LA-UR- 02-1071

Approved for public release;
distribution is unlimited.

Title: Residual Stress Mapping in Welds Using the Contour Method

Author(s): Michael B. Prime (ESA-EA)
Michael R. Hill (University of California, Davis)
Adrian T. DeWald (University of California, Davis)
Robert J. Sebring (MST-7)
Vivek R. Dave (NMT-10)
Mark J. Cola (NMT-5)

Details: Trends in Welding Research, Proceedings of the 6th International Conference , April 15-19, 2002, Pine Mountain, Georgia, eds: S.A. David et al., ASM International, 3003, pp. 891-896.

Residual Stress Mapping in Welds Using the Contour Method

M.B. Prime[1], M.R. Hill[2], A. T. DeWald[2], R. J. Sebring[3], V.R. Dave[4], M.J. Cola[4]

1. Engineering Sciences and Applications Division, Los Alamos National Laboratory, Los Alamos, NM 87545.
2. Mechanical and Aeronautical Engineering Department, University of California, Davis, CA, 95616.
3. Materials Science and Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545.
4. Nuclear Materials Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545.

Abstract

Residual stresses play an important role in determining welded structure integrity and performance. In this work we present a new method for measuring a full cross-sectional map of residual stresses. In this method, the contour method, a part is cut in two using electric discharge machining (EDM). The contour of the resulting new surface, which will not be flat if residual stresses are relaxed by the cutting, is then measured. Finally, the original residual stresses are calculated from the measured contour using a straightforward finite element model. This paper illustrates the measurement process as applied to various weldments, including several that would have been very difficult to measure using other residual stress measurement techniques. First, the contour method is validated by comparing measurements on a multi-pass Gas Tungsten Arc Welded plate to independent neutron diffraction measurements. Next, the contour method is demonstrated on plates of 37 mm thick pressure vessel steel butt-welded using Submerged-Arc Welding. The contour method is then demonstrated on dissimilar welds: stainless steel rods inertia friction (IFR) welded to aluminum rods.

Introduction

The magnitude and distribution of residual stress will have an impact on the integrity and performance of welded structures. Welding residual stresses result from the complex interplay of materials effects, process variables, part geometry and external constraints such as fixtures. Residual stresses are difficult to measure in welds because common techniques such as x-ray and neutron diffraction have limitations when dealing with microstructural gradients, dissimilar material combinations, and thick parts.

In this work we present welding applications of a new method for measuring a full cross-sectional map of residual stresses [1]. In this method, the contour method, a part is cut in two using electric discharge machining (EDM). The contour of the resulting new surface, which will not be flat if residual stresses are relaxed by the cutting, is then measured. Finally, the original residual stresses are calculated from the measured contour using a straightforward finite element model.

The contour method is a powerful tool for measuring residual stresses in welds. The main advantage of the contour method is that it is relatively simple, inexpensive, and utilizes readily available equipment.

Principle

Figure 1 illustrates the basis for the contour method.

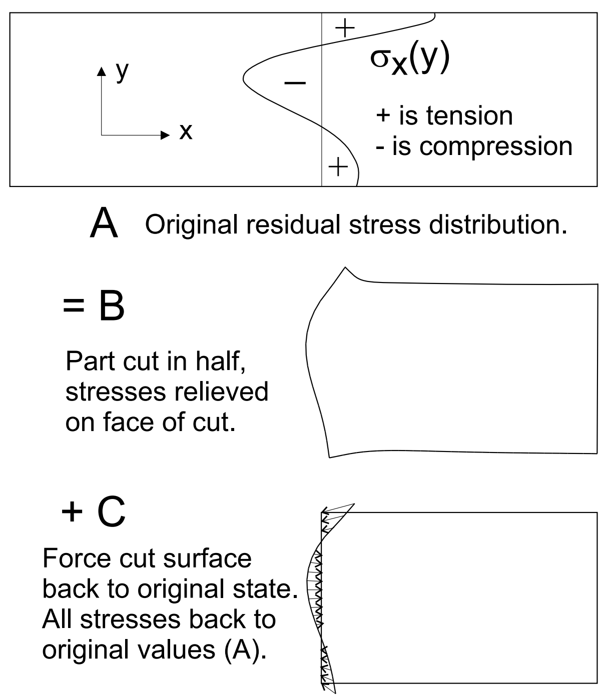

Figure 1. The superposition principle upon which the contour method is based.

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 stresses in **B** are still mostly unknown; however, they are zero on the free surface where the part was cut. Thus, the analysis by itself (**C**) will give the original distribution of $\sigma_x(y)$ along the plane of the cut. Although illustrated in 2-D for simplicity, the same process applies in 3-D to give $\sigma_x(y,z)$, which will be demonstrated in this paper.

Implementation

Making the Cut. The ideal machining process for cutting 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.

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]. Because only one side of the workpiece is usually clamped for wire EDM, such constraint requires an unconventional, but not especially difficult, clamping arrangement to secure the workpiece on both sides of the cut.

Measuring the Surface Contour. In all previous published implementations of the contour method, and several of the examples presented here, the contours of the cut surfaces were measured using a coordinate measuring machine (CMM). A 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 generally with micron-level precision. Typically each surface contour was defined by measuring on the order of 10,000 points, which takes several hours.

This work for the first time also presents contour method results where the contour was measured using a laser system. The laser contour measuring system works by moving one or more precision laser ranging probes, triangulation or confocal based, over the entire surface of the target with two orthogonal axes of motion, acquiring precision *x*, *y* and *z* spatial coordinates to sub-micron precision and resolution. A typical scan may take 30 minutes to an hour to complete with a resolution at 10 microns along the probe direction and 100 microns between scan lines.

Data Handling. First, note that the reference plane for the measured surface contour (**B** in Fig. 1) is arbitrary. Fortunately, the arbitrary orientation (a displacement and two rotations) is uniquely determined by the requirement that the residual stress distribution satisfy force and moment equilibrium. It is convenient before further processing of the contour data to fit a plane to each data set and then remove the planar component by subtraction.

The next step in reducing the data is to align the data from the two measured surfaces—the opposing surfaces from the cut. The alignment generally requires one or more coordinate transformations, i.e., "flipping" the data, such that the data points correctly overlay the opposing points corresponding to the same material point in the part before cutting. Aligning the two data generally further requires translation and rotation of one data set to match the other. Perimeters of both surfaces, measured while in the CMM, are especially useful for this task.

Next, in order to smooth out noise in the measured surface data and to enable evaluation at arbitrary locations, the data are fitted to bivariate Fourier series. Finally, since the surface data generally will not extend all the way to the part edge, and the contour must be defined everywhere for calculating stresses, any missing area of the surface is filled in by extrapolating a constant value from the defined region outward toward the edges. Stresses in this region are not considered valid and are not reported.

At some point in the data reduction process, the surface contours measured on the two halves are averaged. Averaging reduces error from both shear stress existing on the cut plane and from variations of the cut path from a plane [1]. The two data sets can be averaged before fitting the data to the Fourier series, which may require interpolating the two data sets onto a common grid, or after fitting.

Calculating the Stresses. The residual stresses are calculated from the measured surface contours using a finite element (FE) model. A 3-D model of one half of the part is constructed —the condition after it has been cut in two. The bivariate Fourier series fit to the measured contour data is evaluated at a grid corresponding to the FE nodes and then applied as *x*-direction (see Figure 1) displacement boundary conditions. In the 3-D case, three additional displacement constraints are applied to the model to prevent rigid body motions.

This implementation of the Figure 1 superposition principle only applies displacements in the *x*-direction. The *y*- and z-direction displacements are left unconstrained because the measured surface contour provides no information about those transverse displacements. The result is that only the normal stresses (σ_x) are determined, not the shear stresses ($\tau_{xy}\tau_{xz}$), but σ_x is determined correctly [1].

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**). Thus, the cut surface in the model ends up deformed into the opposite shape of the measured contour.

Weld Applications

Validation Test. First we present a weld measurement where the contour method results were validated by comparing with neutron diffraction measurements. This application is examined in greater detail elsewhere [3]. 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 using Bostrand MS65 weld wire, which is specified to produce a weld with a yield strength of 545 MPa. 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.

For the contour method measurement, the weld plate was cut with a Mitsubishi SX-10 wire EDM machine and a 100 μm diameter brass wire. To minimize movement during cutting, a special clamping fixture was used, see Figure 2. After cutting, the plate was removed from the clamps, and the contours of both cut surfaces were measured 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.

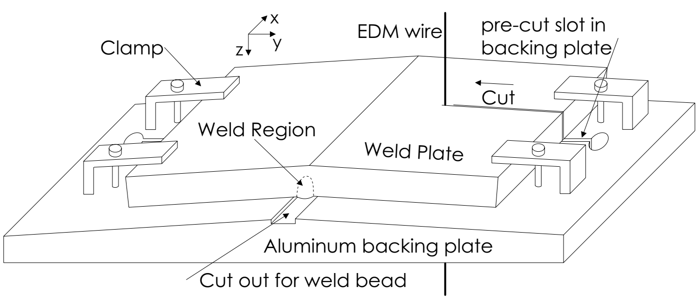

Figure 2. Fixturing arrangement for the EDM cut of the weld plate.

The finite element of the piece 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. Figure 3 shows the finite element model deformed after the application of the displacement boundary conditions.

Figure 4 shows the contour method results compared with the stress map obtained by neutron diffraction [3]. 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 partially be due to the additional smoothing effects of the fitting routines used to generate the continuous maps from the stresses at the finite element nodes (contour method) and individual measurement points (neutron).

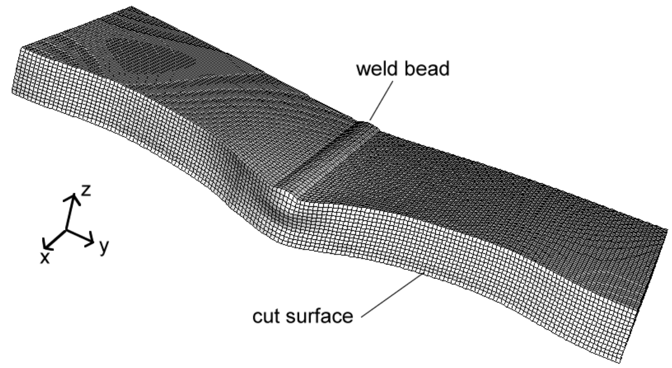

Figure 3. Finite element model of weld plate, cut surface deformed into opposite of measured contour.

The residual stress maps have several notable features. The peak stresses in the weld region are subsurface, at approximately the root of the weld. In the weld region, the stresses are asymmetric. Near the top surface (+*z*) the stresses are more tensile on one side of the weld bead, the +*y* side in Figure 4. Similarly, the tensile stress regions at the edges of the plate are also asymmetric, wider on the +*y* edge of the plate than on the other edge.

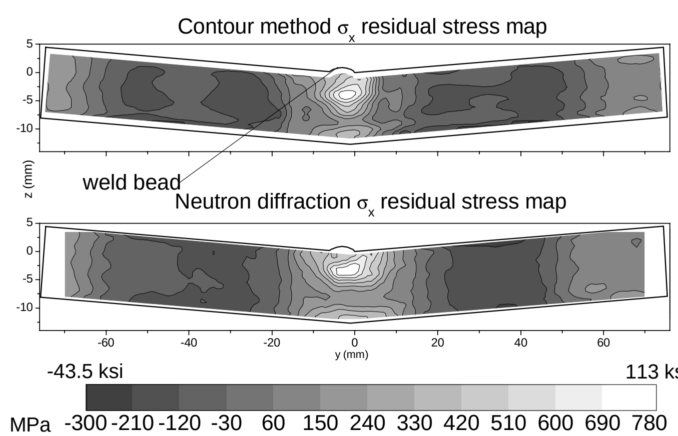

Figure 4. Weld plate maps of longitudinal residual stress.

The peak tensile residual stresses exceed the steel's nominal yield stress of 400 MPa by almost a factor of two. This component of residual stress, the axial stress, can exceed the yield because triaxiality brings the effective stress below yield. Furthermore, the yield stress is usually increased above nominal because of strain hardening due to the weld thermo-mechanical cycle. Such high stresses have been measured before in welds [4].

Thick-Plate Butt Weld. Two 37 mm thick, 105 mm wide, 700 mm long plates of pressure vessel steel were butt welded using submerged-arc welding. A full-width section of the welded plate was removed near the center of the weld length for contour measurement The dimensions of this section prior to measurement by the contour method were 250 mm (weld direction), 215 mm (transverse), and 37 mm (thickness).

The cut was made with a Hansvedt Model DS-2 Traveling Wire EDM machine using a 250 μm diameter brass wire. During the cutting process, the weld plate was clamped to a 44.5 mm thick aluminum plate to prevent movement. The Hansvedt is an inexpensive and older EDM machine, and it does not have many of the advanced features that would allow it to cut robustly, perfectly straight, and with a good surface finish. During the cutting, the machine stopped several times because of wire breakage or other problems. Also, the cutting would occasionally stop advancing for a period of time. All of these instances left distinct features on the cut surfaces that were not reflective of relived residual stresses, as is the assumption behind the contour method, but were rather anomalies caused by the cutting process.

After cutting, the plate was removed from the clamps, and the contours were measured using a Brown & Sharpe XCEL 765 CMM. A 1 mm diameter spherical ruby tip was used on the probe. About 17,000 points were used to measure the surfaces, with a more refined grid in the weld region. Some time later it was discovered that only one of the two surfaces had been measured correctly. The second surface was then measured using a International Metrology Systems Impact II CMM equipped with a 1-mm diameter ruby tip. In this case the surface was measured on a uniform grid and about 33,000 data points were collected.

Because the cut on this plate was less than ideal, there were some challenges in reducing the contour data. The surface profiles were first interpolated to a common grid using Delaunay triangulation [5] and were then rotated and translated to align the data from each side of the cut. The data after alignment are shown in Figure 5 (surface 1) and Figure 6 (surface 2). Since no perimeter measurement was available to guide alignment of the two sets of surface data, it was helpful that the data had steep ridges, which were due to EDM problems stated previously. When surface 2 was aligned with surface 1, the most prominent machining features were at coincident locations. The two surfaces were then averaged and the resulting surface was very smooth (Figure 7), indicating that the surface ridges were due mainly to abrupt changes in the path of the EDM wire. If profile data from only one cut surface were used to determine residual stress, the EDM-induced ridges would produce an erroneous result. Because careful alignment and averaging were able to remove these ridges, it was important to measure both surface profiles and use the average surface for stress determination.

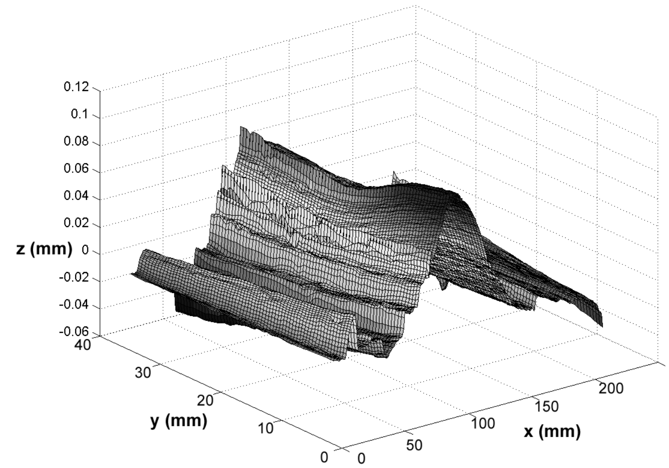

Figure 5. Surface 1 contour after interpolation to a common grid.

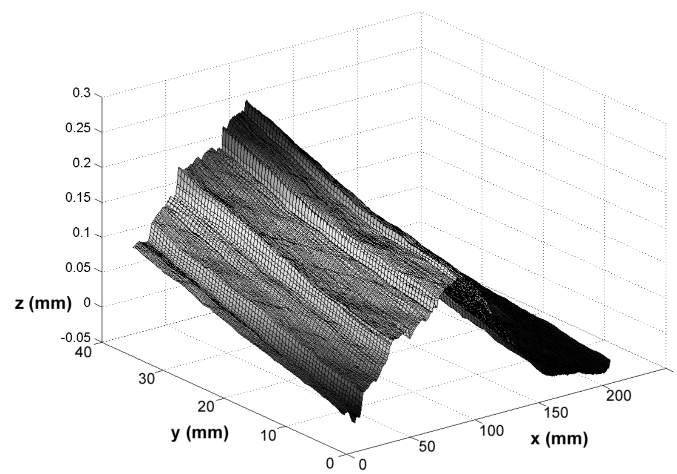

Figure 6. Surface 2 contour after interpolation to a common grid.

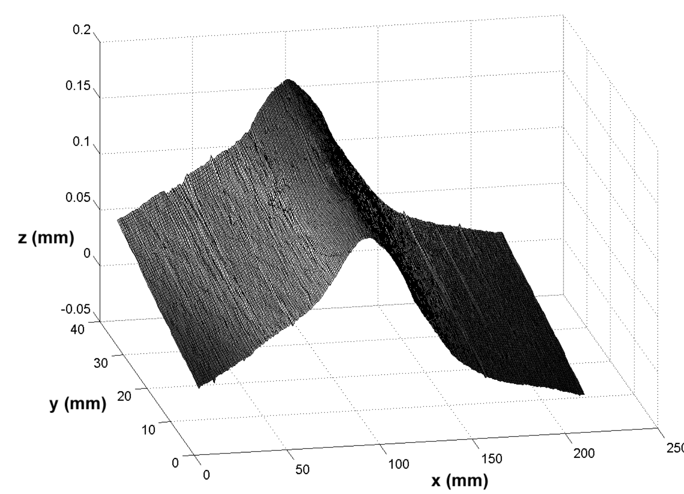

Figure 7. Average of surface 1 and surface 2.

In order to smooth the data further, the average surface (Figure 7) was fit to a bivariate Fourier surface using least squares. A convergence study was done to determine the order of Fourier surface required to adequately fit the data. The root mean square (RMS) error was plotted versus the harmonic order of the Fourier fit, which showed a plateau of approximately 1 μm at 9^{th} order (181 terms). The resulting Fourier surface was further fit to a plane and the planar component of the data was then subtracted to level the surface. Nodal surface displacements for the finite element analysis were then found by interpolation of the leveled surface data. The finite element mesh contained 28,560 hexahedral, eight-noded elements enriched with an incompatible-modes formulation to enhance bending performance [6]. The analysis was fully elastic with a modulus of 207 GPa and a Poisson's ratio of 0.29. The resulting map of the weld direction component of residual stress is shown in Figure 8.

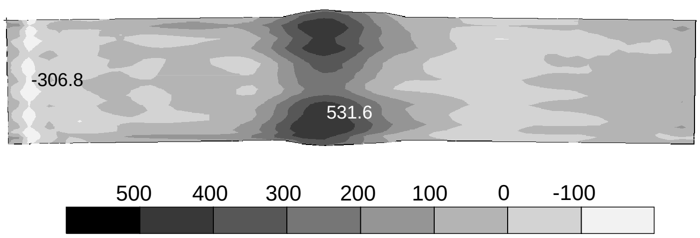

Figure 8. Weld direction residual stress (MPa) in thick, butt-weld steel plate.

For comparison, it is interesting to look at the effect of surface leveling. As mentioned earlier, the CMM can have difficulty measuring the surface profile near the edges of the surface, and profile data are extrapolated at constant value to fill in missing data. The stress estimate in the near-edge region can be significantly influenced by the planar component of the surface if it is not removed prior to extrapolation. Stresses resulting without and with the planar surface component are compared near the weld center in Figure 9. Fortunately, only the stresses near the edges are noticeably affected, and the stresses nearest the edges are already discarded because the assumption of a planar cut is not very good there.

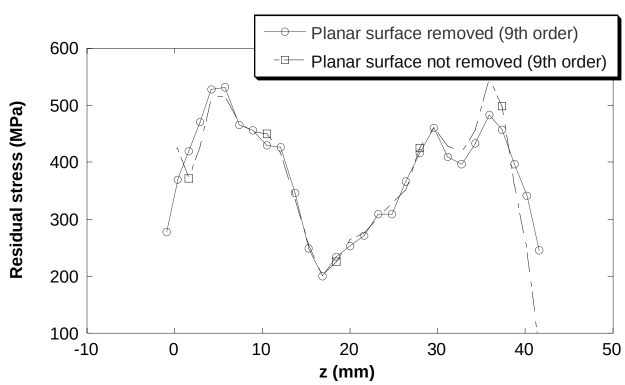

Figure 9. Effect of removal of the planar component of the surface fit before extrapolating surface contour data to unmeasured edges.

Dissimilar Metal Weld. An inertia friction welded sample consisted of a 12.7 mm diameter 316L stainless steel rod joined to an 1100 aluminum rod of the same diameter. The welds were made on an MTI Model 90B Inertia Welder using the following weld parameters: surface velocity: 120 smpm (surface meters per minute), weld pressure: 1.1 MPa; upset velocity: 4.0 smpm, upset pressure: 2.48 MPa. An x-ray microanalysis of the sectioned part showed that the region at the weld where aluminum and steel mixed was only 2 μm thick. For the contour method measurements and data reduction, which are on a scale about 50 times larger, the weld region was treated as a sharp transition.

For this test, the welded rod was cut with a Mitsubishi SX-10 wire EDM machine and a 100 μm diameter brass wire. To minimize movement during cutting, the specimen was bonded using conductive epoxy into an aluminum plate with a cutout for the specimen. After cutting, the welded rod was removed from the epoxy, and the contours of both cut surfaces were measured using an ultra-high accuracy laser displacement probe (Keyence Corp, model LC2420). Line scanning was performed using probe and motion parameters to provide a final data point spacing of approximately 80 microns and line spacing of 500 microns.

Measuring a dissimilar material combination with the contour method involved one unique challenge. A crucial assumption of the contour method is that the cut is planar. When cutting using EDM, the planar cut assumption translates to assuming the amount of overcut (the cut is wider than the wire) is constant. However, the overcut can vary with material. The surface contour measured on the dissimilar weld specimen, combined with the some test cuts, indicated that the cut was wider in the aluminum. This effect was removed by shifting the data on aluminum surface outward by 6 microns. Because the point data along the scanning direction is averaged, the data shift above did not adequately level the transition zone nearest the weld region within 2 data points of either side of the joint. To correct for this averaging artifact left over from shifting the data, a 0.25 mm wide strip of points on both sides of the dissimilar weld were removed, and the surface was later filled in there by smooth interpolation. Results are not reported in this small region where the data was removed.

The finite element model of the piece used 9660 quadratic shape–function brick elements. The material behavior was isotropic linearly elastic with E of 69 GPa and Poisson's ratio of 0.33 for the Aluminum and 193 GPa and 0.297, respectively, for the steel. Figure 10 shows the finite element model deformed after the application of the displacement boundary conditions. A contour map of the hoop stresses is superimposed on the model.

Figure 11 shows the map of residual hoop stress measured by the contour method, with the map focused in on the weld region. The stresses are quite low because the annealed aluminum (1100-O) has a yield stress of only about 34 MPa, which limits the magnitude of stress developed in the weld. Nonetheless, the contour method was able to resolve the stresses. There are tensile stresses in the immediate region of the weld, with higher stresses on the steel side and higher stresses near the axis on both sides. In the steel, a region of compressive stress is evident on the axis located about one radius away from the weld. Other stress features in the steel are relatively constant along the length of the rod, indicating that they predated the weld.

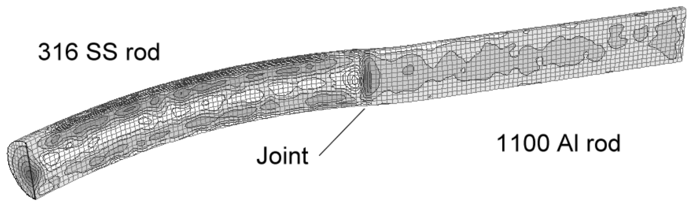

Figure 10. Deformed finite element model of dissimilar weld. Map of residual hoop stresses is superimposed on plot.

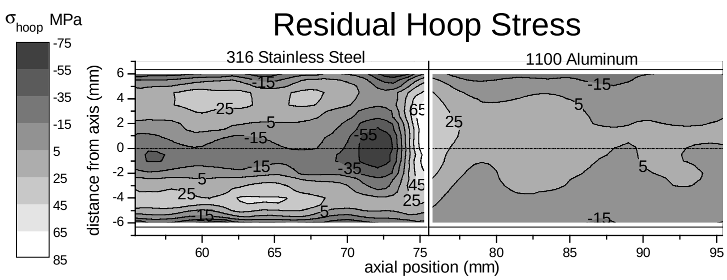

Figure 11. Map of residual hoop stresses near weld region in aluminum-steel rod-rod weld.

The most obvious feature of the deformed shape in Figure 10, which is the opposite of the measured surface contour, is actually not related to the hoop residual stresses that are measured by the contour method. The most obvious feature is the curvature in the stainless steel end of the rod. This curvature after cutting occurs because, after cutting, the *axial* residual stresses in the rod are no longer in equilibrium. In fact, this effect is the basis for the “longitudinal slitting” method for measuring axial stresses, e.g., [7]. The convexity of the cut surface (recall that Figure 10 is the *opposite* of the measured deformed shape) indicates that the axial residual stresses were tensile on the outer diameter of the rod and compressive at the axis. The curvature of the steel rod is relatively constant along the length of the rod, indicating that the axial residual stresses were also present along the length of the rod rather than just near the weld. Hence, the axial residual stresses must have been a result of the manufacturing of the rod. Such a distribution, tensile stresses near the surface and compressive near the axis, has previously been observed for cold-drawn or cold-extruded rods [8].

Conclusions

The contour method for measuring residual stress was demonstrated on several weldments. The contour method is a powerful tool for measuring residual stresses in welds. The main advantage of the contour method is that it is relatively simple, inexpensive, and utilizes readily available equipment. In many cases, the contour method can measure a map of residual stresses on specimens where it would be very difficult to perform the measurements using any other technique.

1. Comparisons with neutron diffraction measurements indicate that the contour method can accurately measure welding residual stresses.
2. The contour method was able to map residual stresses over the cross section of a 37 mm thick butt-welded steel plate. Because of the part thickness, such a map would be difficult to make with any other method.
3. Using a laser triangulation system to measure the surface contour, a map of relatively low residual stresses in a stainless steel to aluminum IFR weld was successfully made.
4. In the case of the thick weld plate, the EDM cutting was performed under rather poor conditions. Still, the results were quite good after carefully handling the data.

Acknowledgements

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

References

1. M. B. Prime, *J. Eng. Mater. & Tech.*, 123, 162-168 (2001).
2. H. F. Bueckner, *Trans. Amer. Soc. Mech. Eng.*, 80, 1225-1230 (1958).
3. M. B. Prime, D. J. Hughes, P. J. Webster, *Proc. 2001 SEM Annual Conf. Exp. Applied Mech.*, June 4-6, Portland, OR, 1, 608-611 (2001).
4. G. A. Webster, A. N. Ezelio: *Int. J. Fatigue*, 23, S375-S383 (2001).
5. F. P. Preparata, M. I. Shamos, *Computational Geometry: An Introduction*, Springer-Verlag, Inc., New York (1993).
6. J. C Simo, M. S. Rifai, *Int. J. Numer. Meth. Eng.*, 29, 1595-1638 (1990).
7. M. S. Abifarin, M. B. Adeyemi, *Exp Mech*, 33, 174-180 (1993).
8. N. T. Rudkins, G. F. Modlen, P. J. Webster, *J. Mat. Proc. Tech.*, 45, 287-292 (1994).