2

Conf-910808--9

MAR 0 6 1992

WSRC-MS-90-298

WELD REPAIR OF HELIUM DEGRADED REACTOR VESSEL MATERIAL (U)

by

W.R. Kanne, Jr.,[1] G.J. Bruck,[2] A. Madeyski,[2] D.A.Lohmeier,[1] M.R. Louthan, Jr.[1] D.T. Rankin,[1] R.P. Shogan,[2] G.G. Lessmann,[2] and E.A. Franco-Ferreira[1]

[1]Westinghouse Savannah River Company
Savannah River Laboratory
Aiken, SC 29808

[2]Westinghouse Science and Technology Center
Pittsburgh, PA 15235

A paper proposed for presentation at the
Fifth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors
Monterey, California
August 25-29, 1991

and for publication in the conference proceedings

This paper was prepared in connection with work done under Contract No. DE-AC09-89SR18035 with the U. S. Department of Energy.

WSRC-MS--90-298

DE92 011174

WELD REPAIR OF HELIUM DEGRADED REACTOR VESSEL MATERIAL

W. R. Kanne, Jr., D. A. Lohmeier,
M. R. Louthan, Jr., D. T. Rankin, and
E. A. Franco–Ferreira
Westinghouse Savannah River Company
Savannah River Laboratory
Aiken, SC 29808

G. J. Bruck, A. Madeyski,
R. P. Shogan, and
G. G. Lessmann
Westinghouse Science & Technology Center
Pittsburgh, PA 15235

ABSTRACT

Welding methods for modification or repair of irradiated nuclear reactor vessels are being evaluated at the Savannah River Site. A low–penetration weld overlay technique has been developed to minimize the adverse effects of irradiation induced helium on the weldability of metals and alloys. This technique was successfully applied to Type 304 stainless steel test plates that contained 3 to 220 appm helium from tritium decay. Conventional welding practices caused significant cracking and degradation in the test plates.

Optical microscopy of weld surfaces and cross sections showed that large surface toe cracks formed around conventional welds in the test plates but did not form around overlay welds. Scattered incipient underbead cracks (grain boundary separations) were associated with both conventional and overlay test welds. Less underbead cracking was present in overlay welds than in stringer beads made at similar heat inputs on the same test plates. Cracking of the test plates increased with increasing helium concentration regardless of the welding process; however, the underbead cracks were only a few grain diameters in length for overlays even at the highest helium concentrations. The cracks were entirely intergranular and are attributed to temperature induced coalescence of helium bubbles on grain boundaries.

Tensile and bend tests were used to assess the effect of base metal helium content on the mechanical integrity of the low–penetration overlay welds. The axis of tensile specimens was perpendicular to the weld–base metal interface. Tensile specimens were machined after studs were resistance welded to overlay surfaces. A significant decrease in ductility and strength was found when the helium content of the test plate was above approximately 35 appm. The failure mode changed from ductile dimpled rupture in weld metal to brittle intergranular fracture of the underbead heat–affected zone. Bend tests were performed on wafer samples machined to contain both weld overlay and base metal. Existing underbead cracks opened but did not propagate during bending, thus demonstrating the localized nature of the helium embrittlement damage.

INTRODUCTION

Cracks were found in the heat affected zone (HAZ) of repair welds joining patches to the tank wall of a nuclear reactor at the Savannah River Site. This reactor is one of five at Savannah River that have produced radioisotopes for national defense purposes and for peacetime applications. These early 1950's vintage reactors are heavy–water moderated and are unpressurized. They operate at temperatures below the boiling point of water and do not generate electricity. The reactor tanks are made from AISI Type 304 stainless steel.

Subsequent analysis showed that helium embrittlement caused the cracking adjacent to repair welds in the reactor tank.[1] Helium was present in the reactor vessel wall due to neutron capture by alloy and impurity elements. The mechanism for this embrittlement was attributed to the nucleation, growth, and coalescence of helium induced microvoids during the welding process. Scanning electron microscopy and transmission electron microscopy showed the formation of small helium bubbles on grain boundaries in the steel and the presence of dimples on fracture surfaces.[2,3] Similar helium induced structures have been found in type 316 stainless steel containing helium.[4,5] Dimples are believed to result from bubble coalescence that leads to a creep like fracture of the austenite–to–austenite grain boundaries in the weld HAZ.

Once helium was identified as the cause of the reduction in weldability, a program was initiated to develop a repair technique that would eliminate or at least minimize helium embrittlement cracking. The application of low–penetration gas metal arc (GMA) weld overlay techniques provided encouraging results by producing a pronounced reduction in cracking compared to the repair welds in the reactor tank.[6] The overlay technique was developed to minimize heat input to the base material while providing sufficient weld penetration to develop a continuous metallurgical bond between the weld and base metal. The technique included a weld weave to produce a one-inch wide weld overlay that is approximately 0.035 inch thick using 308 filler wire. Weld penetration into the base metal was approximately 0.003 inch. This minimal penetration reduced the size of the high temperature and high stress regions in the substrate material. Metal transfer to the overlay was by the short-circuit mode and high speed cross seam mechanical oscillation of the arc. The overlay technique has also been shown to be applicable to welding over stress corrosion cracks in 304 stainless steel. [7]

The apparent success of the weld overlay technique emphasized the need for a qualitative analysis of helium embrittlement cracking of repair welds. The analysis focused on optical metallographic characterization of weld damage and on the mechanical strength of the overlay, including SEM fractography. This paper presents results of the analysis.

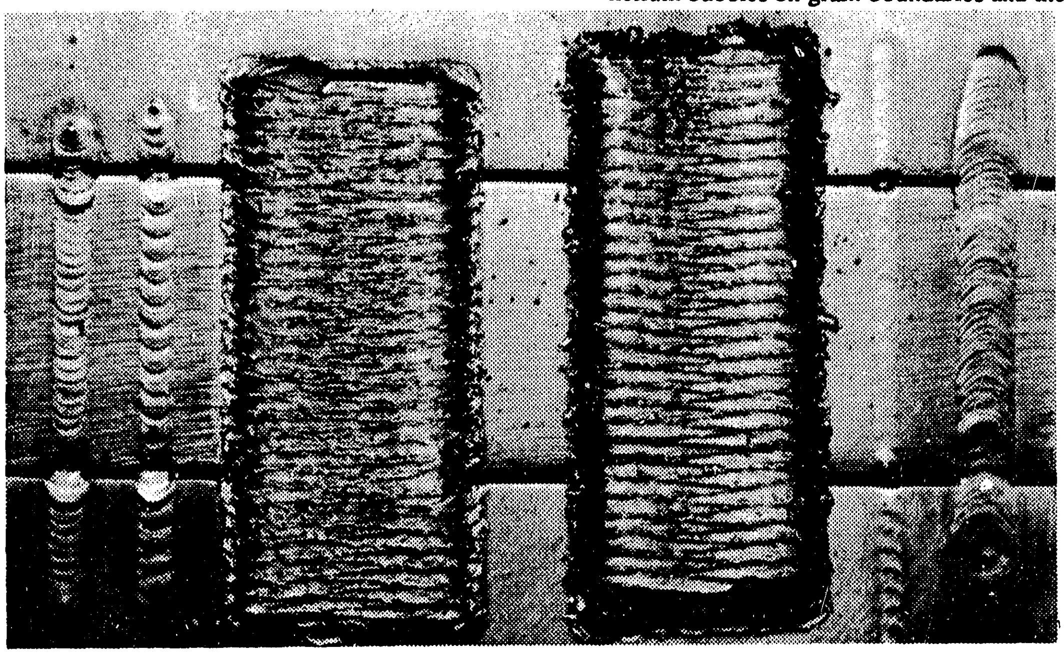


Figure 1. Overlay welds (one inch wide bands in center) and stringer beads (narrow welds on either side) across helium charged plate (center plate)

EXPERIMENTAL PROCEDURES

The effectiveness of this shallow penetration overlay process on helium bearing steel was demonstrated by welding Type 304 stainless steel plates that had been charged with tritium at the Sandia National Laboratory. Helium was produced in the plates by tritium decay, and the tritium was then removed by outgassing at 400°C. Plates contained preselected helium contents between 3 to 220 appm (atomic parts per million). The helium content, which was confirmed by chemical analysis, was controlled by the tritium charging conditions (temperature, pressure and time) and the time for tritium decay. Helium charged plates, 1.25 x 4.75 x 0.25 in., were placed in a welding fixture between plates that had not been charged. The uncharged plates served as weld start and weld stop regions to maximize use of the helium charged plate surface. Overlay welds, along with gas tungsten arc (GTA) stringer beads for comparison, were made across the plates (Figure 1).

External surfaces of the welds were visually examined and penetrant tested for toe cracks and porosity. Toe cracks are large surface cracks in the HAZ around the edge of a weld bead. Porosity is gas bubbles in the weld metal that may be open to the surface or may be trapped within the weld metal below the surface. Both toe cracks and porosity result from helium in the base metal. Toe cracks form from the agglomeration of small (2 to 3 nm diameter) helium bubbles on grain boundaries and the weld induced coalescence of those bubbles to form an intergranular crack. Porosity results simply from the macroscopic release of helium from the base metal during welding. Metallographic cross sections were also prepared and examined.

Two techniques were developed to evaluate the mechanical integrity of the weld overlay process on helium–

containing 304 stainless steel. The first technique involves tensile testing of the bond between the overlay and the base plate, which evaluates the strength and ductility of the HAZ and of the interface between the overlay and the base plate. The second technique involves bend testing which indicates the degree of grain boundary cracking and defect formation in the HAZ resulting from the application of the overlay.

Tensile specimens were prepared by milling a flat on the top surface of the overlay, resistance welding a stud to the flat, trepanning a test bar from the stud–overlay–base metal composite and machining a micro–tensile specimen from the composite. Temperature distributions were measured during stud welding to verify that the operation did not bring either the HAZ or the interface between the overlay and the base metal to temperatures above 500°C. This temperature is considered the minimum temperature required for helium embrittlement of austenitic stainless steel having helium contents similar to those of the test plates. All tensile tests were performed at room temperature and at a constant cross head speed of 0.02 in. per minute.

Side bend test specimens were sliced from the welded test plates and one side was polished to allow SEM examination after completion of the bend test. The direction of bending was such that the base plate, the HAZ, and the overlay were all subjected to the same strain during the bend test. The specimens were bent progressively to higher strains by using smaller radius plungers. After each bend the specimen was examined for cracks. Microhardness indentations were used as position markers so that the growth of individual cracks could be monitored.

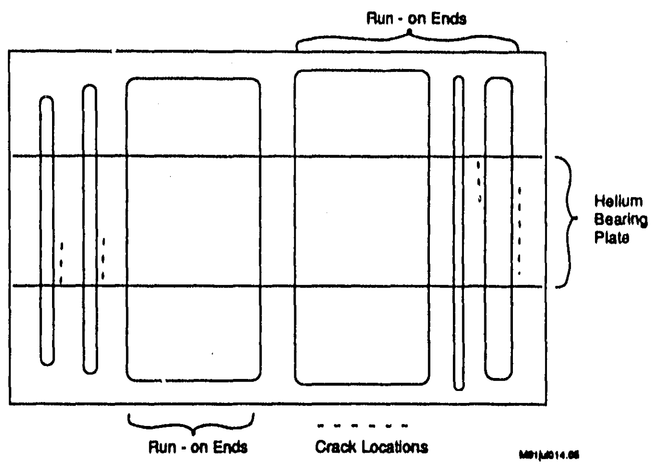
RESULTS

Optical Metallography

Surface Examination

Surface examination of the welded plates revealed no toe cracks or porosity associated with the overlay welds. However, welds made by the conventional GTA process had both toe cracks and extensive surface porosity. Toe cracks for the highest heat input stringer beads were typical of those seen during repair of the reactor tank. Numerous toe cracks were present at the run–on end of the GTA stringer beads. The crack location relative to the plate and the welding direction is shown schematically in Figure 2a. The surface appearance of a toe crack at a run–on location is shown in Figure 2b.

The presence of toe cracks preferentially at run–on locations is consistent with the hypotheses that stress and temperature are key factors in helium embrittlement cracking during welding. Initiating the weld bead in the starting tab and moving onto the relatively cold helium–bearing plate produces thermal shock and high stresses. These high stresses, combined with the high temperature of the HAZ, lead to cracking if sufficient helium is present. As the weld bead moves further onto the helium–bearing plate, general heating of the plate reduces the thermal gradient; thus, the stresses in the weld HAZ decrease and the tendency for cracking is reduced. Only high heat input, deep penetration welds have toe cracks away from the run–on side of the helium–bearing plate.



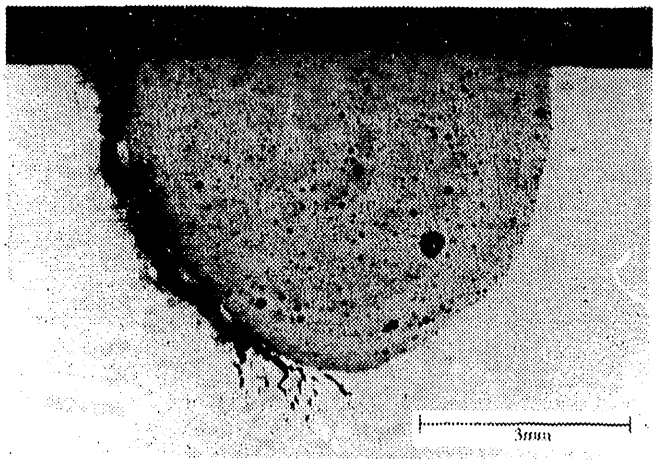
A. Location of toe cracks on plate containing 17 appm helium

B. Surface photograph of run–on toe crack

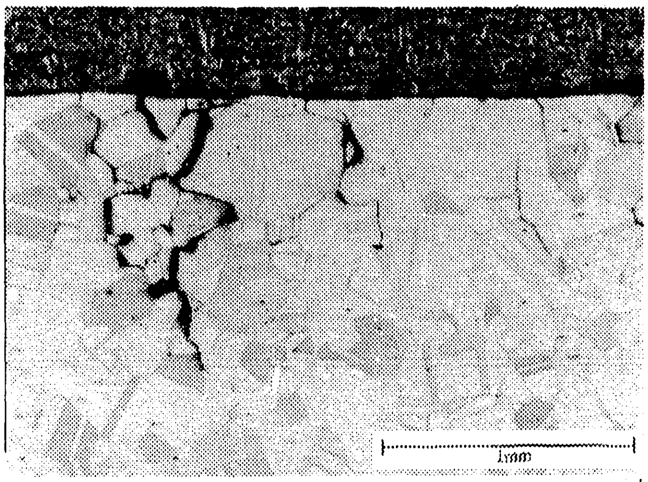
Figure 2. Toe cracks at run–on end of stringer beads

Metallographic Cross–Sections

The helium induced cracks are totally intergranular. This is true for both the surface toe cracks and the underbead cracks (Figure 3). The underbead cracks are located in the HAZ of welds but do not generally intersect the material surface. Typically underbead cracks are smaller than toe cracks and lie in a narrow, 2 mm band adjacent to weld metal. Occasionally, underbead cracks extend for a very short distance (0.05 mm) into weld metal.



A. Toe crack in stringer bead on material with 17 appm helium



B. Underbead cracks below overlay weld made on material with 220 appm helium

Figure 3. Metallographic sections of helium embrittlement cracks

Underbead cracks below overlays tend to be grouped between the individual passes of the weave bead. One such location is shown in Figure 4. This effect is noticeable only where there is a crest in the metal as can be seen in the figure. The concentration of stress that produces toe cracks in stringer beads is believed to be responsible for the grouping of underbead cracks between individual weave passes.

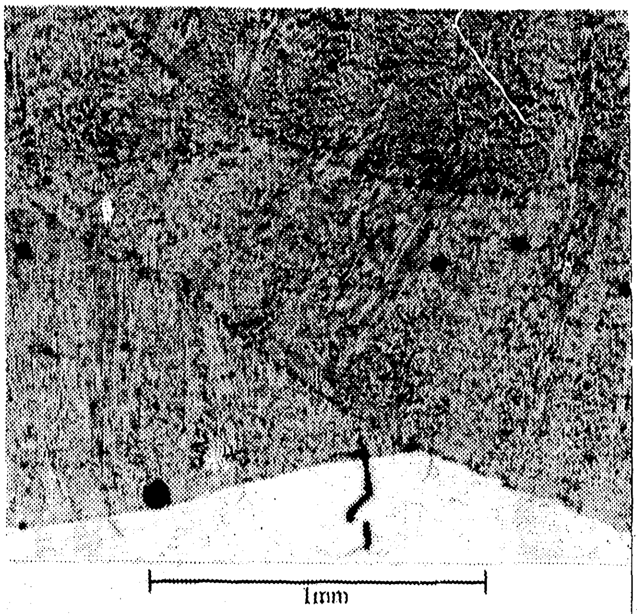


Figure 4. Preferential location of underbead cracks between weld weave passes of overlays

Crack Distributions

The effect of numerous variables on the extent of cracking has been determined. Among the variables are base metal helium concentration, weld penetration, effect of multiple layer overlays, run–on vs. run–off locations, and type of weld. Additional studies are underway to examine the effect of material restraint, to make a comparison of welding on irradiated material vs. tritium charged material, and to compare GMA overlays with GTA overlays.

The extent of cracking increases with helium concentration as can be seen in both Figures 5 & 6. More important for choosing a weld repair procedure for irradiated material is the effect of the type of weld. The overlay technique reduces underbead cracking compared to GTA stringer beads at equivalent weld heat inputs of approximately 25 kJ/in^2 (Figure 5). This result, along with the elimination of toe cracks, is strong evidence for the promising use of the overlay technique for welding on helium–bearing material.

The effect of stress at the run–on side of the welds can be seen for overlay underbead cracks (Figure 6) as well as for stringer bead toe cracks as discussed in a previous section.

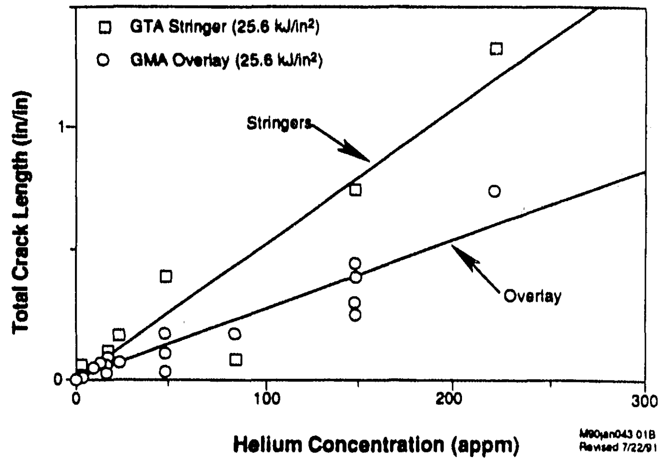


Figure 5. A comparison of underbead cracking for overlay welds and stringer beads made at approximately 25 kJ/in²

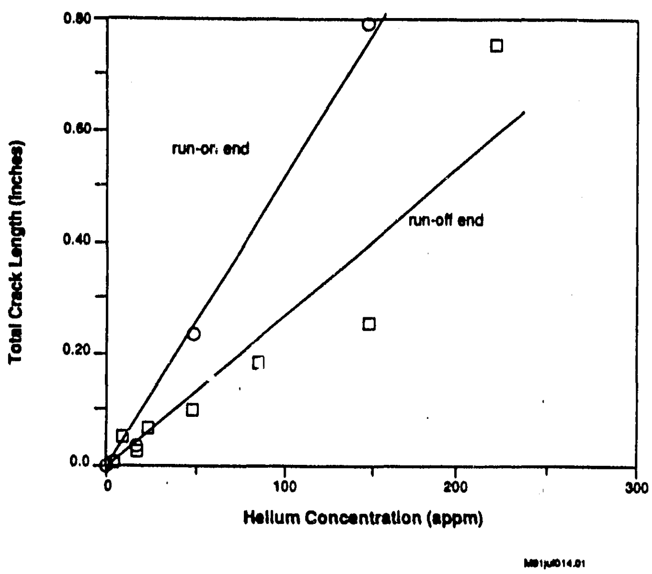


Figure 6. The effect of the high thermal stresses at the run–on location of the welds

An additional practical advantage of use of overlays is the ability to build up multiple layers should a thick overlay be needed. This study has shown that the effect on underbead cracking of adding a second layer is negligible. The data for single and double layer overlays can be seen in Figure 7 to be within the same scatter band.

Tensile Tests

To determine the effect of underbead cracks on weld overlay strength and ductility, a program to test mechanical integrity was undertaken. Values of the ultimate tensile strength, yield strength, and reduction of area were ob-

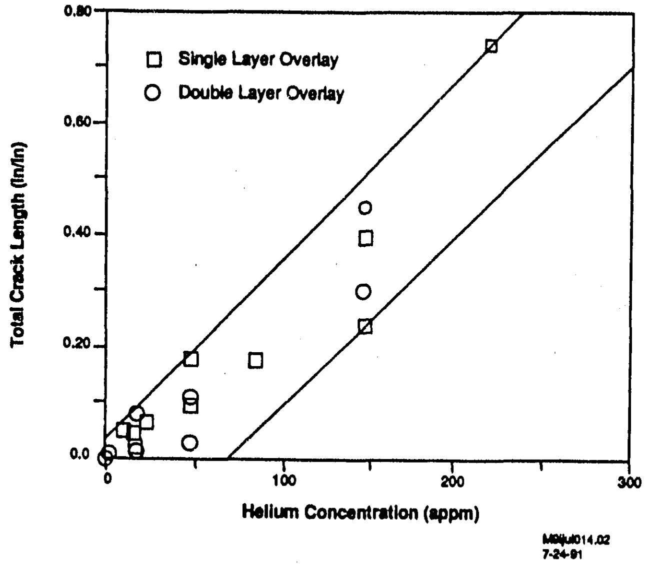


Figure 7. Negligible effect on underbead cracking of adding a second layer of overlay metal

tained according to standard procedures, but because of the small size of the specimens and of the experimental difficulty of testing radioactive materials, elongation values were calculated from the cross–head displacement record. Tensile test results are listed in Table 1.

Typical stress–strain curves for tensile tests of three specimens clearly delineated the effects of helium (Figure 8). Although the elastic limits are comparable, the strengths and particularly elongations vary widely.

Table 1. Tensile Test Results

Helium Content (appm)	Samples Averaged (No.)	Yield Strength (Ksi)	Ultimate Strength (Ksi)	Elong. @ Max Load (%)	Elong. @ Fracture (%)	Reduction of Area (%)
0	1	52.9	90.0	27.7	42.1	81.6
3	3	54.2	84.2	16.8	36.6	78.8
9	2	56.4	88.2	16.9	30.9	68.6
17	3	53.2	86.3	19.3	36.6	76.6
22	2	58.3	87.8	18.7	33.2	65.5
49	4	58.4	84.4	10.8	11.4	27.2
85	2	58.0	70.5	4.1	4.1	7.1
147	3	49.0	54.4	1.6	1.6	7.8
220	1	43.3	44.1	0.5	0.5	0.0

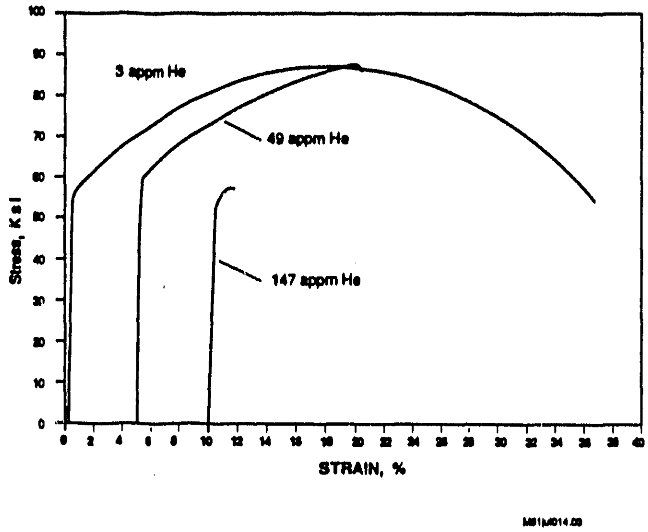


Figure 8. Typical stress strain curves (spaced along the abscissa for clarity)

The change in mechanical properties due to helium embrittlement can best be seen from reduction of area (Figure 9). A pronounced drop at about 35 appm helium indicates a change from failure in the base metal to failure in the weld HAZ. In the uncharged specimen the reduction of area was 81.6%, which dropped to virtually zero at 220 appm helium. Similarly, elongation at fracture is only about 0.5%, compared to about 37% at 17 appm helium, or to 42% in an uncharged specimen. Ultimate tensile strength decreases slowly to half its initial value with increasing helium content.

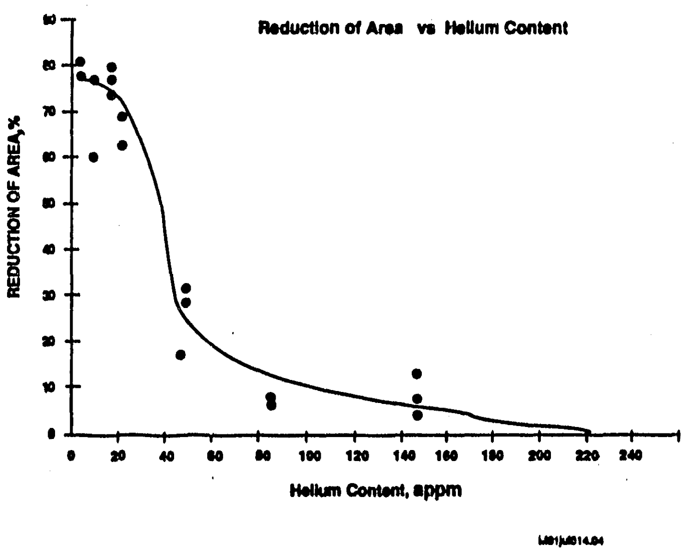
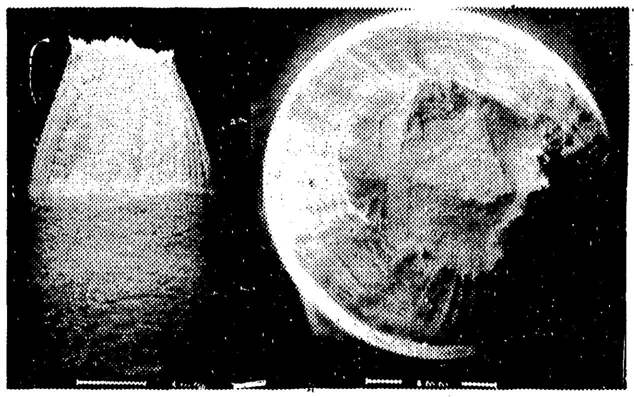
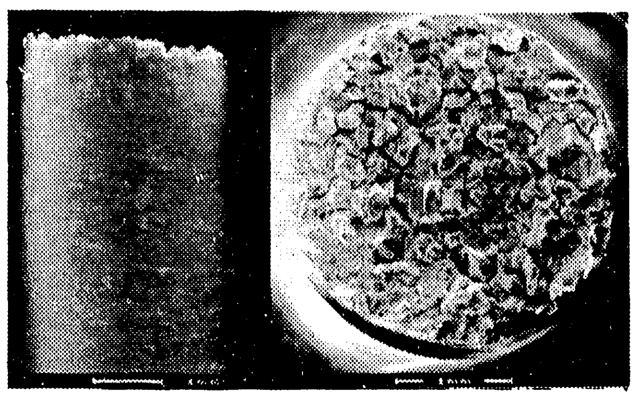


Figure 9. Tensile test reduction of area results as a function of helium content

The reduction in tensile properties with increasing helium content is reflected in the appearance of the fracture surface of the test specimens. The difference in the appearance of the fractures at low (less than 9 appm) and high (greater than 49 appm) helium contents is well illustrated in Figure 10 which shows each fracture in a side view and a top view. It is clearly visible that the low–helium specimen was subjected to considerable elongation and necking before fracture which occurred within the overlay weld metal. In contrast, the high–helium specimen had almost no deformation before it broke in the HAZ. Figure 11 shows the difference in the fracture topography of the two specimens. The low–helium specimen shows a fully ductile ("dimpled rupture") fracture, whereas the high–helium specimen broke in a mixed mode: portions of the fracture which broke along HAZ cracks are fully intergranular, while the fracture areas connecting cracks show dimpled rupture.

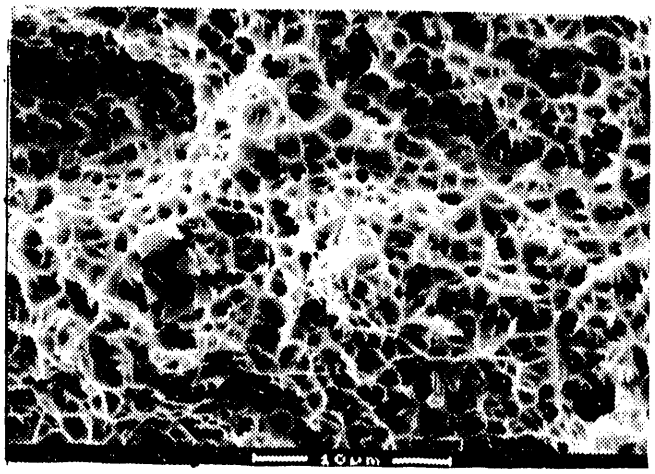


A. Ductile failure at 9 appm helium

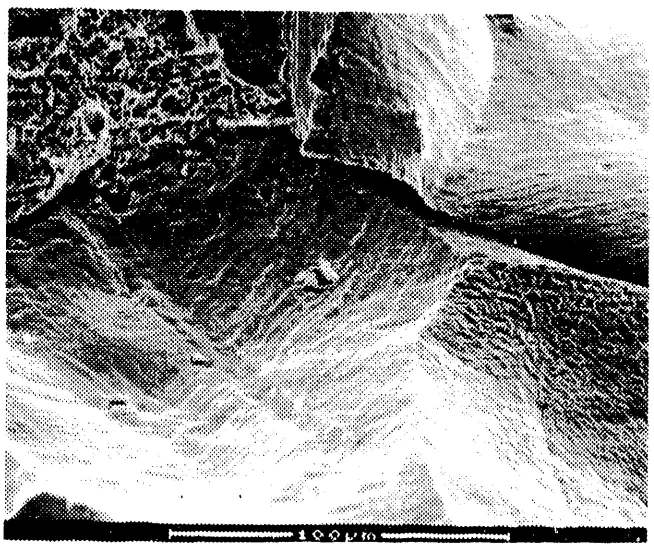


B. Brittle fracture in weld HAZ at 49 appm helium

Figure 10. Tensile test fracture surfaces (side view on left; end view on right)



A. Ductile fracture at 9 appm helium



B. Grain boundary fracture at 49 appm helium.

Figure 11. SEM photographs of tensile test fracture surfaces

The tensile testing matrix also included a determination of how the bond between the base metal and the overlay is affected by the number of layers in the overlay. Single and double layer overlays were compared at low (9 appm) and high (85 appm) helium contents. Differences in strength, ductility, and fracture surface appearance were within the range expected, indicating no effect of the second overlay layer. This result not only means that the second layer does not increase helium embrittlement effects, but also indicates that the impact of the stud weld, made to allow tensile testing, does not affect results, since the stud weld is twice as far from the overlay HAZ for the double layer overlay.

Bend Tests

Bend tests showed that helium embrittlement cracks do not propagate beyond the weld HAZ even under severe stress. Specimens were examined with a scanning electron microscope in the areas of uniform strain near the center of each specimen. After bending, specimens containing very low helium levels had only a few superficial cracks. At higher helium levels, in other specimens, the cracking was intergranular and extensive, but was restricted to the HAZ. A comparison of the behavior of specimens with a low and a high helium content is illustrated in Figure 12. It is interesting to note that although the width and the depth of the cracks increased during bending, their length was almost constant. This result indicates the limited amount of material that is affected by helium embrittlement resulting from the overlay weld. It was observed that if any extension of the length of the cracks did occur the cracks never propagated into the overlay unless a preexistent defect in the overlay connected with a crack. There was no significant difference in the extent of HAZ cracking between samples with one or two layers of overlay.

A. No visible cracks at 9 appm helium

B. Cracks in HAZ opened but did not propogate at 149 appm helium

Figure 12. Convex surface of bend test samples

CONCLUSIONS

Metallographic and mechanical test results indicate that the low–penetration overlay technique has excellent potential for repair of helium–bearing stainless steel. The overlay technique:

- Eliminates weld toe cracking experienced with conventional welding processes
- Reduces underbead cracking compared to conventional welds
- Does not affect mechanical properties beyond a zone of 2 mm into the base metal
- Does not significantly affect strengt' and ductility for material containing less than 30 appm helium
- Minimizes weld metal porosity

ACKNOWLEDGMENT

The information contained in this article was developed during the course of work done under Contract No. DE–AC09–89SR18035 with the U.S. Department of Energy.

REFERENCES

1. W. R. KANNE, JR., "Remote Reactor Repair: GTA Weld Cracking Caused by Entrapped Helium", Welding Journal, vol. 67, pp 33–39, August 1988.
2. W. R. KANNE, JR., D. A. LOHMEIER, K. A. DUNN, and M. H. TOSTEN, "Metallographic Analysi of Helium Embrittlement Cracking of Repair Welds in Nuclear Reactor Tanks", Microstructural Science, vol. 19, in press.
3. S. H. GOODS and C. W. KARFS, "Helium–Induced-Weld Cracking in Low Heat Input GMA Weld Over lays, Welding Journal, p 123–132, May 1991.
4. H. T. LIN, S. H. GOODS, M. L. GROSSBECK, and B. A. CHIN, "Helium–Induced Degradation in the Weldability of an Austenitic Stainless Steel", Effects of Radiation on Materials: 14th International Symposium, vol I, ASTM STP 1046, M. H. PACKAN, R. E. STOLLER, and A. S. KUMAR, Editors, American Society for Testing and Materials, Philadelphia, p 301–314 (1989).
5. H. T. LIN, M. L. GROSSBECK, and B. A. CHIN, "Cavity Microstructure and Kinetics during Gas Tungsten Arc Welding of Helium–Containing Stainless Steel", Metallurgical Transactions A, vol 21A, p. 2585–2596, September 1990.
6. E. A. FRANCO–FERREIRA and W. R. KANNE, JR., "Remote Reactor Repair: Avoidance of Helium–Induced Cracking using GMAW", submitted to the Welding Journal.
7. W. R. KANNE, JR.,E. A. FRANCO–FERREIRA, M. R. LOUTHAN, JR., and M. H. TOSTEN, "Weld Repair of Austenitic Stainless Steels Containing Helium", 72nd American Welding Society Annual Meeting Abstracts, p 157–158, April 1991.

END

DATE FILMED

5/18/92