REPAIR WELDING OF FUSION REACTOR COMPONENTS
SECOND YEAR TECHNICAL REPORT

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Continuation Application
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I. ABSTRACT OF PROPOSED RESEARCH

Experiments have shown that irradiated Type 316 stainless steel is susceptible to heat-affected-zone (HAZ) cracking upon cooling when welded using the gas tungsten arc (GTA) process under lateral constraint. The cracking has been hypothesized to be caused by stress-assisted helium bubble growth and rupture at grain boundaries. This study utilized an experimental welding setup which enabled different compressive stresses to be applied to the plates during welding. Autogenous GTA welds were produced in Type 316 stainless steel doped with 256 appm helium. The application of a compressive stress, 55 MPa, during welding suppressed the previously observed catastrophic cracking. Detailed examinations conducted after welding showed a dramatic change in helium bubble morphology. Grain boundary bubble growth along directions parallel to the weld was suppressed. The results suggest that stress-modified welding techniques may be used to suppress or eliminate helium-induced cracking during joining of irradiated materials.

II. INTRODUCTION

Large amounts of helium will be generated within many materials from transmutation reactions as a consequence of neutron bombardment of structural components in a fusion reactor[1-3]. Due to its inert nature and extremely low solubility in metals, helium will diffuse and agglomerate to form bubbles after being trapped at point defects, dislocations, and grain boundaries. Such bubbles have been shown to degrade materials properties [3-12].

Investigations have also shown that helium bubbles grow rapidly along grain boundaries that are subjected to a tensile stress at high temperature [9-15]. Both high stress and high temperature are typically encountered following conventional gas tungsten arc (GTA) welding upon cooling. Shrinkage-induced tensile stresses are produced due to the volume contraction of the weld upon solidification and subsequent thermal contraction during cooling. Intergranular heat-affected-zone (HAZ) cracking following GTA welding with lateral constraint was observed by Lin et al. in Type 316 stainless steel with helium concentrations greater than 2.5 appm [9-12]. HAZ cracking was found to occur at the grain boundaries parallel to the welding direction, approximately 2 to 3 grain diameters (grain size was about 70 μm) from the fusion boundary. Centerline interdendritic fractures in the fusion zone have also been observed in GTA welds of Type 316 stainless steels containing more than 100 appm helium. These severe failures are attributed to the growth of helium bubbles at both HAZ grain boundaries and weld dendrite boundaries.

The objective of the present study, conducted during the second year of the project was to investigate techniques which might be used to eliminate heat-affected-zone cracking in helium-containing steels subjected to GTA welding. These techniques need to be identified to enable repair and maintenance of the first wall of a fusion reactor. This work investigated the weldability of helium-bearing austenitic Type 316 stainless steel under controlled stress conditions during welding. Modification of the stress field was accomplished by the application of a compressive stress perpendicular to the weld direction during welding. Results from helium containing specimens produced using the tritium trick and sigma-jig testing of unirradiated materials in preparation for hot cell testing of irradiated specimens is presented.

III. EXPERIMENTAL PROCEDURES

The material investigated in this study was 0.76 mm thick austenitic Type 316 stainless steel sheet. Following a solution anneal at 1050°C for one hour, the average grain size was about 70 μm. Helium was implanted into the steel using tritium doping and decay*. The steel was exposed to tritium gas at 125 MPa at 300°C for 30 days. The dissolved tritium was then allowed to decay to helium at -40°C for six months. The excess tritium was then pumped off under a vacuum (10^{-3} Pa) at 400°C to prevent further helium generation. The tritium doping was performed at Sandia National Laboratory, Livermore, CA. This doping process introduced 256 appm helium into the steel. The pump-off treatment resulted in the formation of stable helium bubbles about 4.5 x $10^{20}/m^3$ in density and approximately 1.7 nm in diameter in the matrix while a density of 8.8 x $10^{14}/m^2$ and 2.0 nm diameter bubbles were observed on the grain boundaries.

Autogenous single pass GTA welds were produced under laterally constrained conditions. The edges of the plates parallel to the weld direction were securely fastened to the welding stage to simulate the restraints encountered in practical weld repair and maintenance of structural components. Welding was performed at 10 VDC, 24 A at a torch travel speed of 3.6 mm/s under a protective argon atmosphere. The resulting heat input was 66.7 J/mm, which produced a full penetration weld approximately 3 mm wide.

A theoretical model has been proposed by Lin et al. to describe the helium bubble growth during GTA welding of helium containing materials [9-12]. The model indicates that the growth of grain boundary helium bubbles should be significantly altered by a change in the stress state during cooling of the weld. To investigate this hypothesis, a weld plate fixture system was constructed to apply a controlled compressive stress perpendicular to the weld path (Figure 1). The compressive stress is produced by applying a constant compressive strain perpendicular to the weld direction from the edges of weld plates. Both optical microscopy and scanning electron microscopy (SEM) were used to examine the integrity of the weld and the surrounding heat-affected zone. Transmission electron microscope (TEM) specimens were prepared from the fusion zone/heat-affected-zone interface for both standard (control welds) and stress-modified welds for further examination.

IV. PROJECT RESULTS AND DISCUSSION

According to the proposed model, most of the grain boundary helium bubble growth which occurs during welding is stress-assisted [9-12]. The growth of grain boundary bubbles in the HAZ can be divided into three regimes. In regime I, the heat-up regime before the material reaches its melting temperature, compressive stresses are introduced normal to the welding direction due to thermal expansion of the plates. Although grain boundary helium bubbles can grow by thermal vacancy absorption in this regime, the compressive stress tends to retard the bubble growth. Consequently, it was assumed that there is no bubble growth in this heat-up period. In regime II, as the torch passes, the material reaches the melting temperature and a stress-free state is obtained in the molten region. Therefore, the stress is assumed to be zero in areas adjacent to the melted region. The bubbles grow mainly by

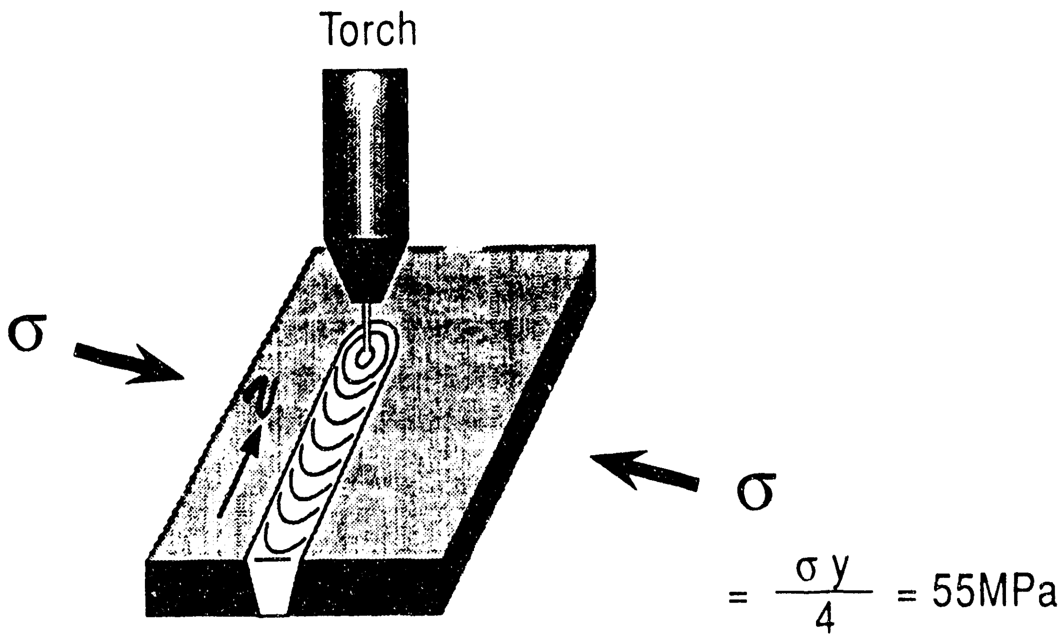

Fig. 1 - Schematic of applied compressive stress during welding.

vacancy absorption during this stage due to the high vacancy concentration and diffusivity at that temperature. The grain boundary bubble growth in this regime is derived based on the theory of helium bubble growth in the matrix by vacancy absorption presented by Greenwood and Speight [16]. The final bubble radius, R, was expressed by Lin et al [9,10,12] as

$$R^3 - R_i^3 = 3\delta_{gb}\Omega D_{gb} C_v \Delta t/2 \qquad (1)$$

where

- R = bubble radius, m,
- R_i = bubble radius at regime I, m,
- δ_{gb} = grain boundary thickness, m,
- Ω = atomic volume, m^3,
- D_{gb} = grain boundary vacancy diffusivity, m^2/s,
- C_v = equilibrium vacancy concentration, m^{-3}, and
- Δt = elapsed time in regime II, s.

Finally, in regime III, the stress state becomes tensile at grain boundaries parallel to the welding direction due to weld solidification and cooling. Stress-assisted bubble growth dominates, and most of the grain boundary bubble growth during welding occurs in this regime. The bubble growth at grain boundaries in this regime can be expressed by the following equation, which is based on Hull and Rimmer's models [17,18]:

$$\Delta R = 2\pi\delta_{gb}\Omega D_{gb}(t)\sigma(t)\Delta t/\{R(t)^2 kT(t)\log(a/R(t)-0.75)\} \qquad (2)$$

where

- k = Boltzmann's constant, J/K,
- a = average bubble spacing, m,
- ΔR = amount of bubble growth, m,
- $T(t)$ = temperature at time t, K,
- $\sigma(t)$ = thermal stress at time t, Pa,
- $R(t)$ = bubble radius at time t, m, and
- $D_{gb}(t)$ = grain boundary vacancy diffusivity at time t, m^2/s.

It should be emphasized that this model is not meant to predict the resulting stress state of the weld but rather to give physical insight into what may be occurring during the weld process.

Results of grain boundary bubble growth calculations for the final stage are shown in Figure 2. In this study, grain boundary thickness is assumed to be 8 Å. The average bubble spacing on grain boundaries was assumed to be 1 μm from examination of the HAZ fracture surfaces which were decorated with uniformly distributed dimples about 1 μm in diameter. The initial bubble radius at regime III, i.e., final radius at regime II, was 0.049 μm after calculations according to equation 1.

In the standard weld, curve A, HAZ cracking occurs approximately 2 seconds after the onset of Regime III, where bubbles reach 1 μm. This is consistent with the results of video-taping during welding, which showed cracks that initiate 1 to 2.2 seconds after passage of the weld pool. When a compressive stress is applied during welding, bubble growth is retarded, and bubble size may never reach the critical size which leads to cracking (curves B, C and D). Bubble growth was also retarded when the bubble surface tension is greater than thermal tensile stresses, as indicated at the beginning region of Figure 2.

Figure 3 shows the results of macroscopic examination of weld integrity. Continuous through-thickness heat-affected zone cracking was observed in standard welds of Type 316 stainless steel containing 256 appm helium. Further examination also revealed that the crack was completely intergranular. The crack ran parallel to the welding direction and was within 2 to 3 grain diameters of the fusion zone/heat-affected-zone interface. Helium bubbles had migrated and grown rapidly at grain boundaries under the combined actions of high temperature and internal tensile stress, which occurred during the welding process. Grain boundary strength decreases as the grain boundary helium bubbles grow and the area fraction of bubbles increases. Rupture occurs as the cohesive strength of the grain boundaries, reduced by the growing bubbles, can no longer bear the shrinkage-induced internal tensile stress during cooling.

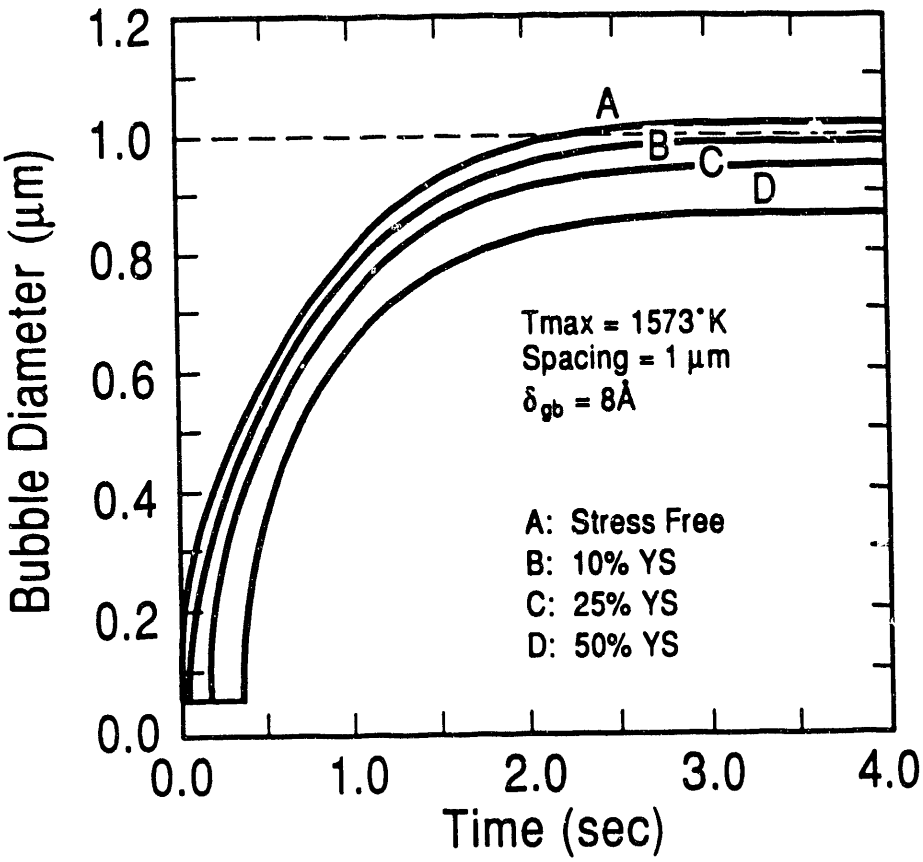

Fig. 2 - The predicted grain boundary bubble size in Regime III. In a standard weld without external applied stress, curve A, bubbles reach critical size, dotted line, at about 2 seconds after the onset of Regime III, while bubble growth is retarded by the application of a compres.ive stress (indicated as a percentage of the yield strength) during welding, curves B, C and D.

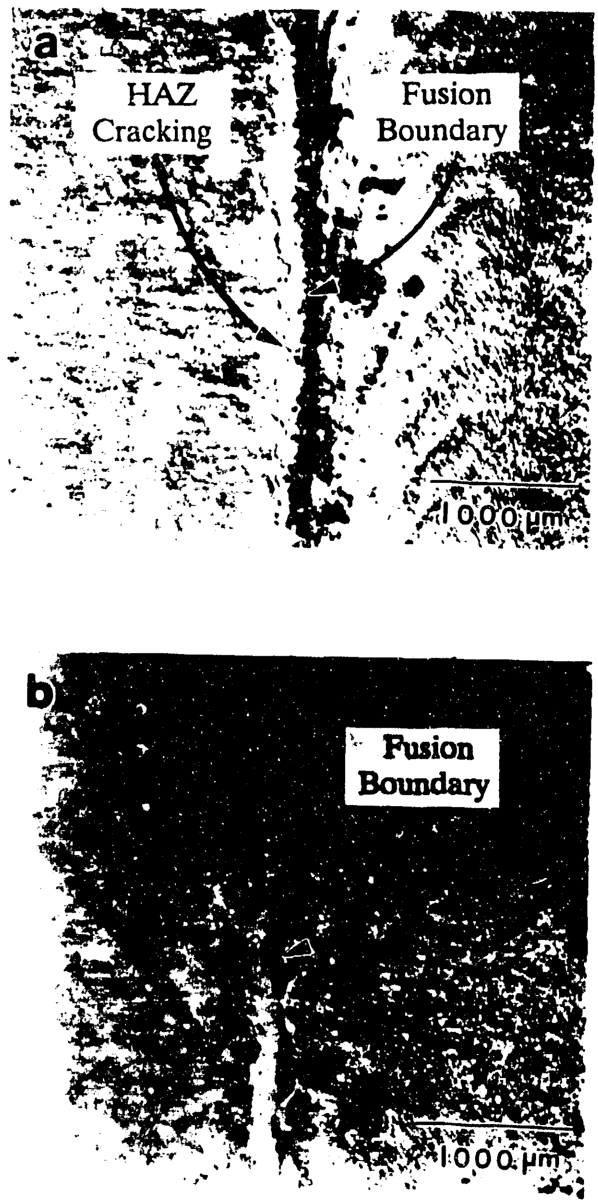

Fig. 3(a) - HAZ cracking observed in 256 appm helium weld; (b) No cracking in 256 appm helium weld when stress modified welding technique is used.

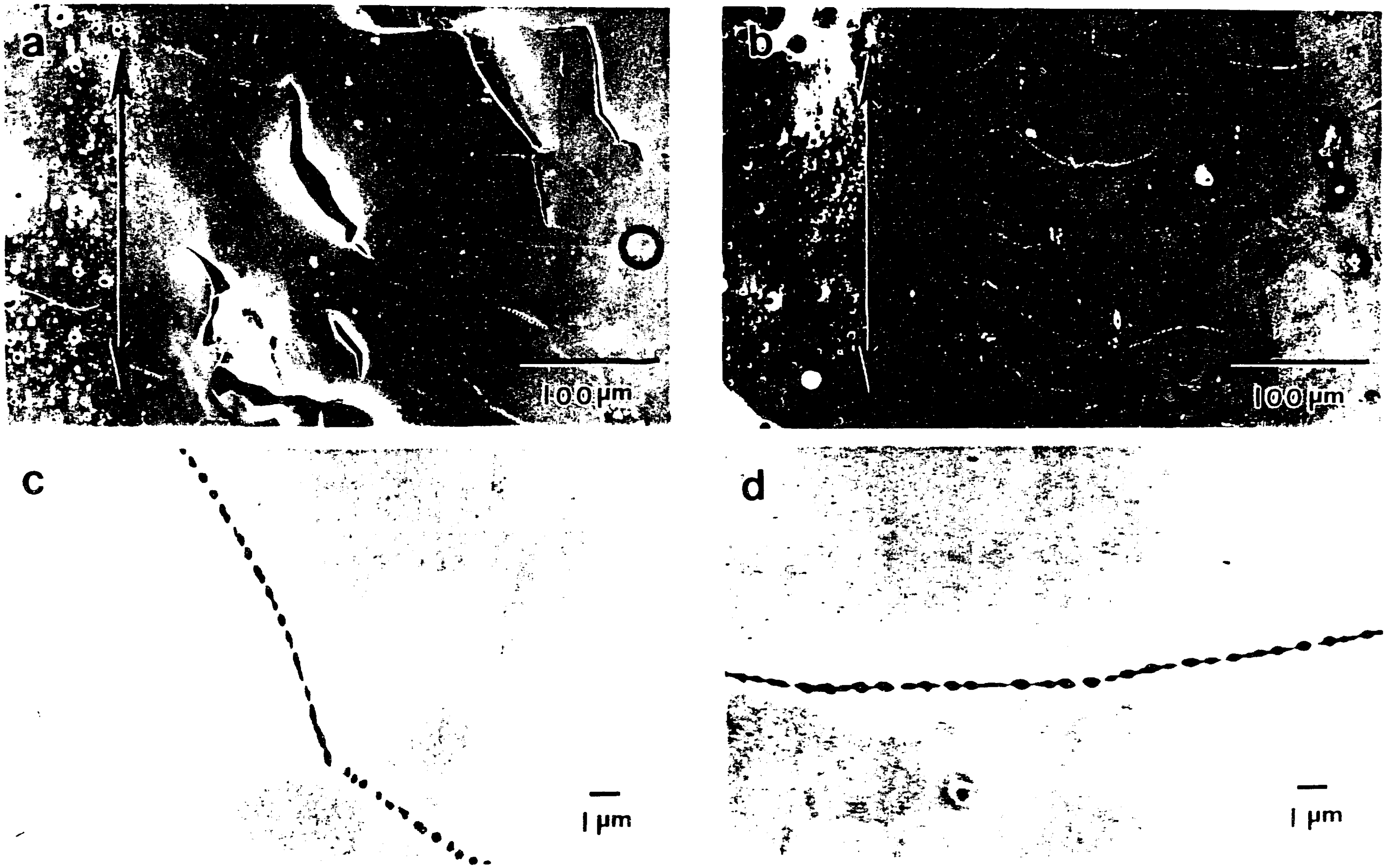

FIG. 4--SEM photographs of the jet-polished TEM discs from (a) standard GTA weld; (b) stress-modified GTA weld. Arrows indicate the welding direction. Note that the applied compressive stress in 3b effectively suppressed grain boundary cracking associated with bubble growth and favored bubble growth on grain boundaries perpendicular to the weld. (c) and (d) are magnified views of the circled areas in (a) and (b) respectively.

Results from stress-modified GTA welds reveal no visible cracks in the heat-affected zone, as shown in Figure 3b. A compressive stress of 55 MPa, about 25% of the room temperature yield stress of Type 316 stainless steel, was applied in these experiments, as measured by strain gauges attached to the weld plates. This result is consistent with the conclusion from Lin's study that high temperature alone is not sufficient to cause significant grain boundary helium bubble growth and HAZ cracking. The combination of both high temperature and high tensile shrinkage stress are required for intergranular HAZ cracking [9-12].

Further examinations on TEM disks, prepared from the fusion zone/heat-affected-zone boundary, were conducted using scanning electron microscopy following jet thinning. The results are shown in Figures 4 for both standard and stress-modified welds. Welding directions are indicated by the large arrows. In the standard GTA weld, as shown in Figure 4a, severe perforation and cracking are observed with cracks tending to align parallel to the welding direction. On the other hand, parallel cracking associated with grain boundary helium bubble growth has been effectively suppressed by the application of a compressive stress in the stress-modified GTA welding process, as shown in Figure 4b. In addition, the bubble growth has been altered such that larger bubbles grow predominantly along grain boundaries perpendicular to the weld direction, whereas previously they occurred principally on grain boundaries parallel to the weld. It should be pointed out that jet polishing during TEM specimen preparation attacks the grain boundaries and enlarges grain boundary holes. Therefore, the grain boundary bubble sizes indicated in Figures 4 are exaggerated as compared to the as-welded material. Figure 4c and 4d are magnified views of the circled areas in Figure 4a and 4b respectively. Results of TEM examinations are not available at this time, and will be presented in the future.

During weld solidification and cooling, the principal shrinkage-induced internal tensile stress is perpendicular to the welding direction. The stress level is enhanced by the lateral constraints as in the repair welding of structural components. This stress causes the helium bubbles to grow rapidly at the grain boundaries at high temperatures, preferentially along grain boundaries aligned perpendicular to the stress (parallel to the weld). Since the shrinkage-induced tensile stress is altered by applying an initial compressive stress perpendicular to the welding direction, the helium bubble growth process is retarded along grain boundaries parallel to the weld; therefore, HAZ cracking is less likely to occur. However, a small number of helium bubbles still grow preferentially along the direction perpendicular to the weld. This may be due to the internal tensile stresses generated by bulk body constraint of the steel along the weld direction during cooling.

V. CONCLUSIONS TO DATE

The following conclusions can be drawn from this study:

1. Severe intergranular heat-affected-zone cracking during welding of helium-bearing Type 316 stainless steel is caused by grain boundary helium bubble growth.
2. Grain boundary helium bubble growth is enhanced by the combined action of high temperature and shrinkage-induced tensile stress generated during the welding process.
3. Sound autogenous GTA welds can be produced in helium-bearing Type 316 stainless steel by the application of a compressive stress to alter grain boundary bubble growth kinetics.

The results of this study suggest that a stress-modified welding process can effectively suppress the helium bubble growth and may be applied to eliminate severe HAZ cracking which occurs during GTA repair welding of irradiated materials.

VI. PROGRESS IN SIGMAJIG TESTING

In order to evaluate the cracking sensitivity during welding of Type 316 stainless steel, Sigmajig tests [19,20] were carried out under different welding parameters. The welding fixture (as shown in Fig. 5) holds a 50 mm by 50 mm square specimen between hardened steel grips and applies a transverse stress prior to and during welding. The load is applied by a pair of strain-gaged bolts and maintained by stacks of Bellville washers in the

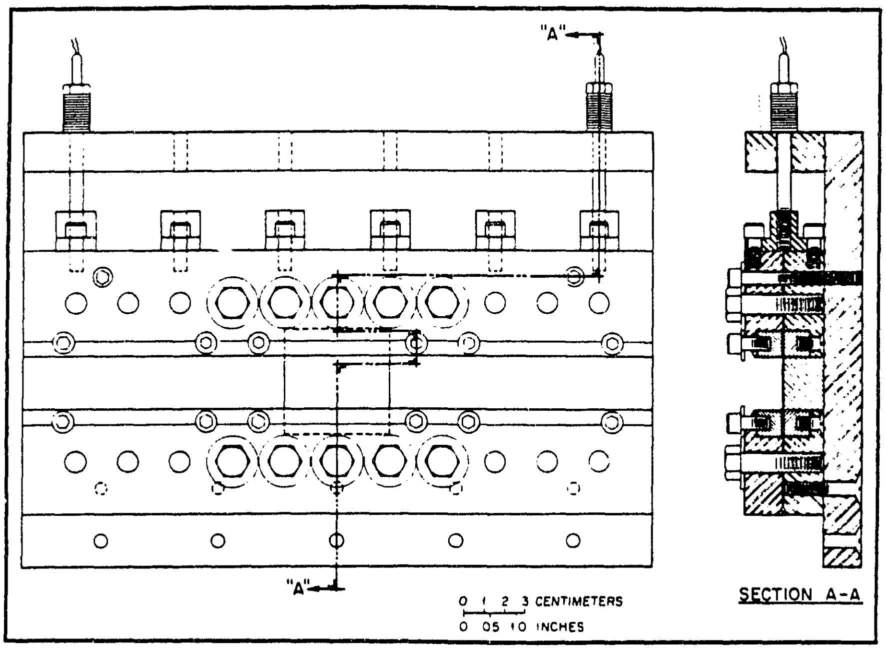

Fig. 5 Schematic of Sigmajig test fixture.

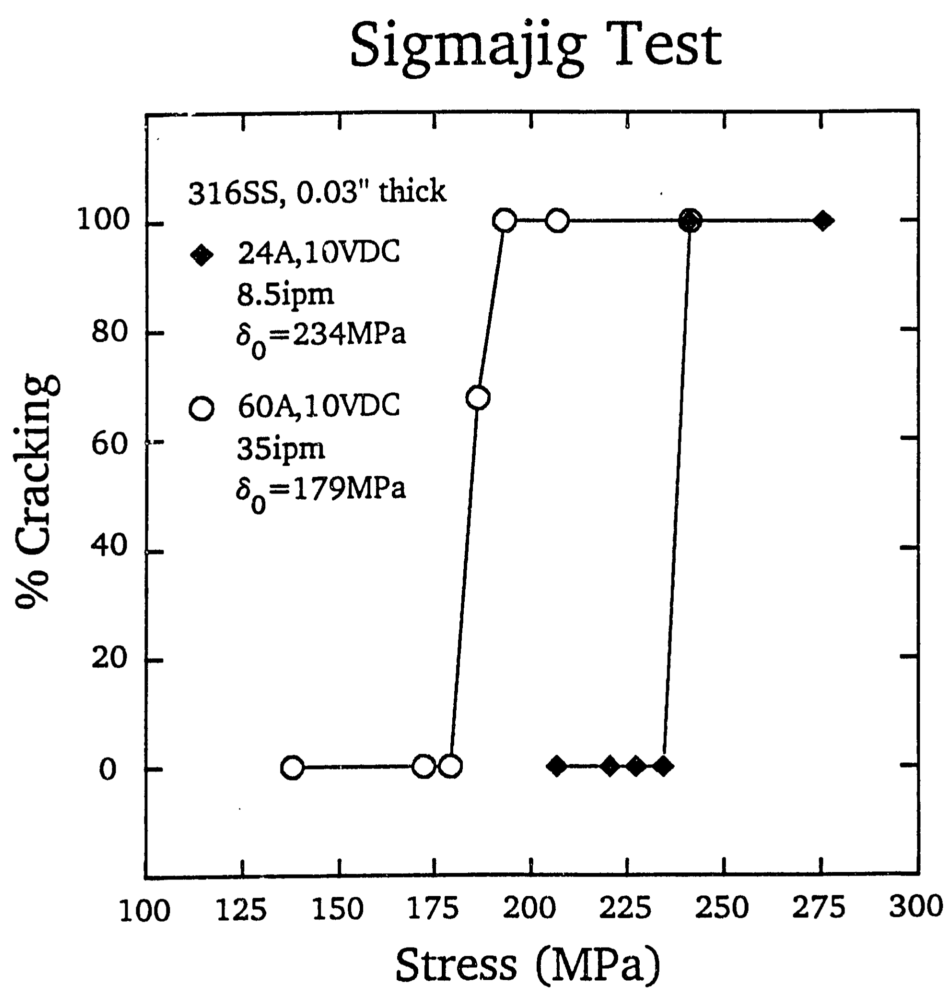

Fig. 6 - Sigmajig test results on 316SS.

load train. After preloading, a full penetration GTA weld is produced along the specimen centerline. The stress applied by the fixture is increased, specimen by specimen, till a level is reached where centerline cracking initiates. At a higher applied stress level, specimen separation occurs. Figure 6 shows the results of Sigmajig testing of control specimens of Type 316 stainless steel, where σ_0 represents the threshold stress values applied to cause cracking during welding. One set of tests used the same parameters as those used in welding of tritium-bearing Type 316 stainless steel described previously. Another set of specimen used typical Sigmajig welding parameters [19,29]. The sharp transition from 0 to 100% cracking indicates good cracking resistance of Type 316 stainless steel under both welding conditions. However with lower heat input, open circles in figure 6, higher welding speeds produce an elongated mucronate weld pool and cause the specimens to crack at a lower stress. All the cracks are found to be hot cracking, as shown in figure 7. More detailed investigations will be conducted in the future using sigmajig test on helium-bearing materials to correlate the stresses, helium bubble kinetics and cracking phenomena during welding.

VII. REFERENCES

[1] R. W. Conn, "Tokamak Reactors and Structural Materials", Journal of Nuclear Materials, 85&86, (1979),9-16.

[2] E. E. Bloom, "Mechanical Properties of Materials in Fusion Reactor First-Wall and Blanket Systems", Journal of Nuclear Materials, 85&86,(1979), 795-804.

[3] M. M. Hall, Jr., A. G. Hins, J. R. Summers,and D. E. Walker, "Fusion Welding of Irradiated AISI 304L Stainless Steel Tubing", Weldment:Physical Metallurgy and Failure Phenomena, Proceedings of the Fifth Bolton Landing Conference, August 1978, pp. 365-378.

[4] J. P. Maloney, D. Baker, W. A. Day, W. G. Fraser, H.R. Huxford, K. E. Kehr, W. R. Kennedy, J. B. McClain, D. H. McKenney, C. A. Meyer, R. F. Mittelberg and J. E. Walls , "Repair of a Nuclear Reactor Vessel", DP-1199, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, SC, June 1969.

[5] S. D. Atkin, "Weld Bend Tests on Irradiated, 20% Cold-Work 316 Stainless Steel", Fusion Reactor Materials, ADIP Semiannual Progress Report, Sept. 30, 1981, DOE/ER-0045/7, pp. 110-117, U.S. DOE, Office of Fusion Energy.

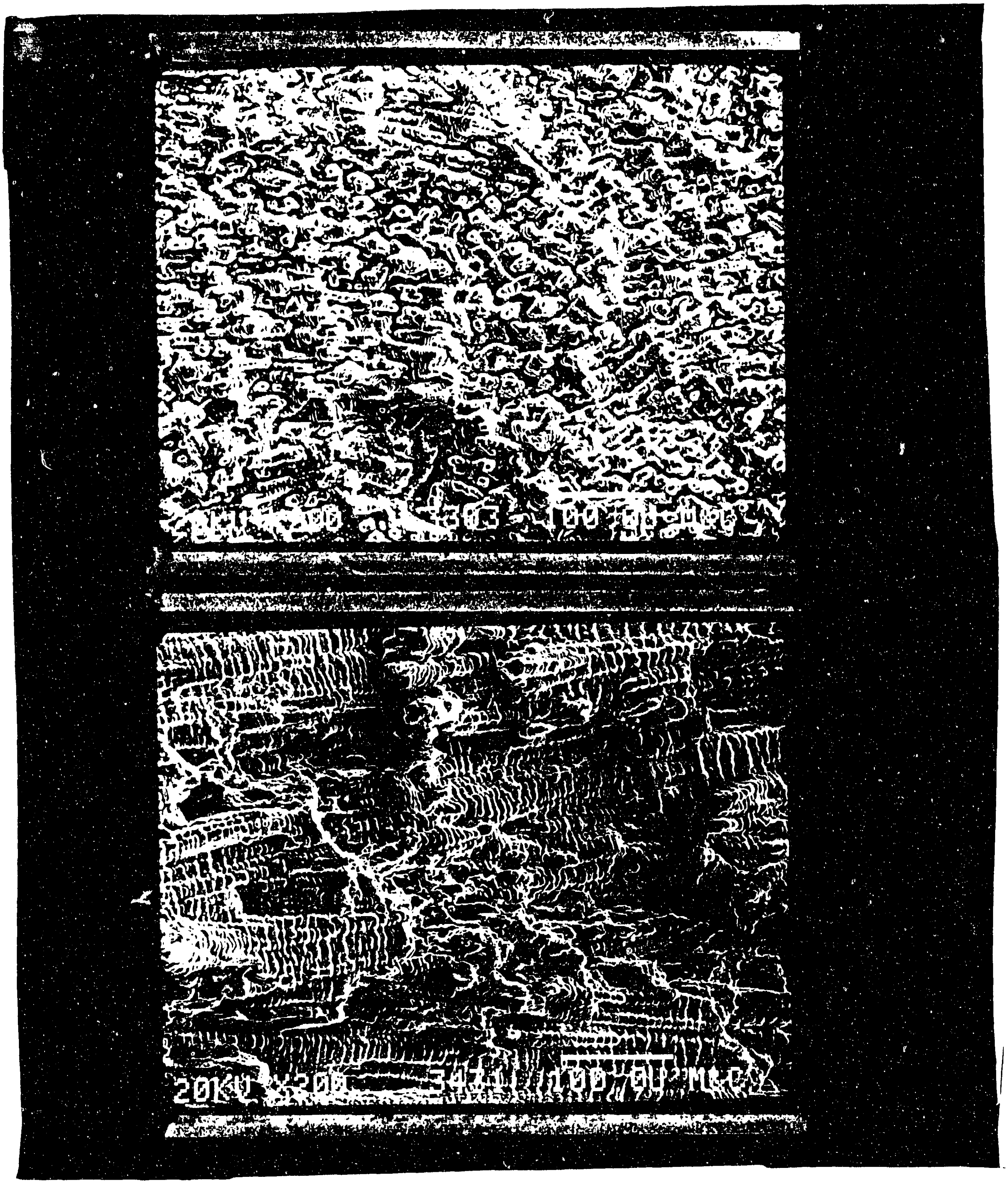

Fig. 7 - Fracture surface after Sigmajig testing of 316SS. (Top) No stress applied. (Bottom) Tensile stress applied.

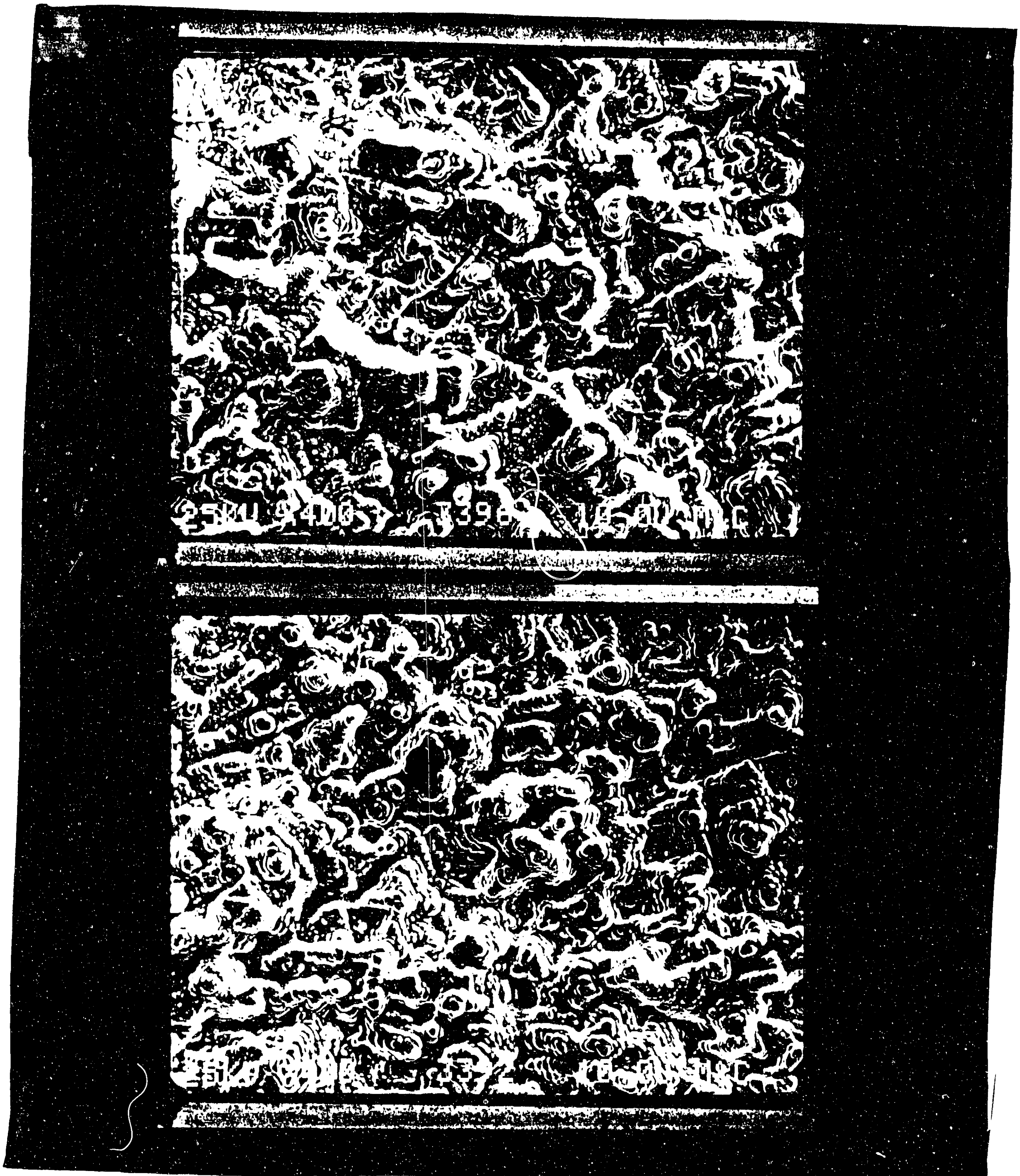

Fig. 8 - Fracture surface after Sigmajig testing of HT-9. (Top) No stress applied. (Bottom) Tensile stress applied.

[6] W. K. Kanne, C. L. Angerman and B. J. Eberhard, "Weldability of Tritium-Charged 304L Stainless Steel", DP-1740, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, SC, February 1987.

[7] W. R. Kanne, "Helium Embrittlement Cracking During Patch Welding in Savannah River C reactor," DPMS-8940, E. I. Dupont Co., Savannah River Laboratory, Aiken, SC, 1989.

[8] A. K. Birchenall, "Helium Induced Weld Cracking in Irradiated 304 Stainless Steel," DPMS-8941, E. I. Dupont Co., Savannah River Laboratory, Aiken, SC, 1989.

[9] 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, V21A, September 1990, pp.2585-2596.

[10] H. T. Lin, Ph.D. Dissertation, Auburn University, 1989.

[11] H. T. Lin, S. H. Goods, M. L. Grossbeck, and B. A. Chin, "Helium-Induced Degradation in the Weldability of an Austenitic Stainless Steel", Effect of Radiation on Materials, 14th International Symposium, Volume I, ASTM STP 1064, N. H. Packan, R. E. Stoller, and A. S. Kumar, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 301-314.

[12] H. T. Lin, "Simulation of the Welding of Irradiated Materials", ORNL/TM-11158, Oak Ridge National Laboratory, Oak Ridge, TN, 1989.

[13] D. Hull and D. E. Rimmer, "The Growth of Grain-Boundary Voids Under Stress," Philosophical Magazine, 4, (1959), 673-687.

[14] M. V. Speight and J. E. Harris, "The Kinetics of Stress-Induced Growth of Grain-Boundary Voids," Metal Science Journal, Vol.1, 1967, pp.83-85.

[15] H. Trinkaus, "Stress Induced Drift Diffusion in Grain Boundaries - Application to Creep and to the Growth of Grain boundary Voids." Berichte der Bundes Gesellschaft fur Physikalische Chemie, 82, (1978), 249-253.

[16] G. W. Greenwood and M. V. Speight, "An Analysis of the Diffusion of Fissile Gas Bubbles and its Effect on the Behaviour of Reactor Fuels," Journal of Nuclear Materials, 10, (1963), 140-144.

[17] D. Hull and D. E. Rimmer, "The Growth of Grain-Boundary Voids Under Stress," Philosophical Magazine, 4, (1959), 673-687.

[18] J. Weertman, "Hull-Rimmer Grain Boundary Void Growth Theory - A Correction," Scripta Metallurgica, Vol. 7, 1973, pp. 1129-1130.

[19] G. M. Goodwin, "Development of a new hot-cracking test- the Sigmajig," Welding Journal, February 1987, 33s-38s.

[20] G. M. Goodwin, "The Effects of Heat Input and Weld Process on Hot Cracking in Stainless Steel,"Welding Journal, April 1988, 88s-94s.

VIII. PUBLICATIONS COMPLETED

The following open literature publications were completed based upon work conducted under this grant:

Refereed Book Submissions

Probal Banerjee and Bryan A. Chin, Special Metallurgical Considerations when Welding Refractory Metals, reviewed and accepted for publication in ASM Welding Handbook scheduled for publication in 1993, 46 pages prepared manuscript.

Refereed Journal Articles Published and Submitted

C.K. Lee, B.A. Chin, S. Zinkle and R.C. Wilcox, "Brazing of Copper-Alumina Alloys," Journal of Nuclear Materials, 191, (1992) pp. 488-492.

C.A. Wang, M.L. Grossbeck and B.A. Chin, "Technique to Eliminate Helium Induced Weld Cracking in Irradiated 316 Stainless Steel," Journal of Nuclear Materials, 193, (1992), pp. 696-700.

C.A. Wang, R.L. Klueh and B.A. Chin, "The Weldability of Low Activation Cr-W Steels, Journal of Nuclear Materials, 193, (1992), pp.831-835.

G.R. Rao and B.A. Chin, "Comparison of Small-Scale Bending and Axial Fatigue Specimens," editors R.E. Stoller, A.S. Kumar and D.S. Gelles, ASTM STP 1125, in press.

S.F. Chen, J.Y. Liu and B.A. Chin, "Effect of Alumina Strengthening Particles on Brazed Joint of Glidcop A1-15 Copper Alloy," submitted for presentation at ICFRM-VI and for publication in Journal of Nuclear Materials, March, 1993.

C.A. Wang, M. Grossbeck and B.A. Chin, "Method to Eliminate Helium Induced Weld Cracking in Irradiated 316 Stainless Steels," submitted for presentation at ICFRM-VI and for publication in Journal of Nuclear Materials, March, 1993.

J.Y. Liu and B.A. Chin, "Brazing of C-C Composites to Stainless Steel," submitted for presentation at ICFRM-VI and for publication in Journal of Nuclear Materials, March, 1993.

W.Y. Wu, J.Y. Liu, R.H. Zee and B.A. Chin, "An Investigation of Residual Stress Distributions in Dissimilar C-C Composite to Stainless Steel Joints," submitted for publication in Welding Journal Research Supplement, April 1993.

Proceedings and Other Articles Published and Submitted

G.R. Rao and B.A. Chin, "Development of a Miniature-Disk Bending Fatigue Specimen," accepted for publication in the ASTM symposium on Small Specimen Test Techniques and their Application to Nuclear Reactor Vessel Thermal Annealing and Plant Life Extension, New Orleans, 1992, in press.

C. A. Wang, M. L. Grossbeck and B. A. Chin, "Stress Modified Welding Process for Post-Irradiated Materials," Proceedings of the Third International Conference on Trends in Welding Research, June 1-5, 1992, American Society of Materials, 1992, pp. 439-443.

Awards and Honors

Probal Banerjee a PhD student of Dr. Chin (supported for six months off this grant while working on refractory metal joining to stainless steel) was selected in a nationwide competition as the US representative to the Henry Granjon Award Competition for Best Research in Welding. The second and third runner ups in the competition were PhD graduates which completed their degree over a year ago. These individuals came from the Colorado School of Mines and MIT. Mr. Banerjee won this award for his work in weld process sensing and control. Mr. Banerjee is expected to complete his PhD degree in December 1994 and will compete at the International Welding Conference which will be held in Europe in Fall 1993 for the Henry Granjon Award. Mr. Banerjee will be the only US representative in the competition.

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