Residual Stress Mapping in Welds using the Contour Method

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Abstract. The contour method, a newly-invented sectioning technique for residual stress measurement, has the potential to measure the cross-sectional residual stress profile of a weld in a simple and time-efficient manner. In this paper we demonstrate the capability of the contour method to measure cross-sectional residual stress profiles, which are compared with neutron diffraction measurements and show excellent agreement. The results provide useful information for safety-critical design of welded components and optimization of welding parameters, and also illustrate the potential of the contour technique as a powerful tool for residual stress evaluation.

Introduction

Residual stresses exist in all welded components as a consequence of their thermal and mechanical processing. The scarcity of reliable weld residual stress data has led to most design standards taking a conservative view of residual stress, with upper-bound yield values often being assumed. This is a reasonable approach if the structure can be assumed to be ‘defect-free’ at start of life. Under these conditions it may also be reasonable to derive a ‘safe life’ based on crack initiation procedures. However, damage-tolerance-based structural integrity remnant-life assessments are now virtually mandatory in both the aerospace and nuclear power industries, and such methodologies are increasingly used for any situation where safety is paramount. As the kinetics of defect growth can be strongly influenced by residual stresses a detailed knowledge of the variation in the residual stress tensor is required for such ‘fitness for purpose’ structural integrity assessments of welds.

Of course, comprehensive data on weld residual stress profiles also deepen our understanding of welding processes, and so improve our capability to achieve high quality welds. In recent years, neutron and synchrotron X-ray diffraction methods have revolutionized our capability to non-destructively measure the residual stresses deep within welded components and structures. But these techniques are both specialised and expensive, and so are best utilized to study specific safety-critical applications or to validate other residual stress measurement processes.

The contour method is a 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: for example, steel welds [2], quenched and impacted thick plates [3], cold-expanded hole [4] and aluminium alloy forging [5]. In this paper, we extend the application of the contour method to measure a full longitudinal (parallel to the weld bead) residual stress map cross-thickness in a bead-on-plate stainless steel weld.

Materials and specimen details

The base material of the specimen under study was AISI type 316L austenitic stainless steel. The test certificate chemical composition (wt.%) was 0.02 C, 1.404 Mn, 0.027 P, 0.0011 S, 0.582 Si, 11.11 Ni, 17.834 Cr, 2.06 Mo, 0.0132 N, balance-Fe.

The as-received plate had dimensions 179 mm long × 120 mm wide × 17 mm thick, supplied by Mitsui Babcock as part of the ENPOWER program. It experienced solution heat treatment in a vacuum furnace for 1 hour at 1050°C, and then cooled down slowly. The test certificate 0.2 % tensile yield stress was 230 MPa and the ultimate tensile strength was 554 MPa. A single manual-metal-arc weld bead, approximately 66 mm long, 8 mm wide and 2 mm high, generated by a low heat input scheme, was introduced on the top surface in the centre of the plate, as illustrated in Fig.1. The weld bead was not, however, uniform throughout, apparently owing to the manual weld process.

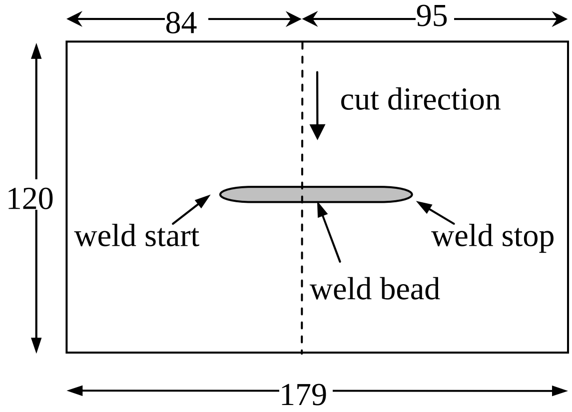

Figure1: Schematic illustration of the specimen and cut arrangement for contour-method measurement. All dimensions in millimetres.

Contour-method Measurement

The concept of the contour method is derived from Bueckner's elastic superposition principle [6]. The explicit description of the contour method and its application procedure have been reported in detail elsewhere [1]. Basically, employment of the contour method involves four steps: specimen cut, contour measurement, data reduction and finite element analysis.

Firstly, the specimen was sectioned across the width of the plate, to determine the longitudinal residual stress profile. The sectioning was achieved by electric-discharge machining with a 0.1 mm diameter brass wire, along the cut line indicated in Figure 1. The cut plane was 5 mm offset from the centre of the weld bead in order to avoid a small hole used for thermocouple measurements during welding. The plate was constrained firmly by clamps during machining. The cutting wire broke at 8 mm by accident, and a second cut was conducted from the beginning. The 8 mm long material was re-cut unfortunately as the consequence of the closure of the first cut slot, proving the presence of a compressive residual stress in that region.

Following the cut, both the sectioned surfaces were measured with a co-ordinate measuring machine (CMM), equipped with a 1 mm diameter ruby-tipped probe, to acquire the contour formed by the release of the residual stress. The contour measurement was performed on a square grid of 0.5 × 0.5 mm, resulting in 8435 points for each side. Care was taken during measuring that the specimen was held steady and each pair of points was arranged to be measured ideally in a mirror position. Thermal compensation should be taken into account if the temperature varies significantly in the course of the contour measurement.

After the measurement, the contours of both sides were averaged point-by-point correspondingly, as illustrated in Figure 2. This averaged resulting contour is associated with the residual stress on the original plane before cut. The peak-to-valley magnitude of the contour was measured to be 163 μm. The sharp drop in the measured contour observed in Figure 2 is due to the re-cut, as mentioned earlier, and was deleted from the contour measurements. The remainder was valid for further data reduction. A least-squares approximation with a cubic spline function was utilized to minimize the scatter in the measurements [7]. The standard deviation of the cubic spline smoothed surface was 1.2 μm. A spline function was employed again to extrapolate the deleted measurements, aiming to generate full data covering the whole plane. Figure 3 illustrates the final smoothed contour, ready for subsequent finite element analysis.

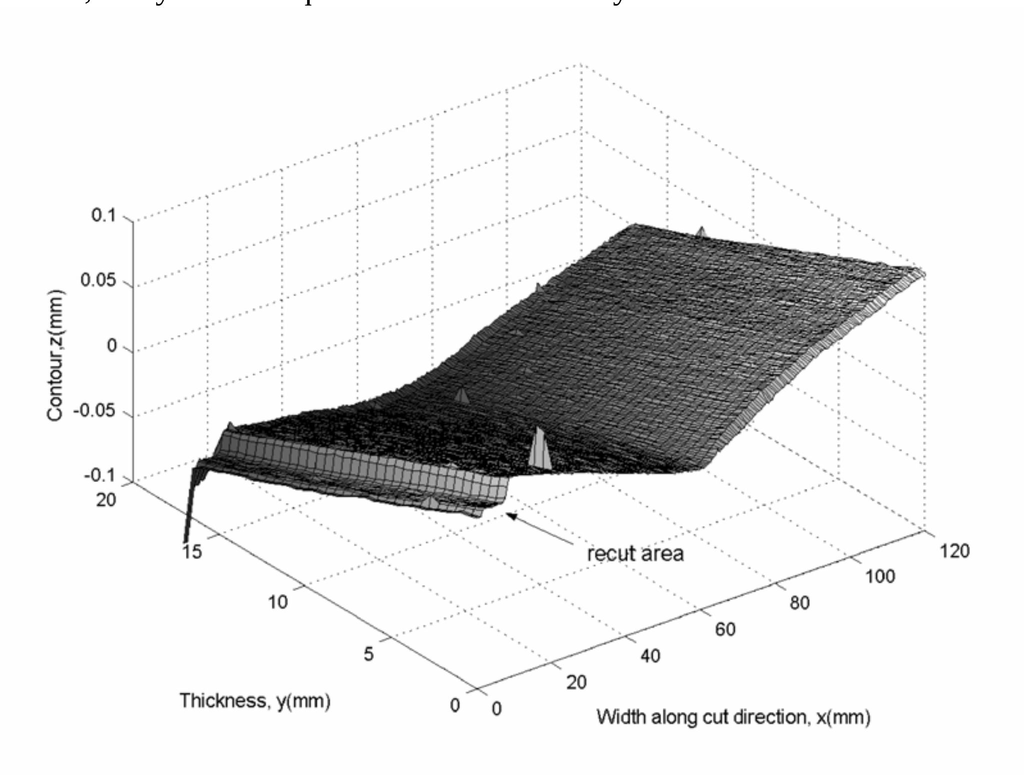

Figure 2: Measured contour, showing the recut area at the far left from the cut start

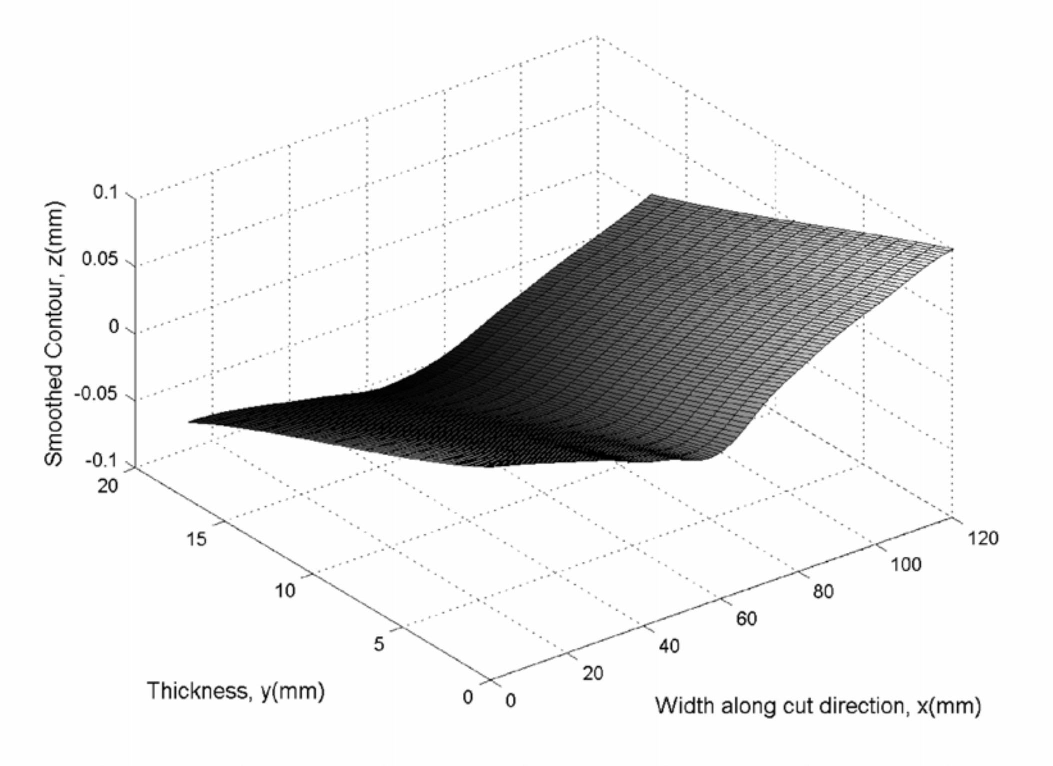

Figure 3: Final contour after cubic spline smoothing and extrapolation

Finally, the smoothed contour was input into a finite element model, as displacement boundary conditions. The 1 × 1 mm meshed model, characterized with 8-node linear elements with reduced integration, was used to simulate one of the cut pieces. A flat plane, representative of the cut surface, was assumed and the contour in an opposite sign was discretely applied to the nodes of the meshed plane. Young's modulus of 195.4 GPa and Poisson's ratio of 0.294 were chosen for the finite element analysis to calculate the corresponding stress by performing a linear solution.

Results and discussion

Figure 4 shows the overall profile of longitudinal residual stresses across the thickness measured by the contour method. The line plot of the stresses in Figure 5 gives clearer information. The results in the shaded area in Figure 5 cannot be relied on since it is derived from extrapolated data in the re-cut region, rather than actual measurements. It can be seen from Figures 4 and 5 that the bead-on-plate welding indeed generated significant longitudinal residual stresses, showing a roughly symmetrical profile of the stress. In the vicinity of the weld centre the stress is tensile with the peak in the middle, gradually becoming compressive towards the edges, as would be expected. The tensile stress varies more sharply in magnitude than the compression. The closer to the welded surface, the higher the tensile stress. The peak tensile stress is found to be ~320 MPa, 40% higher than the test-certificate yield stress of the parent material. The most compressive stress is near the edge, up to ~100 MPa.

Non-destructive neutron diffraction was also performed on the same sample before cutting using a time-of-flight technique on the newly-developed ENGIN-X instrument at ISIS in Didcot (UK). Residual strains along the longitudinal, transverse (perpendicular to the weld bead) and normal (in the normal direction of the free surface of the plate) directions were measured, with a gauge volume of 2 × 2 × 2 mm^3 for all orientations, at a depth 2 mm below the welded surface. Unstrained reference lattice parameters were measured far from the weld bead, close to the corner and 2 mm below from the surface, where zero stress was assumed. The diffraction spectra were fitted by a Pawley refinement technique [8] using GSAS software [9] to determine the lattice spacing. The measured triaxial strains were then converted into stresses using Hooke's law, with the reasonable assumption that the principal stresses were in the longitudinal, transverse and normal directions. The average error of the neutron measurement was ~20 MPa.

The results of longitudinal residual stresses measured by both the contour method and neutron diffraction are depicted in Figure 6. It is evident that both techniques measure an identical trend of longitudinal stresses around the weld bead with the maximum tensile stress in the weld centre. It is also evident that there is an almost uniform shift of ~50 MPa in stress between the two measurements. It is possible that the d_0 used to evaluate strains in neutron diffraction may partly contribute to this difference, as the location where the d_0 was measured may not be fully free from stress. There can also be error associated with the contour method: removing the data from the re-cut area will change the stress balance of the results, and the EDM cutting is known to introduce a periodic error of up to 3 µm, which may not be filtered out completely by the technique of spline smoothing. As a result, a certain amount of error arising from the cutting can be introduced into the resulting stress in the contour method. Despite that, the comparison of results from the two methods is good.

Conclusions

- A full cross-sectional profile of longitudinal residual stresses was measured from a bead-on-plate 316L austenitic stainless steel weld by the contour method, showing a symmetrical bell-shaped profile with tensile stresses around the weld bead and compressive stresses near the edge. The peak tensile stress reached ~320 MPa in the middle of the weld and the most compressive stress was generated close to the edges of the plate.

- Time-of-flight neutron diffraction was performed on the same sample before contour-method measurement to obtain the stress profile 2 mm below the welded surface. The accuracy of the neutron measurement was within ±20 MPa.
- The comparison of the two methods shows a similar trend of the longitudinal stress variation with peak tensile stress in the weld centre. The comparison also shows that the diffraction experiment measured the longitudinal residual stress to be approximately 50 MPa higher, in general, than the contour method. This amount of shift in stress magnitude can be primarily attributed to the inaccuracy of the d_0 determination in the neutron measurement as well as the cutting error in the contour method.

In summary, the current study has shown that the contour method is a powerful technique able to measure a full cross-sectional map of residual stresses, and to provide reliable information for any engineering purposes where residual stresses are of paramount concern.

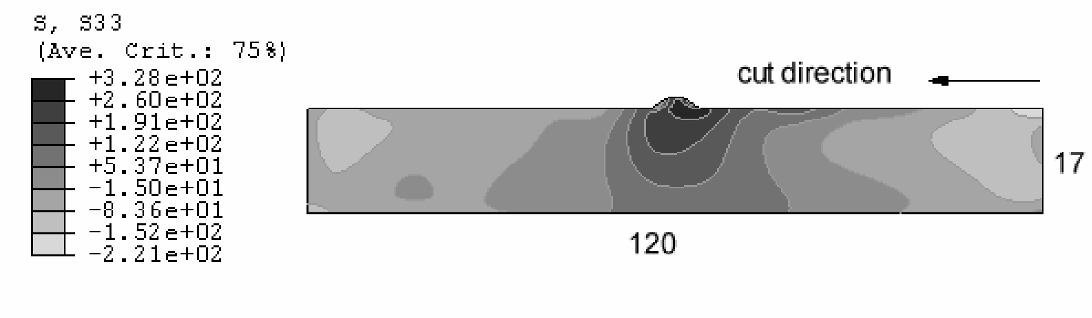

Figure 4: Cross-sectional longitudinal residual stresses measured by the contour method

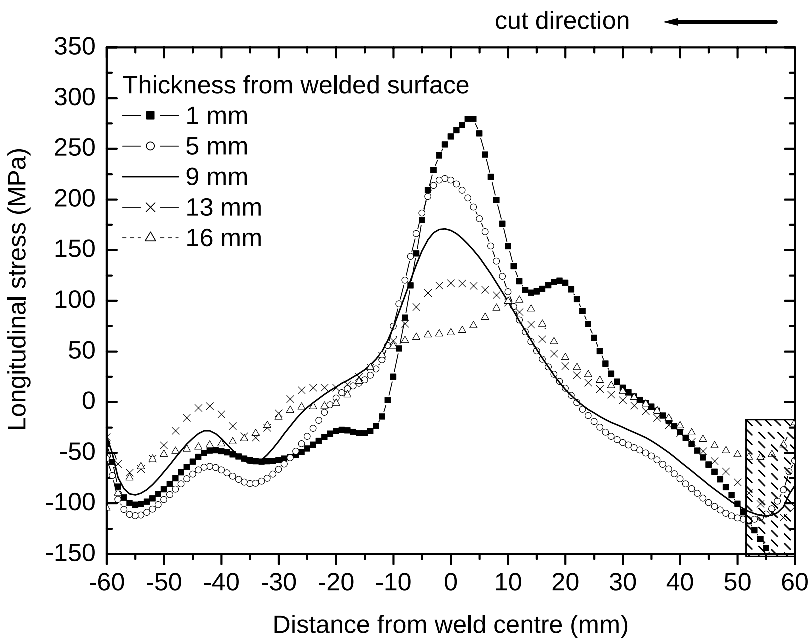

Figure 5: Line plot of longitudinal residual stresses at specified thicknesses measured by the contour method

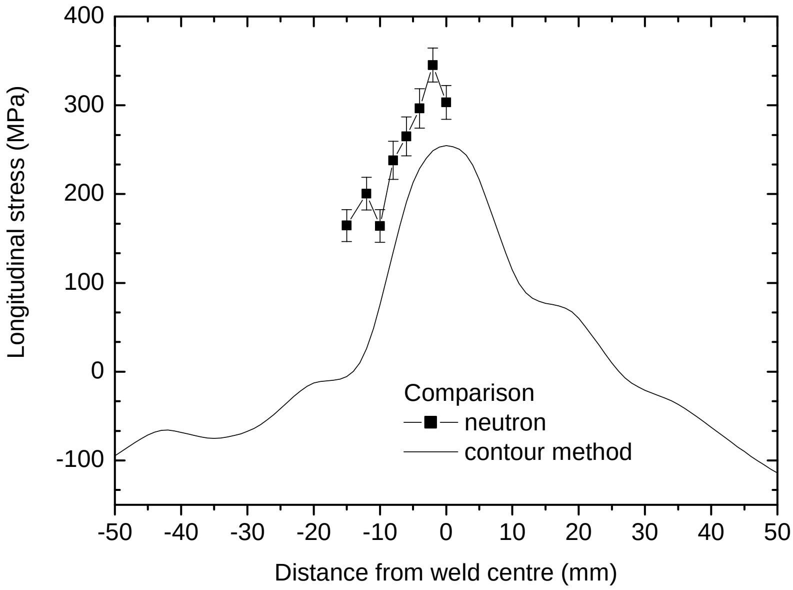

Figure 6: Comparison between the contour method and neutron diffraction at a depth 2 mm from the welded surface

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