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Weld Application of a New Method for Cross-Sectional Residual Stress Mapping

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ABSTRACT

The new “contour method” was used to measure a cross-sectional map of residual stresses in a welded plate. Comparisons with neutron diffraction measurements confirm the capability of the contour method to measure complex, 2-D stress maps. Compared to other methods, the contour method is relatively simple and inexpensive to perform, and the equipment required is widely available

INTRODUCTION

A new relaxation method for measuring a cross-sectional map of residual stresses has recently been developed [1]. This new method, the contour method, differs significantly from other methods for measuring residual stress. With conventional relaxation methods, the deformations caused by material removal and subsequent stress relaxation are measured on a *pre-existing free surface* using strain gages, displacement gages, or interferometry. Then the original residual stresses are calculated using an analytical *inversion* process. With the contour method, the contour of the new surface created by cutting a part in two is measured. By assuming that the contour is caused by elastic stress relaxation, a full cross-sectional map of the original residual stresses normal to the cut can be calculated *directly* using a finite element model.

The results in this paper are the first significant evaluation of the 2-D mapping capabilities of the contour method. The contour method has been experimentally validated on a bent beam with a known, but basically 1-D, residual stress distribution [1]. In this paper, the contour method is applied to a weldment with a complex 2-D stress variation and compared with neutron diffraction measurements.

PRINCIPLE

Figure 1 illustrates the basis for the contour method. **A** shows a body with residual stresses. In **B**, the body has been cut in half along a flat plane, and then the release of stresses has caused the body to deform. In **C**, the body has been forced back to its original configuration along the new free boundary. Assuming that the stress relief process was elastic, the whole body has returned to its original stress state (**A** = **B** + **C**). This principle is merely a re-arrangement of Bueckner’s classic superposition principle [2].

The contour method for measuring residual stress involves *experimentally* making the cut and measuring the deformed shape, or contour, along the cut plane in **B.** Then the opposite of the contour is *analytically* applied as displacement boundary conditions to a model of the body (**C**). The analysis will give the original distribution of σ_x along the plane of the cut because we know that the stresses in **B** are zero normal to the free-boundary plane of the cut. Although illustrated in 2-D for simplicity, the same process applies in 3-D.

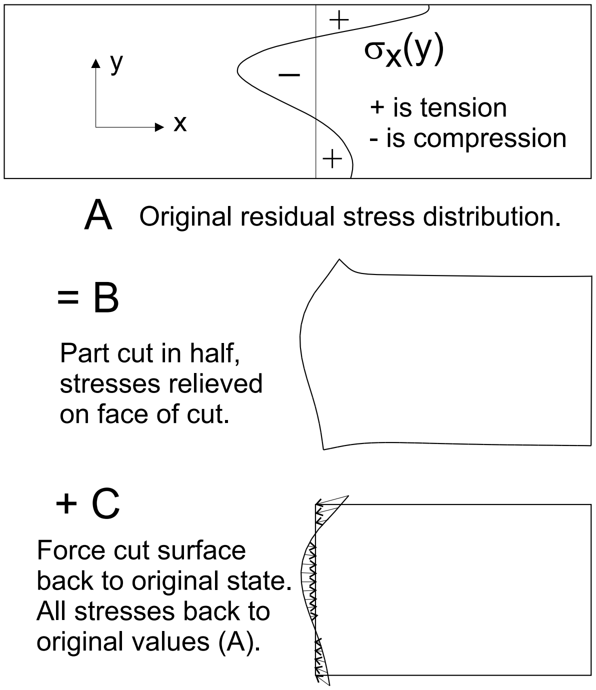

Figure 1. The superposition principle upon which the contour method is based.

Four practical considerations, which are detailed elsewhere [1], merit mentioning here. (1) The reference, or zero, for the measured surface contour (**B** in Fig. 1) is arbitrary. Fortunately, this zero is uniquely determined by the requirement that the residual stress distribution satisfy equilibrium. (2) In practice, the surface contour measurement reveals only the normal (x) displacements of the surface and not the transverse (y,z) displacements. Hence, the analytical implementation of **C** will apply only normal displacements to the cut surface and will determine only the normal stress (σ_x) on the cut plane, not the shear stresses (τ_{xy} and τ_{xz}). (3) Several experimental error sources can be minimized by measuring the contour on both halves of the cut part and averaging the two. (4) Because the displacements are small, the analytical implementation of **C** can, for convenience, start with a flat surface rather than the actual deformed shape (**B**).

APPLICATION

Specimen. A welded steel plate was prepared by TWI Ltd UK for the VAMAS TWA20 program to develop standard procedures for neutron diffraction measurements of residual stress. The material is ferritic steel BS 4360 grade 50D, commonly used in offshore structures. The plate prior to welding was nominally 1000 x 150 x 12.5 mm. It had been flame cut from a larger sheet and the rough edges had then been ground to produce reasonably smooth and square edges. A 6 mm wide U-groove was machined in the middle of the plate along its length to a depth of 8.5 mm. A 12-pass TIG weld was made in the groove. The plate was clamped for the first 10 passes but released for the last two. The resulting weldment was bent upwards towards the weld side around the line of the weld at an angle of approximately 7°. Because of flame-cutting variations and restraint during welding, residual stresses near the transverse extremities are not necessarily close to zero, and the residual stress pattern is not totally symmetrical. Several 200 mm long samples were cut from the central region of the 1000 mm long plate for the round robin. The contour method and neutron measurements reported in this paper were performed on different, but essentially similar, samples.

Make The Cut. For the contour method, the ideal machining process for separating the part would make a precisely straight cut, would not remove any further material from already cut surfaces, and would not cause any plastic deformation. Wire electric discharge machining (wire EDM) is probably the choice closest to the ideal. In wire EDM, a wire is electrically charged with respect to the workpiece, and spark erosion removes material. The cutting is non-contact, whereas conventional machining causes localized plastic deformation from the large contact forces. The part is submerged in temperature-controlled deionized water during cutting, which minimizes thermal deformations.

For this test, the plate was cut with a Mitsubishi SX-10 wire EDM machine and a 100 μm diameter brass wire. “Skim cut” settings, which are normally used for better precision and a finer surface finish, were used because they also minimize any recast layer and cutting-induced stresses [3]. Including the overcut, the slot was about 120 μm wide.

To prevent the cut from deviating from the original cut plane, the part must be constrained from moving as stresses are relaxed during the cutting [1]. Such constraint requires an unconventional clamping arrangement because usually for wire EDM only one side of the workpiece is clamped. Figure 2 shows how the weld plate was clamped on both sides for this test. Before clamping, the plate and all the clamps were allowed to come to thermal equilibrium in the water tank

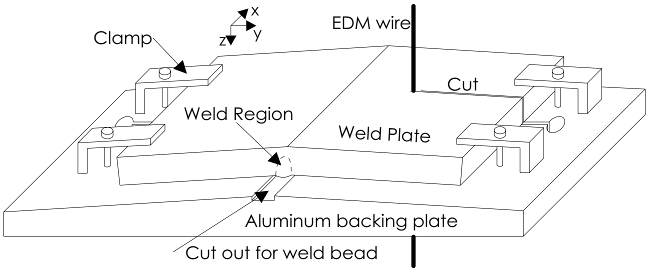

Figure 2. Cutting the weld plate in two.

Measure The Contour. After cutting, the plate was removed from the clamps, and the contours of both cut surfaces were measured using a common inspection tool. A coordinate measuring machine (CMM) registers mechanical contact with a touch trigger probe. An opto-electric system using glass scales gives the probe location, which is combined with machine coordinates to locate the surface.

For this weld plate, the contour measurements were taken using a Brown & Sharpe XCEL 765 CMM, which resides in a temperature and humidity controlled inspection laboratory. A 4 mm diameter spherical ruby tip was used on the probe. The cut surfaces were measured on a 0.4 mm spaced grid, giving about 12,000 points on each cut surface.

In order to smooth out noise in the measured surface data and to enable evaluation at arbitrary locations, the data were fitted to bivariate Fourier series. It was not possible with a single expression to adequately capture all the features in the contours. Therefore, the contour in the central 35 mm of the cross-section (i.e., weld region) was fit with one expression, the contour on the remaining regions (overlapping) was fit with another, and the two fits were blended together to define one surface. The same process was repeated on both halves of the plate. The r^2 for the fits ranged from 0.985 to 0.996, and the root-mean-square error ranged from 1 to 2 μm, which approximately matches the noise level in the data.

The contours measured on the two halves of the plate were approximately the same shape but not the same amplitude. On one side the maximum peak-to-valley distance was about 95 μm, and on the other side it was about 60 μm. The difference likely occurred because the cut was not centered between the clamps (the clamps on one side of the cut in Fig. 2 were twice as far from the cut as the other side). Such asymmetries will cause the plane of the cut to move slightly as stresses are released, and the cut will proceed on a different plane. Fortunately, this deviation is anti-symmetric with respect to the cut plane and, hence, will not cause errors in the results so long as the two contours are averaged before calculating stress [1].

Calculate The Stresses. The residual stresses were calculated from the measured surface contours using a finite element (FE) model. A 3-D model was constructed of one half of the plate—the condition after it had been cut in two. Using the commercial code ABAQUS, the model used quadratic shape–function (i.e., 20 node) brick elements. The elements were approximately cubes 1 mm on a side, resulting in 98,800 elements and 1,278,927 degrees of freedom. The material behavior was isotropic linearly elastic with *E* of 209 GPa and Poisson's ratio of 0.3.

The bivariate Fourier series fits to the measured contour data were evaluated at a grid corresponding to the FE nodes, averaged between the two sides, and then applied as *x*-direction displacement boundary conditions. Three additional displacement constraints were applied to prevent rigid body motions. Figure 3 shows the deformed FE model. Recall from the discussion under PRINCIPLE that, for convenience, the stress calculation step starts from a flat cut surface rather than the actual deformed shape.

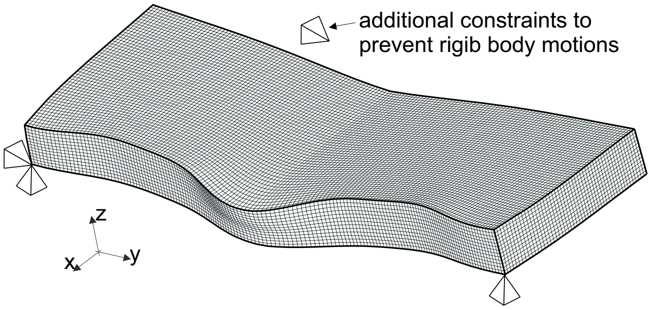

Figure 3. Deformed shape of finite element model. This shape represents the *opposite* of the measured contour of the cut surface.

The surface stresses were then obtained by evaluating the values of σ_x at the nodes of the surface elements and averaging among all elements sharing a given surface node.

Neutron Measurements. The neutron technique determines the lattice strain, as defined in equation 1, from the small shift in the angular position of a Bragg diffraction peak that results when polycrystalline materials are strained [4]. Stresses are then derived using equation 2 by combining the strains measured in usually three directions at each point.

$$\varepsilon = (d - d_0)/d_0 \qquad (1)$$

$$\sigma_x = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_x + \nu(\varepsilon_y + \varepsilon_z)\right] \qquad (2)$$

In this investigation measurements were made in the three orthogonal near-symmetry directions: along the weld, perpendicular in-plane, and normal to the plate surface. The (211) reflection was measured using a wavelength of 1.836 Å and gauge volumes of 2 x 2 x 2 mm or 2 x 2 x 20 mm for longitudinal and for transverse and normal orientations respectively. Measurements were made over the full cross-section using a rectangular scanning matrix of over 1200 locations with point densities related to the strain gradients and physical features of the weld.

Results. Figure 4 shows the cross-sectional maps of residual longitudinal stresses measured by both the contour and neutron diffraction methods. The maps are also expanded in the weld region, where the stress gradients are large. The agreement between the two maps is excellent. In fact the agreement surpasses what would be expected by considering that estimated uncertainties for both methods were each about ± 40 MPa. This may be due to the additional smoothing effects of the fitting routines used to generate the continuous maps from the stresses at the FE nodes (contour method) and individual measurement points (neutron).

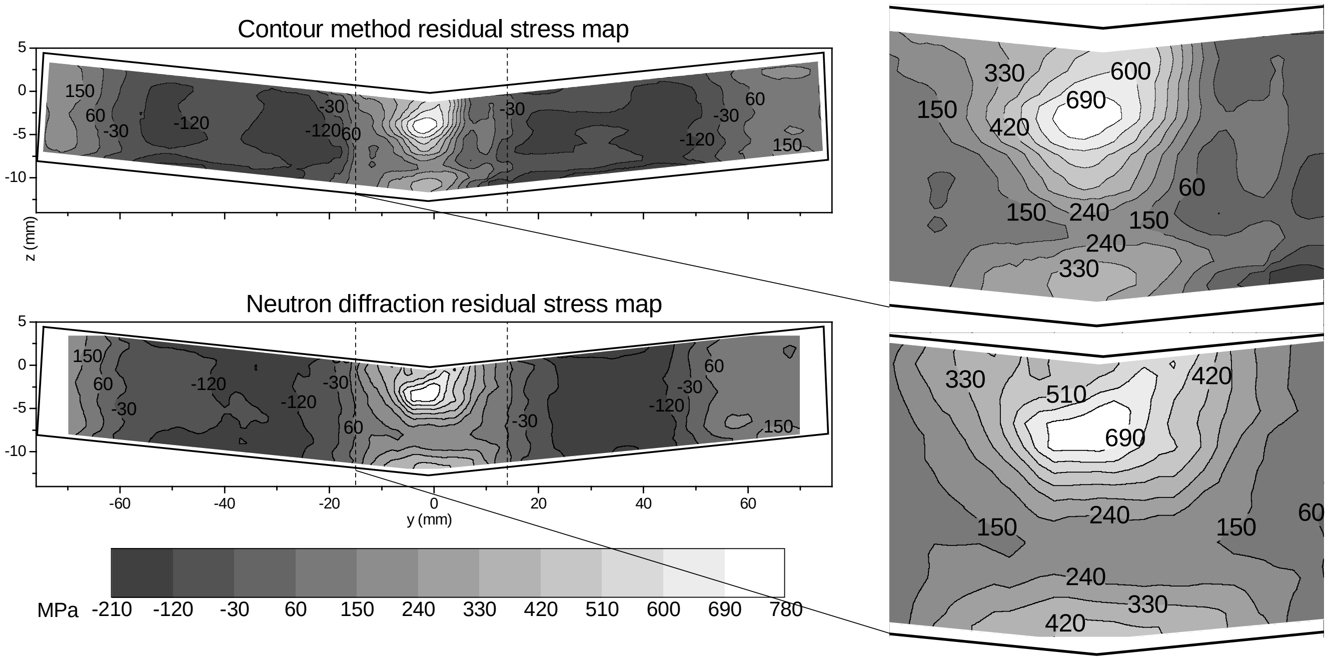

Figure 4. Measured longitudinal residual stresses (σ_x in MPa) in cross-section of weld plate. The contour and neutron measurements were performed on different sections of a long plate.

DISCUSSION

The results in this paper confirm that the contour method can, at least in this case, measure very high residual stresses without any yielding problems. The contour method assumes that the stress relaxation process is elastic. However, larger residual stresses could possibly lead to yielding as the stresses are released during cutting. The residual stresses in the weld plate exceed the material's non-strain-hardened yield strength of about 400 MPa. Yet the contour method results agree very well with the neutron diffraction results, which are completely independent of the possibility of yielding during relaxation. Qualitatively, yielding is minimal because relaxation involves *unloading* of stresses, which is usually elastic, and because the local yield strength in stressed regions has been raised by strain hardening. Recent experimental studies have confirmed that yielding does not necessarily occur in relaxation measurements even when the residual stresses exceed the nominal yield strength of a material [5].

The results on the weld plate also confirm that the contour method can be applied without a correction for curvature in the wire EDM cut surface. In a previous test [1], an unfortunate choice of material for the EDM wire resulted in the cut surface being slightly curved even for a cut in stress-free material. On the weld plate in this paper, a measurement of a test cut in a stress-free region of the plate indicated that the surface was flat to within about 1 µm.

As presented in this paper, the contour method measures only the stress component normal to the cut surface. By contrast, the neutron diffraction method can measure all of the stress components. Indeed, all three normal stress components were measured by neutron diffraction in the weld plate. Nevertheless, it should be possible to extend the contour method to measurements of additional stress components. The same calculation that determines σ_x from the measured surface contour, Fig. 1**C**, also determines the *change* in σ_y and σ_z. Hence, adding the remaining transverse stress on the face of the cut, measured for example using x-ray diffraction, would give the original stresses.

CONCLUSIONS

The ability of the contour method to measure a complex, cross-sectional residual-stress map has been verified by comparing with neutron diffraction results in a weld plate. The contour method is a significant addition to the range of techniques currently used, all of which have their particular advantages and limitations.

The X-ray technique, for example, can be portable and has good non-destructive surface stress measuring capability but surfaces have to be eroded when it is used for near-surface depth profiling. The hole-drilling technique can be used to greater depth than X-rays and also has the advantages of being portable, but is to a more-or-less significant extent destructive depending upon the relative dimensions of the drilled hole and the size of the component being measured. The hole-drilling is also limited to measuring 1-D spatial variations, i.e., residual stress as a function of hole depth.

The neutron diffraction method can potentially measure more complex stress maps than the contour method, and it is often used to measure non-destructively through several centimeters of most engineering materials. For example it would be possible in principle to measure, with adequate spatial resolution, non-destructively, accurately and economically, the strain at any point in any direction within the ferritic steel weld that was investigated. However, if the steel plate thickness had been greater than 40 mm, full 3-D mapping would have been practically and economically constrained by neutron beam attenuation. The neutron diffraction technique can only be performed at large central facilities but has advantages separate from spatially resolved stress measurements; such as measuring *in situ*, i.e., at temperature or under external loading, and distinguishing phase-specific stresses.

This comparative study shows that, for the ferritic steel weld investigated, the new contour method gives results directly comparable to the neutron method for internal 2-D mapping. It could also give similarly accurate results for thicker samples. The contour method is destructive but has a wide range of applications. Its biggest advantage is that it is relatively simple and inexpensive to perform, and the equipment required is widely available.

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