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Mitigating cutting-induced plasticity in the contour method. Part 2: Numerical analysis

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ABSTRACT

Cutting-induced plasticity can have a significant effect on the measurement accuracy of the contour method. The present study examines the benefit of a double-embedded cutting configuration that relies on self-restraint of the specimen, relative to conventional edge-crack cutting configurations. A series of finite element analyses are used to simulate the planar sectioning performed during double-embedded and conventional edge-crack contour cutting configurations. The results of numerical analyses are first compared to measured results to validate the cutting simulations. The simulations are then used to compare the efficacy of different cutting configurations by predicting the deviation of the residual stress profile from an original (pre-cutting) reference stress field, and the extent of cutting-induced plasticity. Comparisons reveal that while the double-embedded cutting configuration produces the most accurate residual stress measurements, the highest levels of plastic flow are generated in this process. This cutting-induced plastic deformation is, however, largely confined to small ligaments formed as a consequence of the sample sectioning process, and as such it does not significantly affect the back-calculated residual stress field.

1. Introduction

One of the most recently developed residual stress measurement techniques is the contour cutting method (Prime, 2001, Prime et al., 2004, Prime and DeWald, 2013), which is based on a variation of Bueckner's principle (Bueckner, 1973) of elastic superposition. The contour method is a "destructive"[1] stress-relief method that is performed in four stages: (i) planar sectioning of the specimen along the region of interest; (ii) measurement of the resultant out-of-plane deformation caused by the relief of internal residual stresses; (iii) post-processing of the measured data (i.e. 2D data smoothing/fitting); and (iv) numerical back-calculation of initial residual stresses using finite element (FE) analysis. In this final stage, the sectioned specimen geometry is uploaded into a fully elastic FE model, and the measured out-of-plane displacement is applied as a displacement boundary condition. The original (pre-cutting) residual stress field in the specimen is thus recovered using FE linear elastic stress analysis. A primary advantage of the technique is that it is insensitive to any microstructural changes that often arise between weld and parent metal, as well as the ability to measure very thick specimens (Woo et al., 2014, Simoneau et al., 2009, Kelleher et al., 2003). The required equipment is also readily available and easy-to-use when compared to "non-destructive"[2] (e.g. diffraction) techniques (Hutchings et al., 2005). On the other hand, the contour cutting method is limited in that only one stress component (perpendicular to the cutting surface) can be determined from a single cut unless additional techniques or multiple cuts are also used (Pagliaro et al., 2011).

While planar sectioning of the specimen using electric discharge machining (EDM) is straightforward relative to diffraction techniques, the accuracy of the contour method is dependent upon a number of theoretical assumptions inherent to its methodology (Prime, 2001, Prime et al., 2004, Prime and DeWald, 2013, Bueckner, 1973, Woo et al., 2014, Simoneau et al., 2009, Kelleher et al., 2003, Hutchings et al., 2005, Pagliaro et al., 2011, Prime and Kastengren, 2010). Measurement errors can be divided into "symmetric" and "anti-symmetric" components (Prime and Kastengren, 2010). Anti-symmetric errors are often caused by residual shear stresses in the sample or by crooked cutting; these errors

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

[2] 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.

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can be removed by averaging the measured out-of-plane deformation on both cutting surfaces (Prime and Kastengren, 2010). In contrast, symmetric errors that depend on the magnitude of residual stresses[3] in the sample can be caused by *plastic flow* during cutting (Prime and DeWald, 2013, Prime and Kastengren, 2010, Dennis et al., 2008, Shin, 2005) and so-called *bulge* (Prime and Kastengren, 2010); these errors cannot be corrected after the cut is performed. Metal plasticity introduced during the cutting procedure is one of the biggest challenges in achieving accurate residual stress measurements. Traditionally, researchers have attempted to mitigate this source of error through significant clamping of the specimen during cutting (Prime and Kastengren, 2010, Hacini et al., 2009, Frankel et al., 2012, Hosseinzadeh and Bouchard, 2012, Liu et al., 2014), to varying degrees of success. Clamping is intended to minimise the transient stress redistribution caused by the introduction of a free surface in the specimen during cutting, so that these transient stresses do not exceed the yield strength of the material.

Rather than relying on significant clamping of the specimen during cutting, a novel double-embedded cutting configuration has been proposed to minimise cutting-induced plasticity during the cutting process. This procedure takes advantage of self-constraint of the specimen, and is a stress-informed cutting configuration in that the length and direction of each cut is made based on the assumed residual stresses in the component. Part 1 of the present study (Hosseinzadeh et al., 2015) elucidates the rationale behind this novel cutting configuration, based on the results obtained from a three-pass austenitic steel weld specimen. Part 2 (the present paper) quantitatively examines the benefit of a double-embedded cutting configuration for the minimisation of cutting-induced plasticity by means of numerical parametric analysis. The experimental results from Part 1 (Hosseinzadeh et al., 2015) are reproduced numerically using a validated weld FE model previously developed for this benchmark weld specimen (Muránsky et al., 2012a). The stress predictions from this configuration are then compared to the predicted weld residual stresses (WRS) recovered using conventional edge-crack contour cutting configurations that assume (i) minimal constraint is present during the cutting process, and (ii) traditional clamping is used during the cutting process. The use of a validated weld FE model in this fashion provides a rare opportunity to quantify the benefit of a given contour cutting configuration, and may serve in the future as an optimisation tool for the contour method stress measurement community.

2. Benchmark specimen and residual stress measurement

One of the most common applications of residual stress measurement involves welded metallic structures (Schajer, 2013), owing to the reduced service lifetimes of welded components caused by WRS. In an effort to improve WRS prediction and measurement techniques, a task group (TG4) has been established by the European Network on Neutron Techniques Standardisation for Structural Integrity (NeT). Within NeT TG4, the WRS in a three-pass slot weld in AISI 316LN austenitic steel was measured using a variety of techniques, and predicted using FE simulation of the welding process. A series of benchmark weld specimens were manufactured using an identical weld procedure, ensuring process repeatability and allowing simultaneous WRS measurement as part of the international round-robin study. The weld design comprises a three-pass ER316L austenitic steel slot weld in solution heat-treated AISI 316LN austenitic steel plate. The nominal dimensions of the plate, shown in Fig. 1a, are (150 × 18 × 194) mm with an 80-mm long and 6-mm deep centreline slot. The slot was filled with three superimposed weld passes via a mechanised Tungsten Inert Gas (TIG) welding process.

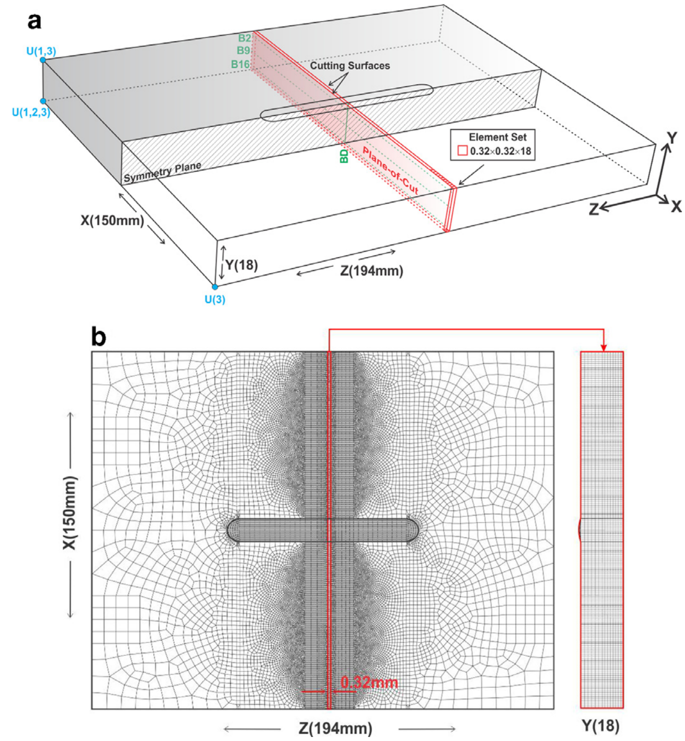

Fig. 1. (a) Schematic of the NeT TG4 benchmark specimen, and its representation for numerical FE analyses. X = transverse direction; Y = normal direction; Z = longitudinal direction. Note that the initial welding analysis used a half-model (the shaded region shown), while the contour cutting models use a full 3D FE mesh. (i) Planar sectioning of the model is performed along the plane-of-cut, which is comprised of a series of element sets with an assumed cut thickness of 0.32 mm. In cases where clamping is not used, a set of pin constraints to prevent rigid body rotation is applied to the model (shown here by blue dots). Lines (in green) highlight the nominal location of cross-weld stress profiles taken using neutron and synchrotron diffraction techniques (Muránsky et al., 2012a). (b) The mesh of the contour cutting model, comprising 396,626 hexahedral quadratic elements with reduced integration (ABAQUS designation C3D20R). The mesh was significantly refined along the plane-of-cut as well as the through the plate thickness relative to the weld model (Muránsky et al., 2012a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In terms of contour method measurements, previous studies (Muránsky et al., 2012a, 2012b) identified the longitudinal WRS profile to be the most significant in the NeT TG4 samples; therefore, cross-weld planar sectioning (Fig. 1a) was performed to measure these stresses. Since a standard contour method will provide a single stress component, only the longitudinal stress field will be measured. However, for most welding applications it is the longitudinal WRS that are of greatest importance, and they are the focus of this work.

3. Numerical analysis

Numerical (FE) analysis is split into two components. First the predicted WRS in the NeT TG4 specimens were validated against diffraction measurements (Muránsky et al., 2012a). Then numerical simulation of the contour cutting method was conducted and validated against the recovered (back-calculated) WRS measured from the double-embedded contour method (Hosseinzadeh et al., 2015). Alternate cutting methods were then simulated, and the results compared to assess the efficacy of the double-embedded cutting procedure to recover original (pre-cutting) WRS. The following sections highlight the specifics of each modelling effort.

[3] There are some symmetric errors that do not depend on the magnitude of residual stress in the sample. These errors can be corrected by an offset of the measured contour (Prime and Kastengren, 2010).