Diffraction Notes

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EFFECT OF PRIOR MACHINING ON RESIDUAL STRESS IN WELDS

Lambda Research recently completed a study of residual stress distributions developed in partial J-weld penetrations in nuclear pressure vessels. Stress corrosion cracking (SCC) field failures had occurred near similar welds. Initial phases of this work have been published [1,2]. Additional testing was undertaken to provide high depth and spatial resolution of the residual stress, cold work, and yield strength distributions present on the inside surface of the Alloy 600 penetration. The results confirm that cold working by initial machining produces a pronounced yield strength gradient which strongly influences the residual stress distributions developed by subsequent weld shrinkage. Space allows only portions of the study to be presented here. The complete paper has been submitted for publication in *Corrosion*.

A mockup of an Alloy 600 heater sleeve pressure vessel penetration was prepared from actual heater sleeve tubing removed from service. The sleeve was decontaminated and welded into a massive SA-533B reactor vessel steel block, which had been faced with an overlay of Alloy 82 weld metal. The weld procedures duplicated those used in original fabrication. The sample geometry is shown in Fig. 1.

The residual stress was determined at a series of locations through the heat affected zone (HAZ) on the "low" (left) side of the J-weld into the inside surface of the Alloy 600 sleeve. To expose the inside surface for x-ray diffraction residual stress measurement, a series of electrical resistant strain gage rosettes were applied along the inside surface, and the weldment was sectioned axially on a plane perpendicular to Fig. 1. The subsequent x-ray results, obtained with Mn Kα radiation and the (311) planes, were corrected for sectioning stress relaxation using the strain gage results.

An empirical relationship was established between the (311) diffraction peak width and known amounts of cold work expressed as true plastic strain [3]. The empirical curve, shown in Fig. 2, was used to estimate

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ANNOUNCEMENTS

Laboratory Recognized by ISO 9002 Registration

Lambda Research has been accredited to ISO/IEC Guide 25 since 1989, and now has its quality system formally recognized as meeting the ISO 9002 requirements as well. The laboratory is now registered to the ANSI/ASQC Q92 (ISO 9002) required by all major automotive firms under the QS9000 quality system, and recognized internationally.

Presentation at First International Gear Conference in Indianapolis, May 15-17

Doug Hornbach will present a paper at the International Conference on Induction Hardened Gears and Critical Components in Indianapolis, IN on May 15-17. The paper entitled "X-ray Diffraction Characterization of the Residual Stress and Hardness Distributions in Induction Hardened Gears" will examine FEA modeling for layer removal, stress relaxation correction and hardness determination from line broadening.

Current Applications of XRD Residual Stress Measurement to be Presented at IMS

An invited paper will be presented by Paul Prevey at a symposium of the International Metallographic Society in Albuquerque, NM, July 23 and 24. The presentation, "Current Applications of X-ray Diffraction Residual Stress Measurement" will address recent developments in the use of macrostress and line broadening for the prediction of material property gradients in machined and shot peened surfaces. The development of models for the prediction of thermal residual stress relaxation will be described.

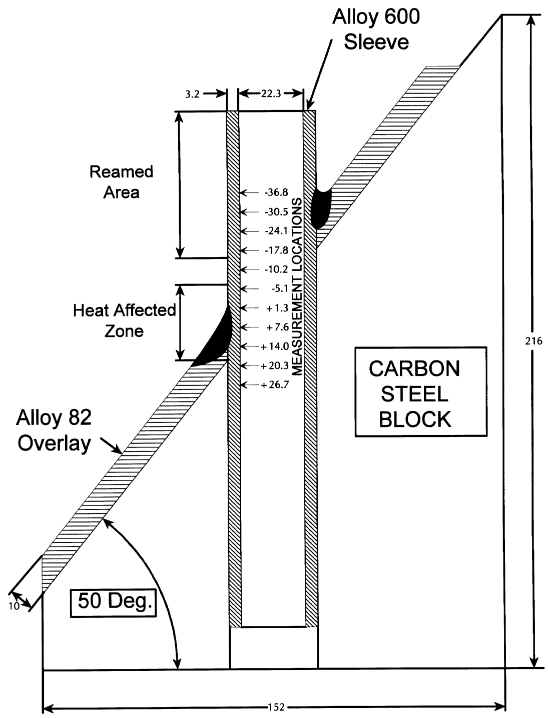

Fig. 1 - *Alloy 600 50 deg. heater sleeve penetration J-weld mockup specimen geometry*

the accumulated true plastic strain produced by machining deformation and weld shrinkage from the (311) diffraction peak width obtained during measurement of the lattice strain required for calculation of the macroscopic residual stress.

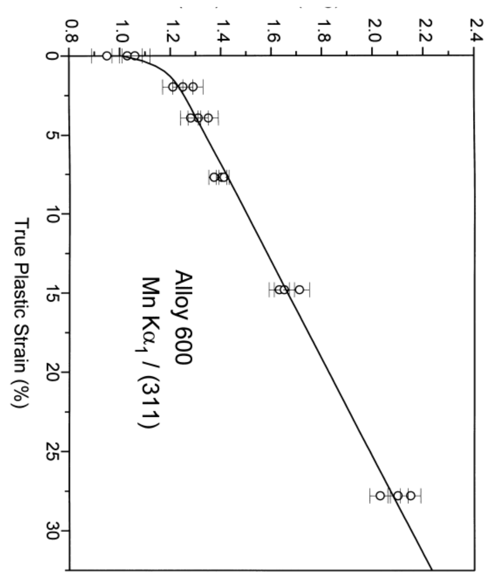

Fig. 2 - *Empirical relationship between (311) peak width and cold work (true plastic strain) for Alloy 600*

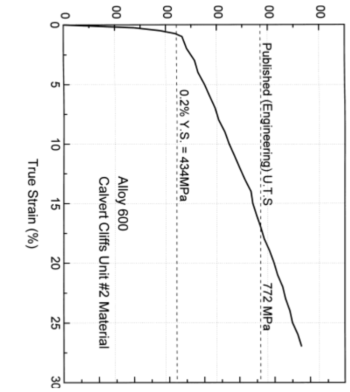

Fig. 3 - *True stress-strain curve measured for Alloy 600 heater sleeve material removed from service*

A true stress-strain curve was obtained for the actual Alloy 600 archival material used to fabricate the mockups. The curve, shown in Fig. 3, was used to estimate the yield strength resulting from the accumulated cold work introduced by machining and weld shrinkage [3].

To separate the effects of welding and prior reaming of the inside surface of the Alloy 600 sleeve, a reamed sleeve was examined as a function of depth into the inside surface prior to welding. The subsurface residual stress distributions in the circumferential direction were near zero, and only slightly compressive in the axial direction. Reaming alone could not produce the +276 MPa required to initiate SCC [4]. However, the surface was cold worked nearly 50%. The level of cold work dropped off exponentially to zero at a depth of approximately 200 μm. The resulting yield strength after reaming ranged from nearly 1000 MPa at the surface to the 434 MPa bulk yield strength at a depth of 200 μm.

Measurement of the J-weld mockup revealed a complex distribution of yield strength as a function of axial displacement and depth into the inside surface of the previously reamed sleeve as shown in Fig. 4. The yield strength exceeds 1000 MPa on the surface in the reamed area, and remains well above the bulk yield to a depth of 127 μm. Welding produced a yield strength increase due to the added cold working caused by weld shrinkage at the edge of the reamed area and HAZ. Annealing within the HAZ reduced the yield strength at depths greater than 13 μm. The immediate surface, even in the HAZ, was found to have a yield strength well over 800 MPa. Material on the immediate inner surface evidently did not reach sufficient temperature to anneal the alloy during welding.

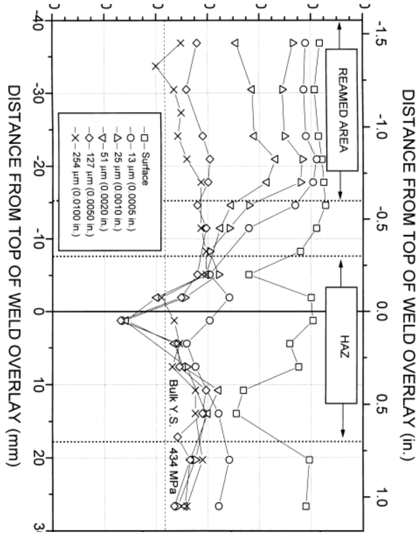

Fig. 4 - *Variation in yield strength with axial displacement and depth in the HAZ and machined regions of the low angle side of the 50 deg. Alloy 600 J-weld mockup, relative to the bulk yield strength*

The residual stress distributions in the axial and circumferential directions are shown in Fig. 5 and 6 as functions of axial displacement and depth through the HAZ and reamed areas. The SCC threshold stress is plotted in both figures. Tensile stresses are observed in excess of the SCC threshold in the axial direction at the surface and through all depths examined between nominally -15 and -20 mm from the weld, a region where SCC cracking was observed in field failures. A similar increase in tension exceeding the threshold is seen in the circumferential direction at the same location.

The increase in tension at the edge of the reamed area closest to the HAZ is attributed to weld shrinkage deformation of material which was cold worked during prior reaming sufficiently to increase the yield strength well beyond the bulk yield of the alloy, but which was not heated sufficiently during welding to be annealed. The axial stresses at all depths become compressive in the HAZ, but remain tensile in the circumferential direction because of the radial expansion of the tube resulting from weld shrinkage and the constraint imposed by the massive steel encasement.

The results indicate that the cold working produced by prior machining and weld shrinkage itself produced pronounced changes in yield strength of the austenitic alloy which dominate the resultant residual stress distributions produced. Similar yield strength gradients are observed in nickel base super alloys and 300 series stainless steels. The highly local nature of

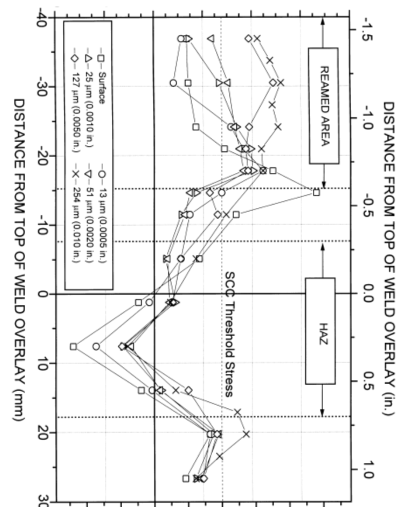

Fig. 5 - *Variation in axial residual stress with axial displacement and depth through the HAZ and machined regions on the low angle side of the 50 deg. J-weld Alloy 600 mockup.*

SCC failures are attributed to zones of high tension produced by the combination of machining induced yield strength increase and weld shrinkage. Clearly, any attempt to model the residual stresses using finite element methods would require a detailed empirical determination of the yield strength distributions produced in actual components by the prior fabrication process.

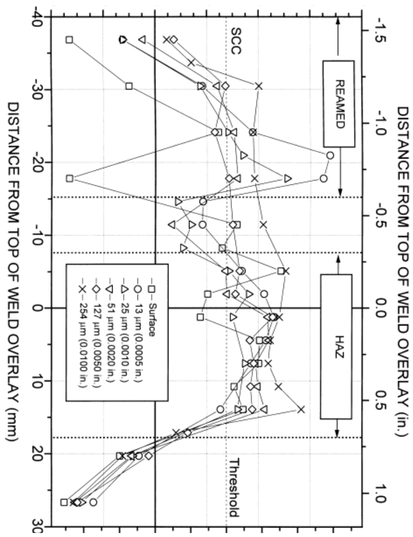

Fig. 6 - *Variation in circumferential residual stress with axial displacement and depth on the low angle side of the 50 deg. Alloy 600 J-weld mockup showing stresses in excess of the SCC threshold.*

References

1. J.F. Hall, J.P. Molkenthin, and P.S. Prevey, "XRD Residual Stress Measurements on Alloy 600 Pressurizer Heater Sleeve Mockups," Proceedings of the Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, (San Diego, CA: TMS, ANS, NACE, 1993), pp 855-861.

2. J.F. Hall, J.P. Molkenthin, P.S. Prevey, and R.S. Pathania, "Measurement of Residual Stresses in Alloy 600 Pressurizer Penetrations," Conference on the Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors, (Paris: Societe Francaise d'Energie Nuclear, Sept. 12-16, 1994).

3. P.S. Prevey, "The Measurement of Residual Stress and Cold Work Distributions in Nickel Base Alloys," Residual Stress in Design, Process and Material Selection, (Metals Park, OH: ASM, 1987), pp 151-168.

4. J.A. Gorman, "Status and Suggested Course of Action for Nondenting-Related Primary-Side IGSCD of Westinghouse-Type Steam Generators," EPRI, Report MP-4594-LD, May 1986.