface out-of-plane displacement (profile) measurement, (iii) post-processing of measured surface deformation profile, followed by (iv) elastic back-calculation of residual stresses from the deformation profile. A linear elastic stress analysis is conducted to recover the original (pre-cutting) residual stresses using a 3D FE model of the cut part (for more details see Prime, 2001; Prime and DeWald, 2013; Hosseinzadeh et al., 2014).

It is important to emphasise that, like all other mechanical stress-relief techniques for measuring residual stress (e.g. slitting, deep hole drilling), the contour method assumes that stress relaxation (redistribution) during cutting process is fully elastic (Prime, 2001). Any plasticity that occurs during cutting will affect the out-of-plane deformation associated with stress release as the cut faces are created. Any resultant plastic deformation will introduce error into the contour residual stress measurement (noting that this is back-calculated from the applied cut surface deformation boundary condition). Plasticity is of particular concern when applying the contour method to weldments, as residual stresses of the material yield strength magnitude are likely to be present.

3. NeT TG4 benchmark weld specimen

The benchmark weldment of interest was made from a 194 mm × 150 mm × 18 mm block of AISI Type 316LN austenitic stainless steel with a central slot 80 mm long and 6 mm deep (see Fig. 1). Prior to welding, the machined piece was stress relieved by furnace-heating from room temperature to 1050 °C at 5 °C/min, held at 1050 ± 5 °C for 45 min, furnace-cooled to 300 °C and then air-cooled to room temperature. The slot was then filled with three superimposed tungsten inert gas (TIG) weld passes. The specimen was welded (via automated TIG) free of restraint. The specimen

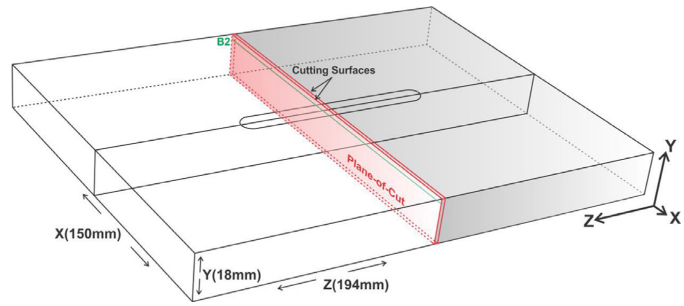

Fig. 1. Schematic drawing of the NeT TG4 weld specimen showing the plane-of-cut for the contour method and B2 line along which neutron and synchrotron diffraction WRS measurements were collected (Muránsky et al., 2012; Martins et al., 2010).

distorted upon welding by bending along the line of the weld (Z-axis) by about ± 0.8°, and also by bending about a line perpendicular to the weld (X-axis) by ∼0.4°. In total 12 samples were manufactured from which 7 were made available for round-robin residual stress measurements in the NeT collaboration. Three of these specimens were extensively instrumented with a range of thermocouples at various locations in order to provide an input for the FE residual stress round robin simulations (I.T. 21432:2005, 2005).

4. Stress-informed optimisation of cutting configuration

Practitioners of the contour method generally aim to minimise cutting plasticity by clamping the test specimen as rigidly as possible, close to and symmetrically about both sides of the cut as this helps to control the redistribution of residual stress during cutting (Prime and Kastengren, 2010; Traore et al., 2014). The ideal (rigid) clamping is, however, impossible to achieve in practice.

A conventional contour cut involves cutting the component by electric discharge machining (EDM) from one side to the other in a single cut. During the cutting process, the advancing notch resembles introducing an edge-crack within a solid body. The stress field at the cut tip, which has a finite radius, is related to the stress field at a sharp crack, which can be characterised by the Mode I stress intensity factor (SIF). Moreover the plastic zone size can be estimated from the Mode I SIF and material yield properties (Janssen et al., 2002). This stress-informed fracture mechanics approach is based on the extension of Bueckner's superposition principle (Bueckner, 1973). When a cut of certain length is introduced in a body, which contains residual stresses, the stresses on the cut faces are relaxed. This stress relaxation process is the same as imposing a stress field of the same magnitude of the original residual stress with a different sign on the cut faces. Therefore, by having prior knowledge of residual stress distribution in the body, FE linear elastic stress analyses can be performed, treating simulated EDM contour cuts as sharp cracks in the 2-D idealisation of the body and applying the original residual stress magnitudes with a different sign on the crack faces, in order to determine SIFs.

This stress-informed fracture mechanics analogy can be used to assess the level of plasticity introduced by different cutting configurations (Traore et al., 2011) and thereby control (to some extent) the location and magnitude of cutting-induced plasticity. Implementation of this approach in Ref. (Traore et al., 2011) suggested that starting the cut from a pilot hole close to the edge of the specimen (described as a single-embedded crack cutting configuration) would be beneficial. In practice the cutting proceeds from the pilot hole to the far end of the specimen, leaving a small ligament to be removed at the end of the sectioning process. The concept here is that for a given residual stress field, the crack opening