This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-96SR18500 with the U. S. Department of Energy.

WSRC-MS-2004-00580

Residual Stress Measurements in Side Bonded Resistance Welds

E.G. Estochen, P.S. Korinko, G.J. McKinney, M.J. Pechersky
Westinghouse Savannah River Company
Savannah River National Laboratory, Aiken, South Carolina, USA

Presented at Trends in Welding Research, 2005,
Pine Mountain, GA. May 16-20, 2005

This work was conducted for the US Department at Savannah River National Laboratory under Contract DE-AC09-96SR18500.

Residual Stress Measurements in Side Bonded Resistance Welds

E.G. Estochen, P.S. Korinko, G.J. McKinney, M.J. Pechersky
Westinghouse Savannah River Company
Savannah River National Laboratory, Aiken, South Carolina, USA

Abstract

Resistance upset welding is used to attach small diameter machined tubes to small gas vessels. Recently there has been interest in determining the level of residual stresses caused by this attachment method and its influence on environmental interactions. A test program was initiated to determine the residual stresses present due to welding using the nominal weld parameters and varying the interference between the foot and the counter bore. In this paper, the residual stress measurement technique is described, the welding conditions are provided, and the residual stress due to welding at the nominal conditions are presented.

Background

Resistance upset welding (RW) is a welding technique in which electrodes are used to apply force and current to the mating parts for the specified time. Heat is generated at the interface by current passing through the joint. The force is applied before heating and held through cooling. The entire weld is heated circumferentially at the same time. Upset welds were made using side bonding. This weld geometry is used for small foot diameters of nominally 0.25 inch as well as large plug welds of nominally 5 inches (1).

This process is used extensively at the Savannah River Site (SRS) to recycle gas containing vessels and also to make new vessels at other facilities. It was developed in the early 1960s to reduce costs. The process has been highly successful in production with no problems of vessels in the field. However, the residual stress levels caused by the interference fit are of interest since they may influence the effect of environmental interactions. The residual stresses are due solely to the extent of intereference at nominal weld conditions for alloy 21-6-9 (Fe – 21 Cr – 6 Ni – 9 Mn), a Mn and N stabilized austenitic stainless steel that is highly work hardenable.

This paper describes the work to fabricate the weldments and also the results from the laser residual stress measurements.

Experimental

Weld samples were comprised of production stems joined to test bases. A schematic of the stem, cross section of a test base and cross section of the assembly are shown in Figure 1. The range of interference fits were selected from the dimensional tolerances indicated on the engineering drawings. The interference limits tested are shown in Table 1. Three welds were made for each interference fit. The variation in the interference was accomplished by fixing the fill stem foot diameter and varying the bore diameter in the test base. All the other stem and test base dimensions were held constant.

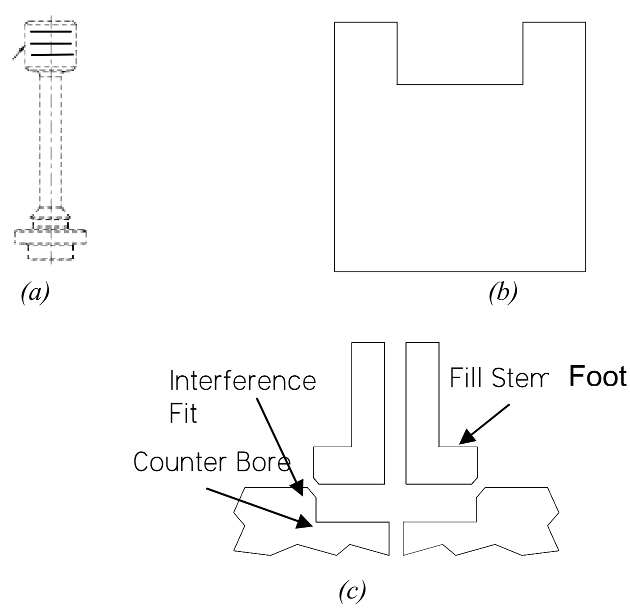


Figure 1: Sketch of components (a) fill stem (b) test base and (c) an assembly prior to welding.

Table 1. Interference fits between the fill stem foot and test bases for the samples welded. (in (mm))

	Bore	Foot	Interference
Maximum	0.249 (6.325)	0.275 (6.985)	0.026 (0.660)
Nominal	0.253 (6.426)	0.275 (6.985)	0.022 (0.559)
Minimum	0.257 (6.528)	0.275 (6.985)	0.018 (0.457)

In order to keep the test matrix small and to elucidate the residual stress due to mechanical interference, the welds were all made at the nominal welding conditions. The possible range of weld conditions, fixing the weld duration at 20 cycles, are shown in Table 2. This table shows the technical standard limits, which indicates the entire range that has been proven to yield acceptable welds, and the operating limits that are a more conservative subset of the parameter range, as well as the nominal weld conditions used for this study.

Table 2. Production welding conditions for standard and operating limits as well as the nominal conditions used for this study.

Standard Limits Force (lbs) Low/High	**Standard Limits** Current (A) Low/High	Duration (Cycles) (X 1/60th sec.)
1615 / 1811	5882 / 6746	20
Operating Limits Force (lbs) Low/High	**Operating Limits** Current (A) Low/High	Duration (Cycles) (X 1/60th sec.)
1630 / 1795	6030 / 6575	20
Nominal Conditions Force (lbs)	**Nominal Conditions** Current (A)	Duration (cycles) (X 1/60th sec.)
1700	6300	20

The method of residual stress measurement, used for this work, was to determine the strain relief after laser heating. The strain relief is determined by electronic speckle pattern interferometry (ESPI). This method uses an infrared laser for relieving stress in a small spot (2, 3). Temperature indicating paint is applied to the spot and a specklegram of the spot and the surrounding area is captured. The temperature indicating paint spot diameter can range from about 1 mm to 4 mm. A surrounding area of about 2 cm in diameter is normally captured in the specklegram. The paint is then heated with a laser until it melts. The heat is transferred from the paint into the material resulting in a small amount of localized stress relief as the yield stress of the material drops below the stress levels surrounding the spot. Once the spot and area around it start to cool, a series of additional specklegrams are captured and the images are processed to determine the in-plane strain. The amount of stress relief depends on the final temperature attained as indicated by the thermal paint since both the yield stress and the amount of thermal expansion are functions of temperature.

The residual stress is given by the following equation:

$$\sigma = A_D \times \frac{EE_H}{E-E_H} \cdot 2\varepsilon - B_D \times \frac{EE_H}{E-E_H} \cdot \frac{d}{L-d} \cdot \alpha\Delta T$$

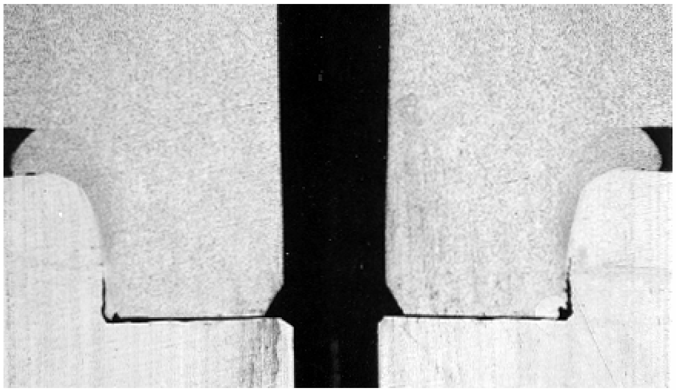
where:

L is the distance over which the strain is averaged;
d is the diameter of the heated spot, which is the actual area for which σ is determined;
α is the coefficient of thermal expansion;
E is Young's modulus at the initial temperature
E_H is Young's modulus when evaluated at the elevated temperature
ΔT is the temperature rise ($T_H - T_L$), T_L being the initial temperature, and A_D and B_D are empirically determined coefficients

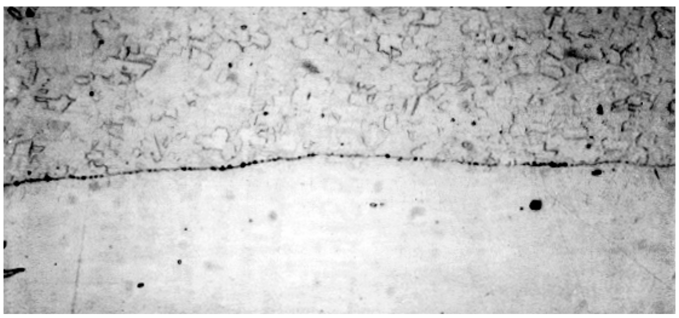
Use of this empirical equation does not require plastic deformation to obtain a measurement. This is a crucial improvement, over earlier original applications of this measurement technique where knowledge of the material yield stress was required (4). Even if the material is known, precise yield stress values and the amount of work hardening or annealing as a result of joining processes are not generally known. On the other hand, thermal properties and Young's modulus are fairly insensitive to these factors.

Results

The actual samples welded for this study will be tested further using other non-destructive residual stress measurement techniques so metallographic results are not yet available. However, a sample that was welded using an interference fit close to the nominal conditions but at lower current and higher force was sectioned for metallographic examination. These weld conditions result in a "colder" weld. The macrograph and micrograph of the welded sample are shown in Figure 2.



(a)



(b)

Figure 2:Ttypical welds of fill stems to test bases in 21-6-9 material at colder weld conditions that those used in this study. (a) low magnification of weld and (b) high magnificaton of weld interface Note that bond is considered acceptable and that the weld is rotated 90 degress from the low magnification image.

Figure 3 shows the measured hoop residual stress as a function of diametral clearance. The nominal diameter of the foot of the stem and weld cavity were 0.25 and 0.27 inches, respectively.

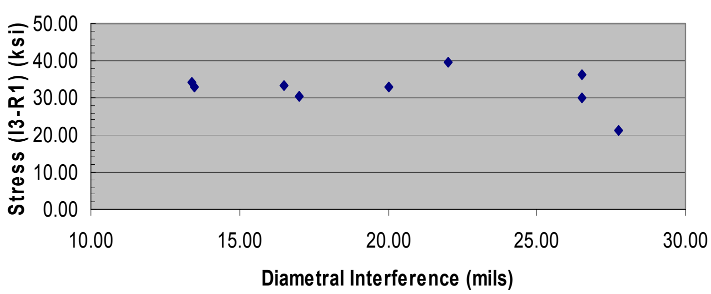


Figure 3. Residual hoop stress as a function of diametral clearance.

The location of the measurement can be seen from Figure 4 which is a specklegram used in the stress measurement. This is a view looking at the bottom of the base/stem weldment. The darkened spot near the top of the base is the heated spot (~ 3.3 mm diameter) which is where the stress was evaluated with the ESPI system. It is on the far end of the base away from the weld.

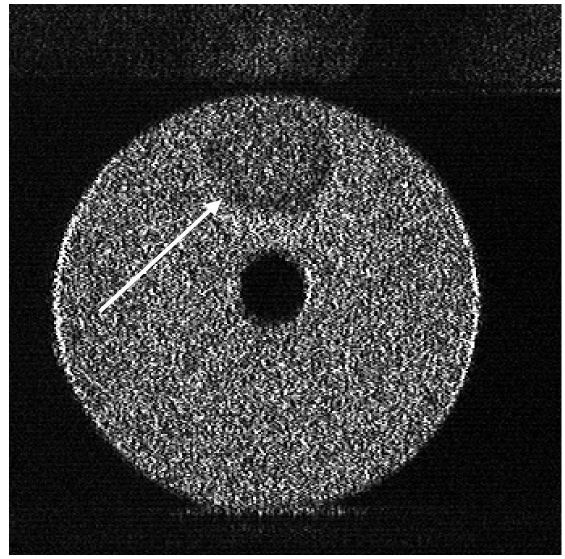


Figure 4. Location of Hoop Residual Stress Measurement, highlighted by arrow

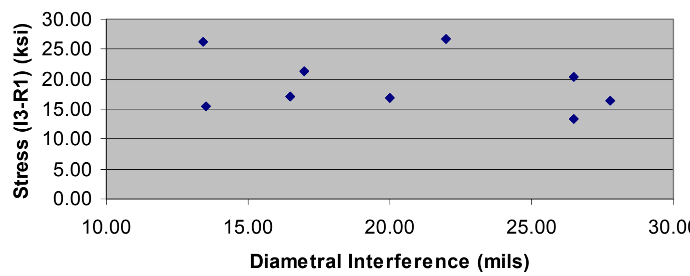


Figure 5. Residual longitudinal stress as a function of diametral clearance.

Figure 5 shows the measured longitudinal residual stress and Figure 6 shows the location that was used to measure the longitudinal residual stress.

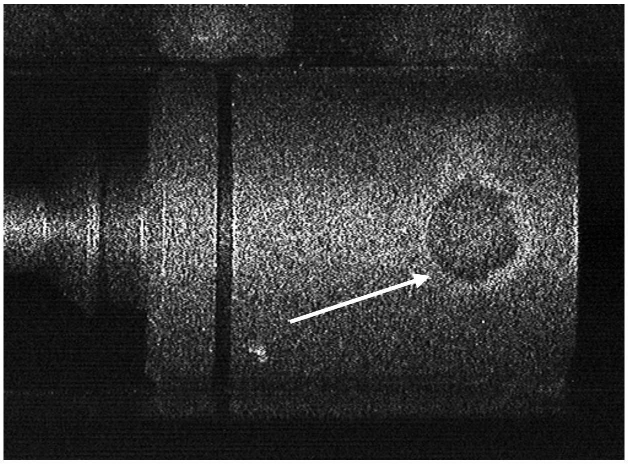
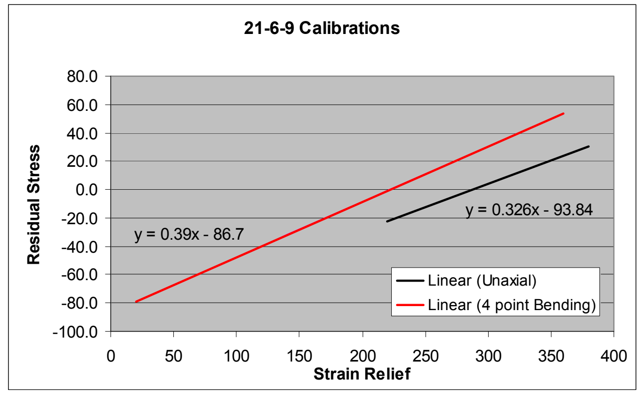


Figure 6. Location of longitudinal hoop stress measurement, highlighted by arrow.

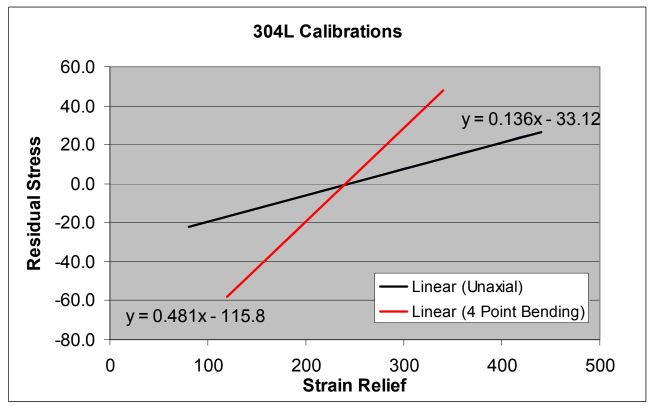
Discussion

As expected the hoop stress is somewhat larger than the longitudinal stress. The hoop stress is roughly 30% of the material's nominal yield strength and the longitudinal stress is about 20% of the yield strength, and both are insensitive to the diametral clearance. Notice that in both the hoop and longitudinal directions the measurement locations were relatively far from the weld. These locations were chosen for ease of measurement and we expect to perform more measurements at locations closer to the weld. Finally, the calibration data to generate the stress values from the measured strains is subject to a fair amount of uncertainty so that the absolute values of stress should not be considered to be very precise. This uncertainty is the result of difficulty in maintaining a fixed load on the 21-6-9 calibration specimens during calibration experiments. To address this issue, calibrations were performed on four point bend specimens as well as sheet type tensile specimens. The material variability presents issues for calibrating standards of 21-6-9 and is consequently problematic. The results of these calibrations are shown in Figure 7 along with similar calibrations for 304L stainless steel.

Ideally the calibration curves for the four point bend specimens and the tensile specimens should intersect at zero stress since this a zero stress state and hence the through thickness distribution is the same for both. Also, the slope four point bend specimens should be steeper than the sheet type specimens since the average stress near the surface is lower. While these trends exist for the 304L calibrations, Figure 7b, they do not for the 21-6-9 calibrations, Figure 7a which exhibit near parallel lines for the four point bend specimen and sheet type tensile specimen data. Therefore, the absolute magnitude of the residual stresses that are indicated in Figures 3 and 5 are most likely not accurate.



(a)



(b)

Figure7. Residual Stress Calibration Curves for(a) 21-6-9 and (b) 304L Stainless Steel

Conclusions

Resistance welds were fabricated using nominal welding conditions and variable amounts of interference that were within the expected range allowed form the engineering drawing. The residual stress was measured using laser speckle interferometry. There were no significant differences in the measured residual stress values by varying the test base diameter form the minimum to the maximum allowable on the engineering drawing. Unfortunately, the absolute magnitude of the residual stresses are in question due to difficulty in obtaining acceptable calibration data for 21-6-9, but the relative values are valid.

Additional testing that will use a simpler test base as well as the better behaved type 304L stainless steel is planned.

References

1. Eberhard, B.J. and Kelker, J. W., Jr., High Current Resistance Welding of Nuclear Waste Containers. Welding Journal Volume 61, Pages 15-19, June 1982.

2. Pechersky, Martin J., Chandra S. Vikram, Enhanced Measurement of Residual Stress by Speckle Correlation Interferometry and Local Heat Treating for Low Stress Levels, Journal of Pressure Vessel Technology, Volume 124, Number 3, August 2002.

3. Pechersky, Martin J., Determination of Residual Stresses by Thermal Relaxation and Speckle Correlation Interferometry, STRAIN, Volume 38, pages 141 -149, November, 2002.

4. Pechersky, Martin J., Edwin Estochen and C. S. Vikram, "Enhanced Measurement of Residual Stress by Speckle Correlation Interferometry and Local Heat Treating for Low Stress Levels", Proceedings of ASME PVP 2001: 2001 ASME Pressure Vessels and Piping Conference, Atlanta, Georgia, 22-26 July 2001.

Acknowledgements

This work was conducted for the US Department at Savannah River National Laboratory under Contract DE-AC09-96SR18500. The authors would like to thank S. R. Howard for providing the micrographs.