DPST-89-255

PROGRESS REPORT
WELDING FOR REACTOR VESSEL REPAIR

JANUARY 1989

2/28/89

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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY UNDER CONTRACT DE-AC09-76SR00001

DPST--89-255

DE89 010408

NRTSC

NUCLEAR REACTOR TECHNOLOGY
AND SCIENTIFIC COMPUTATIONS

Keywords: Helium
Stainless Steel
Reactor Vessel
Welding

Retention - Permanent

PROGRESS REPORT
WELDING FOR REACTOR VESSEL REPAIR

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ISSUED: JANUARY 23, 1989

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E. I. du Pont de Nemours & Company, Inc.
Prepared for the U. S. Department of Energy under Contract DE-AC09-76SR00001

PROJECT: ALTERNATIVE REPAIR TECHNOLOGIES

DOCUMENT: DPST-89-255

TITLE: PROGRESS REPORT - WELDING FOR REACTOR VESSEL REPAIR

TASK: LOW HEAT INPUT WELDING

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Introduction

Repair of intergranular stress corrosion cracking which may develop in SRP reactor vessels will be complicated by helium-induced weld cracking. The current leading candidate repair technique is a low heat input weld overlay which reduces the helium effect.

Summary

Recent experiments show that low heat input Gas Metal Arc (GMA) weld overlays dramatically reduce helium-induced weld cracking in Type 304 stainless steel. The experiments indicate that helium-induced cracking is controlled by the heat input of the weld and the helium content of the material. Subsequent experiments may prove this type of weld overlay to be a suitable sealing technique for intergranular stress corrosion cracks (IGSCC) in irradiated stainless steel.

Background

Helium-induced weld cracking in Type 304 stainless steel was identified in the 1985/86 attempt to repair the "knuckle region" of the C-Reactor vessel. L, P, and K reactors vessels are configured differently from the C-vessel. The primary difference is that L, P, and K vessels do not contain a curved transition piece (knuckle) between the vessel bottom plate and the vessel side wall. This region in C-vessel was particularly susceptible to IGSCC because of its fabrication history.

In the C-vessel repair attempt, a patch was installed to isolate leaking IGSCC in the knuckle region. Upon pressure testing of the patch, leak paths were found around the patch-to-vessel welds. Subsequent investigations showed these leaks to arise from helium-induced cracking in the vessel wall material adjacent to the patch-to-vessel welds[1].

Helium is generated by reactions of thermal neutrons with constituents (mainly nickel and boron) of Type 304 stainless steel. High temperature thermal cycling, such as that associated with welding, promotes formation of helium bubbles on grain boundaries. Under applied stress at elevated temperature, the bubbles serve as initiation sites for the growth of larger grain boundary cavities which lead to intergranular fracture of the stainless steel[2]. The 0.2" deep, autogeneous welds used around the patch produced both the elevated temperatures and the stresses necessary to create helium-induced "toe cracks" in the heat-affected zone of the base metal adjacent to the weld. This result was confirmed in laboratory tests[3].

The toe cracks extended from beneath the repair welds to the vessel surface and were detectable by dye penetrant testing, a surface examination technique. Such cracks would also be in contact with the reactor moderator, the electrolyte responsible for IGSCC. As such, toe cracks might grow by subsequent IGSCC. Indeed, part of the 1986 repair focused on the heat-affected zone (HAZ) of an 1968 patch weld where helium-induced toe cracking may have initiated IGSCC.

In view of the problems with reactor vessel repair by Gas Tungsten Arc welding, the Alternative Repair Technologies program was initiated to identify and develop suitable repair technologies. This program includes vessel repair by fused plasma spray coatings, brazing, and sol-gel composite coatings as well as modified welding techniques. These techniques are all at different stages of maturity. This report focuses on low heat input overlay welding which is currently the most promising and mature repair technology.

In the course of investigating the cause of toe cracking, a group of low penetration, autogenous Gas Tungsten Arc (GTA) welds were studied. The depth of penetration is generally proportioanl to the heat input. Lower penetration implies there is a smaller volume of weld metal to solidify. This translates into reduced stress in the HAZ accompanying solidification. In mechanical tests of simulated patch joints using lower penetration, autogenous welds, a helium-concentration dependent transition in the joint fracture behavior was noted[3]. This observation led to the current experiments aimed at determining the relationship between weld heat input (and related HAZ stress) using GMA welding and the sample helium content. It was also hypothesized that the use of filler metal would further reduce HAZ stress by increasing the free surface-to-weld metal volume ratio as compared to autogenous welds. Reduction of the solidification stresses around welds may inhibit the growth of helium bubbles into the larger cavities by suppressing vacancy transport to the small helium bubbles. Since helium diffusion is rapid at temperatures associated with the HAZ[4], it is unlikely that nucleation of grain boundary helium bubbles can be suppressed. The key element in suppressing helium-induced weld cracking is assumed to be inhibition of bubble growth into larger, creep-like cavities by reduction of the stress in the HAZ.

As with the earlier patch attempt in C-Reactor, a thin (0.060") GMA overlay is a non-structural repair. The goal is to stop crack growth by isolating cracks from the moderator (simultaneously sealing any through-wall leaks). This would serve to preserve vessel safety margins with regard to crack instability as calculated in reference 5.

Experimental Approach

In order to determine the relationship of heat input and helium content for cracking onset, test samples with a range of helium contents were prepared. The samples were 0.25" x 1.25" x 4.7" bars of Type 304 stainless steel. The samples were exposed to tritium by the Sandia National Laboratory - Livermore at 400°C. Tritium diffuses into stainless steel and decays to helium. The final helium content can be manipulated by changing the amount of tritium in the metal or the time available for decay to helium. In this experiment, both techniques were used. Since the desired helium contents ranged from approximately one to over one hundred atomic parts per million (appm), two sets of samples with different helium ingrowth rates (proportional to the tritium solubility) were used. By changing the tritium pressure over the samples from 575 to 9200 psi, the helium ingrowth rate was increased from 3 to 17 appm/month as measured by vacuum fusion mass spectroscopy of companion analysis samples. When the desired helium content was obtained, the tritium was outgassed by heating to 450°C and the helium content was fixed. Samples with measured concentrations of 3, 9, 17, and 85 appm helium were used in experiments to date.

There is the potential for grain boundary helium bubble formation during the 400°C tritium exposure and the 450°C outgassing. However in studies of room temperature tensile properties of similarly prepared samples but at higher helium contents, no decrease in the ductility could be measured until the samples were heated to 1000°C[6]. This suggests that extensive formation of large grain boundary helium bubbles does not occur at 450°C. Any prior grain boundary bubble formation would be conservative with regard to post heat treatment weldability.

Prior to welding, test samples were clamped in a fixture between two similarly-sized plates of stainless steel used to start and stop the weld as shown schematically in Figure 1. Test welds were placed across the 1.25" dimension. The weld was started on one of the outer plates, traversed across the helium-bearing plate, and stopped on the second outer plate. The second outer plate was machined from the same heat of steel as the tritium-exposed plate, thus providing a helium-free check of the weldability.

Figure 2 shows three test welds placed across the sample containing 85 appm helium in the central plate. The welds numbered 10 and 11 are overlays produced by mechanical oscillation of the weld bead perpendicular to the major travel direction. Both welds were made at 20 volts, 1.5"/min. travel speed, and an oscillation linear speed of 40"/min. Weld 11 was made at 45 amps, yielding a heat input of 1.3 kJ/in. For Weld 10, the current was increased to 80 amps for a heat input of 2.3 kJ/ in. Overlay penetration into the base metal did not exceed 0.010" for either weld. The lower heat input weld (weld 11) would probably be inappropriate for actual reactor repair in that it exhibited some regions of "lack of fusion" between the overlay and the base metal. Thus weld 11 represents a practical lower bound on heat input accessible to GMA welding.

Weld 9 is an unoscillated "stringer bead" made at a heat input of 15 kJ/in. It had a penetration depth of 0.090" into the base metal and was intentionally made at a high heat input to induce cracking, thus demonstrating the susceptibility of the samples to the helium-induced cracking phenomena. Figure 3 shows dye penetrant test results for welds 9 and 10. Toe crack indications are present around the deeper, hotter stringer bead (weld 9) on the helium-charged plate, but not around the low penetration, low heat input overlay (weld 10). There are also "artifact" indications, which should be ignored, stemming from the gaps between the helium-bearing and the helium-free plates.

These three types of welds, one hot stringer and two low heat input overlays, were placed on test samples with 9, 17, and 85 appm helium. The initial sample with 3 appm helium included an additional intermediate heat input overlay and a second stringer bead for a total of five test welds. Controllable test weld parameters are summarized in Table 1.

Experimental Results

The results of this experiment are summarized in Figure 4, a plot of metallographically observed cracking behavior as a function of heat input and sample helium content. For region I at low heat inputs and low helium concentrations, no cracks were observed. Occasional HAZ grain boundaries adjacent to the fusion line of the weld were decorated with intermittent cavities. As shown in Figure 5, some interlinkage of the cavities can be observed. These cavities, such as in Figure 5, may be helium-induced precursors to cracking but would not be expected to propagate without further stress at high temperature. These areas are not in contact with the moderator. Fracture surfaces of toe cracks of the type produced in C-Reactor were covered with fine (1 micron diameter) dimples[3], consistent with fracture by intergranular creep rupture. The cavities in Figure 5 probably correspond to the fracture surface dimples and would have coalesced into a crack had the solidification stress under the weld been higher. For region I welds, cavity formation was localized to a band within 40 microns of the weld interface. Since these overlays were made at the lower limit of penetration, it is unlikely that such cavity formation in the first grain boundary intersecting the weld interface can be further suppressed by weld parameter modification. Since cavities have not been found on the first set of grain boundaries parallel to the weld interface, no measurable effect on the adhesion of the overlay to the base metal is expected. Figure 6 shows the general appearance of the overlay/base metal interface in region I.

In region II, isolated intergranular cracks a maximum of three grains deep were observed perpendicular to the fusion line under even the lowest heat input overlay at 85 appm helium. In Figure 7 showing the weld/base metal interface region from weld 11, no interconnected cracking is visible. Hence the effect on clad adhesion will probably be negligible. Since the observed cracks are subsurface as opposed to toe cracks which emerge on the surface, growth by IGSCC or leakage could not occur.

Isolated cracking from region II can be compared with Figure 8 from region III (15 kJ/in. weld on a sample with 85 appm helium). Here a network of cracks is visible. This network structure is similar to that of previous GTA welds such as those made during the C-tank repair effort[3]. The weld in region III was the only weld to exhibit toe cracks which emerged on the sample surface and were thus detectable by dye penetrant inspection. Such welds would be inappropriate for reactor service.

Path Forward

Further experiments are needed to quantify the relationships between base metal helium content, weld heat input, and weld quality. These include expanding this test weld experiment to higher helium concentrations, filling in some gaps in the existing data, destructive mechanical testing of overlays to determine adhesion, and investigation of low heat input techniques other than GMA welding.

1. Perform additional welding experiments on Type 304 stainless steel samples containing up to 250 appm helium. This work will include welds identical to the previously completed experiments described above. The specific helium levels in the planned experiments are 25, 50, 160, and 250 appm. For comparison, the maximum helium concentrations in SRP reactor vessels are calculated to be approximately 140 appm at the mid core region of P and K reactors[7]. The maximum helium content in L reactor vessel is estimated to be 40 appm. In the knuckle region of the C-Reactor vessel, the helium content was measured to be 1 to 3 appm[1]. These additional welding experiments are expected to begin during the summer of 1989.

2. Perform mechanical tests to determine the adhesion of the overlay to the base metal as a function of base metal helium content. Overlay adhesion is an essential element in assuring that the repair weld would remain functional under operating and/or accident conditions. Adhesion is primarily significant if cracking exists in the heat-affected zone under the repair weld. Since this report has shown cracking depends on helium content of the base metal, overlay adhesion should also be helium concentration dependent. The objective of the mechanical testing is to assure that sufficient adhesion exists between the overlay and base metal for the range of helium present in SRP reactor vessels.

   The proposed mechanical test is essentially a modification of the stud weld pull test. The stud pull test is applied in the SRP fuel fabrication area to assure adherence between aluminum target cladding and uranium core material. This test is being modified for testing adhesion between Type 308 stainless steel overlay and Type 304 base metal. Basically, the test involves welding a stud of known strength to the overlay. The stud weld is made in such a way that the heat-affected zone from the stud weld is entirely contained in the overlay and does not affect the overlay/base metal interface. In the test, the stud is pulled until failure. The failure location and load associated with failure are recorded. In tests of initial samples of these GMA overlays on helium-free material, fracture did not occur at the overlay/base metal interface in question[8]. The fracture stress is at least 77 ksi (70% of the ultimate strength of Type 304 stainless steel) with all failures occurring in either the stud itself or the stud-to-overlay weld. This implies that, in the absence of helium effects, the low heat input overlay is strongly adherent to the base metal.

3. Perform additional developmental research to study other welding techniques to apply low heat input overlay to Type 304 base metal. These techniques include laser welding. Since the penetration depth of the overlays reported in the present study is as low as practically

achievable, additional benefits with regard to helium may not be expected for the other welding techniques. However, there may be benefits from logistical and/or economical points of view with regard to remote, robotic delivery.

Conclusions

The extent of helium-induced weld cracking depends upon the helium concentration of the base metal and the heat input of the welding technique. This is probably due to reduction of the HAZ stress as the heat input and penetration depth of the weld decrease. To reduce cracking at a given helium content, the heat input of the weld, and hence penetration into the base metal, should be reduced. Low heat input GMA overlays have been shown to eliminate emergent toe cracks at helium contents up to at least 85 appm. Additional test welds at higher helium contents as well as destructive mechanical testing to qualify the welding process and resulting adhesion to the base metal are planned for the near future.

AKB:sgm
MTD-88.433

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Table 1 - Test Weld Parameters

Weld No.	Sample No.	Helium (APPM)	Current (AMPS)	Voltage	Travel (in./min.)	Oscillation (in./min.)	Heat Input (kJ/in.)
1	1	3	45-50	19.5	1.6	40.5	1.3
2	1	3	78	19.5	11.25	0	8.1
3	1	3	150	26.5	16.0	0	14.9
4	1	3	60-70	19.5	1.85	40.5	1.9
5	1	3	80	19.5	2.4	40.5	2.3
6	9	17	45-50	19.5	1.5	40.5	1.3
7	9	17	80	19.5	2.3	40.5	2.3
8	9	17	150	26.5	16.0	0	14.9
9	11	85	150	26.5	16.0	0	14.9
10	11	85	80	19.5	2.3	40.5	2.3
11	11	85	45-50	19.5	1.5	40.5	1.3
12	3	9	45-50	19.5	1.5	40.5	1.3
13	3	9	80	19.5	2.3	40.5	2.3
14	3	9	150	26.5	16.0	0	14.9

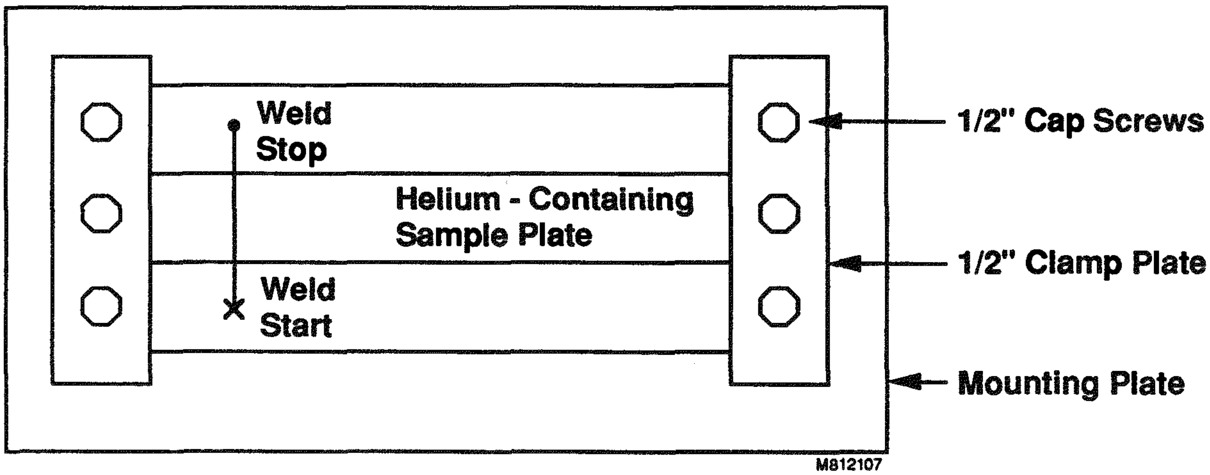

FIGURE 1. Schematic of Test Weld Fixture

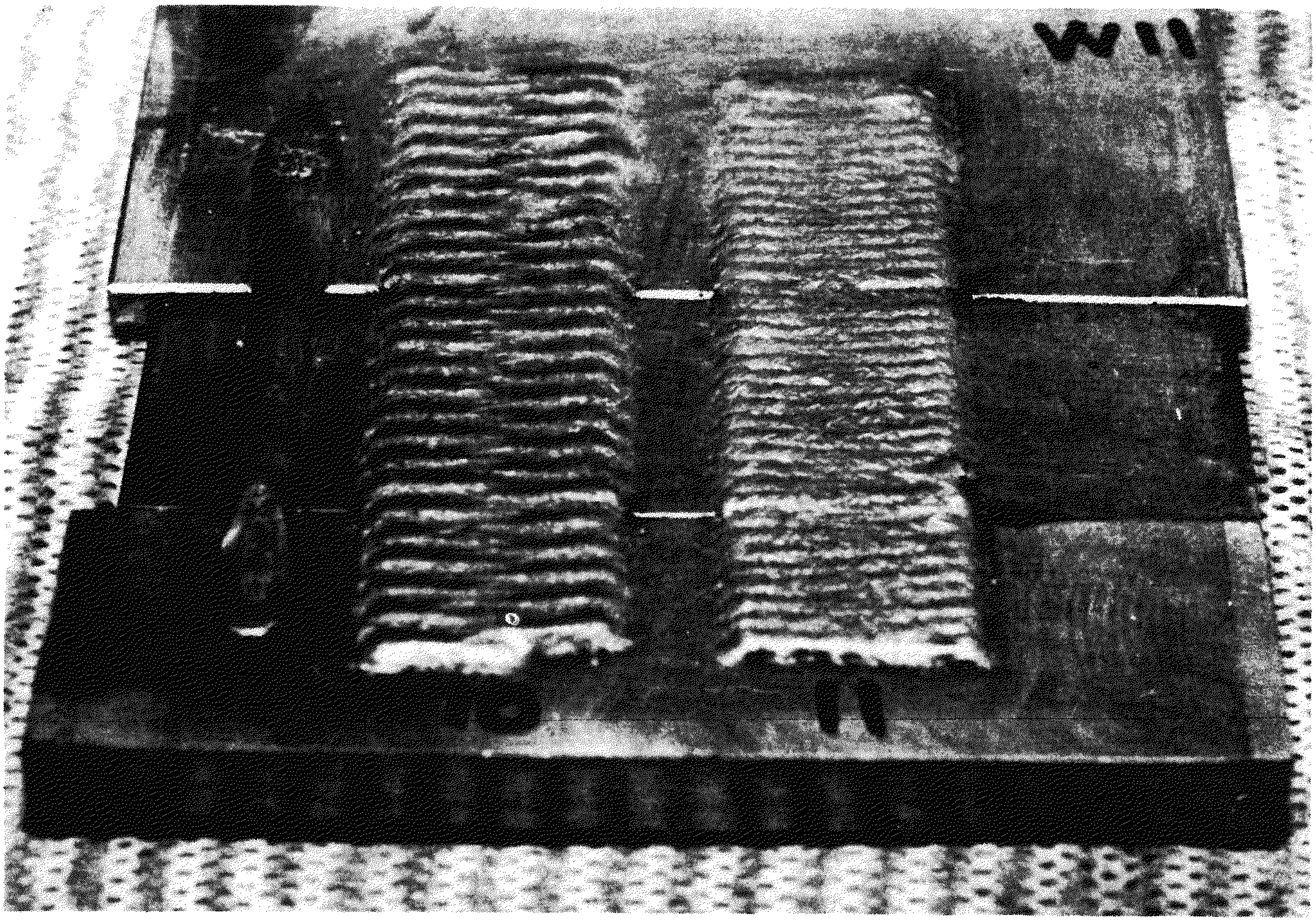

FIGURE 2. Photograph of Weld Test Sample

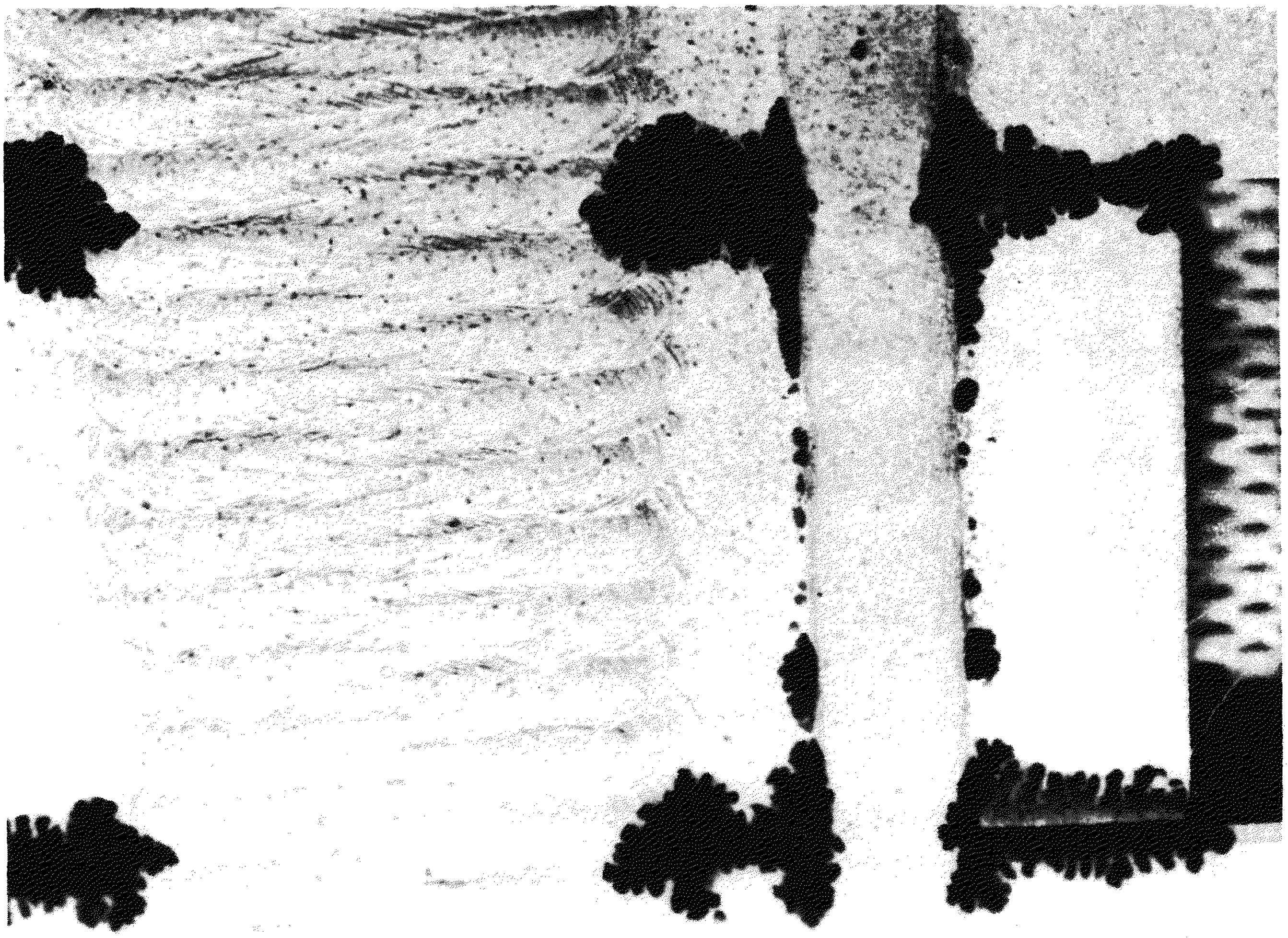

FIGURE 3. — Dye Penetrant Test Results for a High Heat Input Stringer Bead and a Low Heat Input Overlay on a Test Plate with 85 Appm Helium

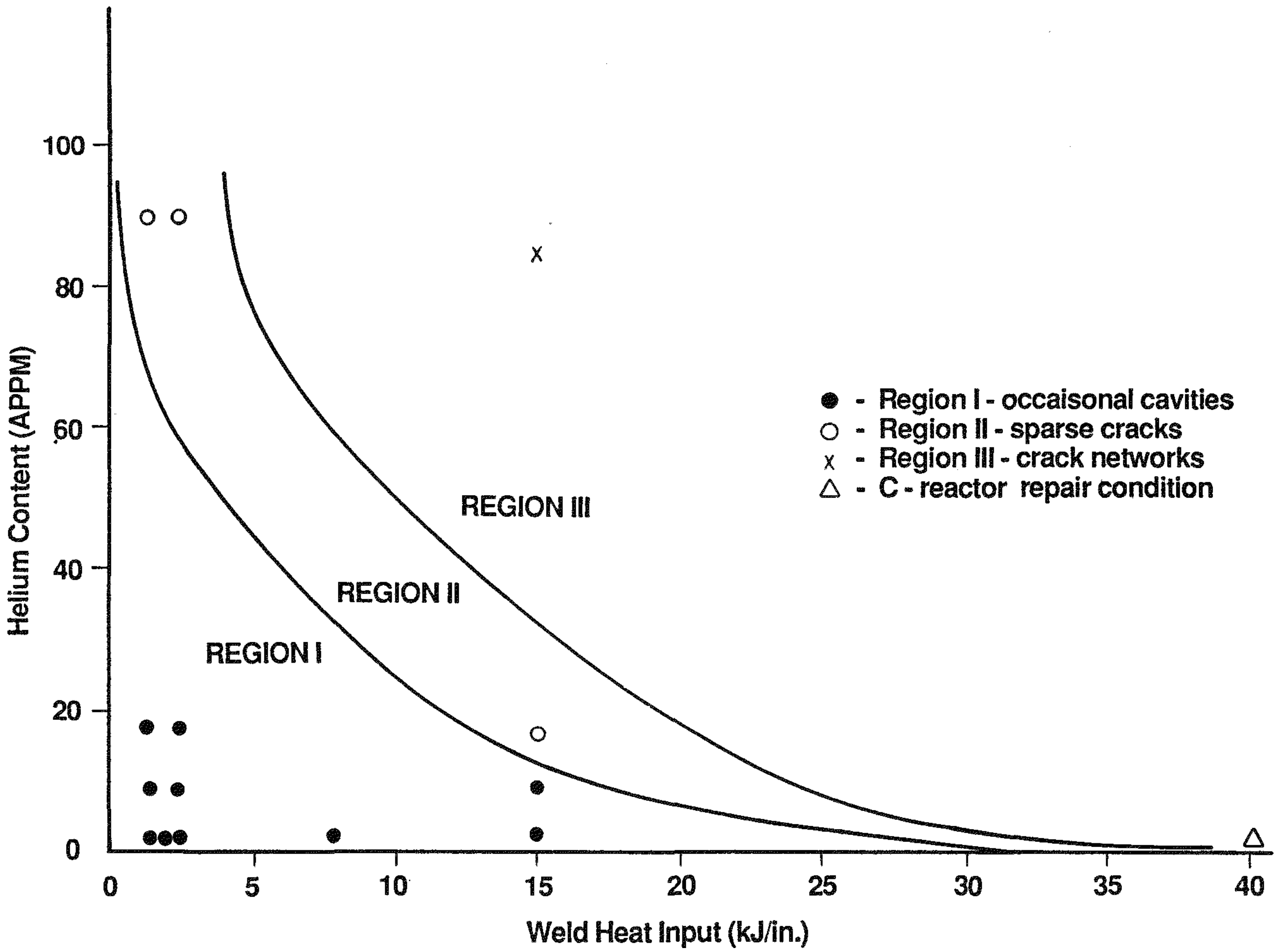

FIGURE 4. Helium - Induced Cracking of 304 Stainless Steel

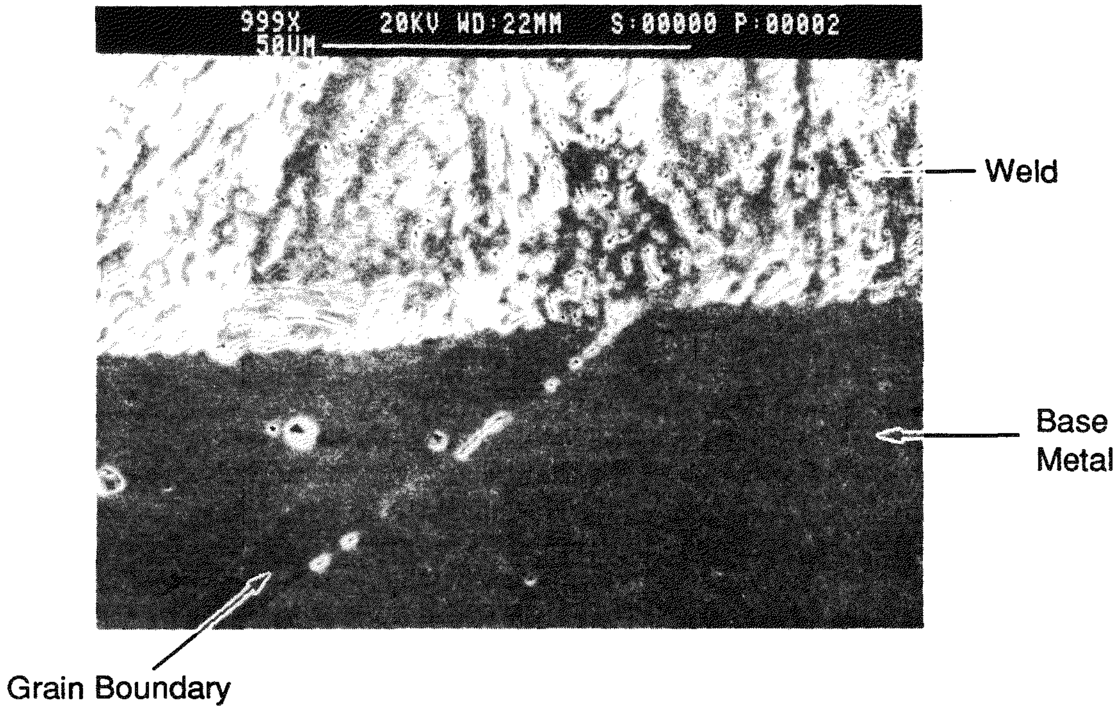

FIGURE 5. Scanning Electron Micrograph of Cavities on a Grain Boundary Adjacent to a Low Heat Input Overlay with 17 Appm Helium (Magnification = 1000X)

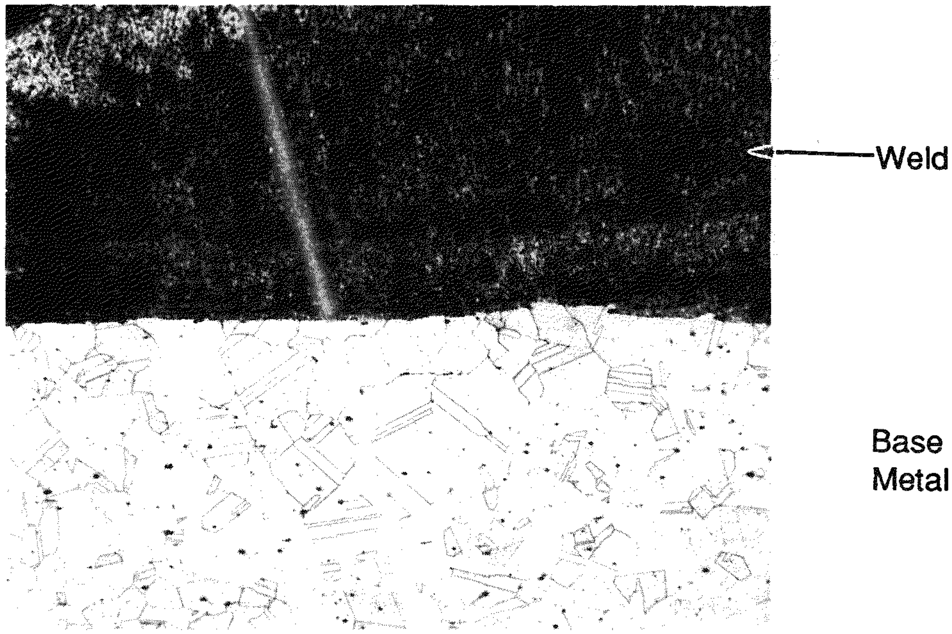

FIGURE 6. Micrograph of the Fusion Line of a Low Heat Input Overlay on a Sample with 9 Appm Helium (Magnification = 40X)

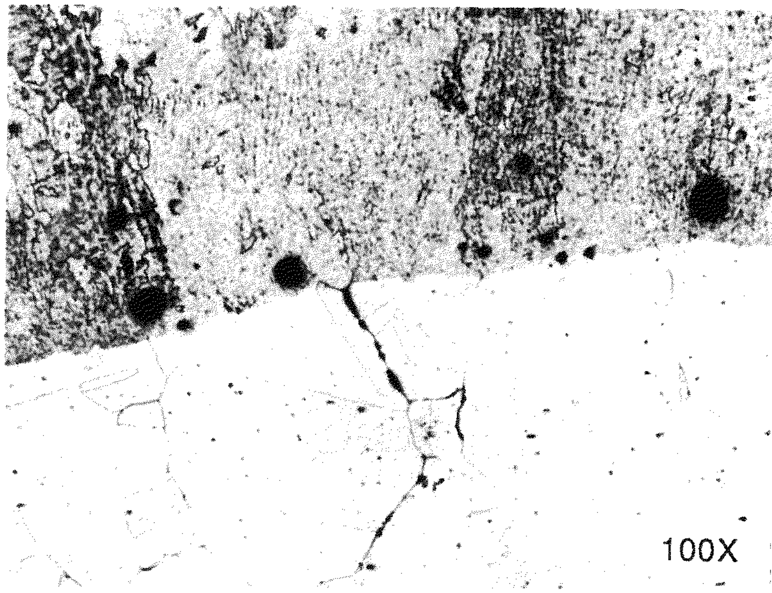

FIGURE 7. An Isolated Crack Under a Low Heat Input Overlay on a Sample with 85 Appm Helium

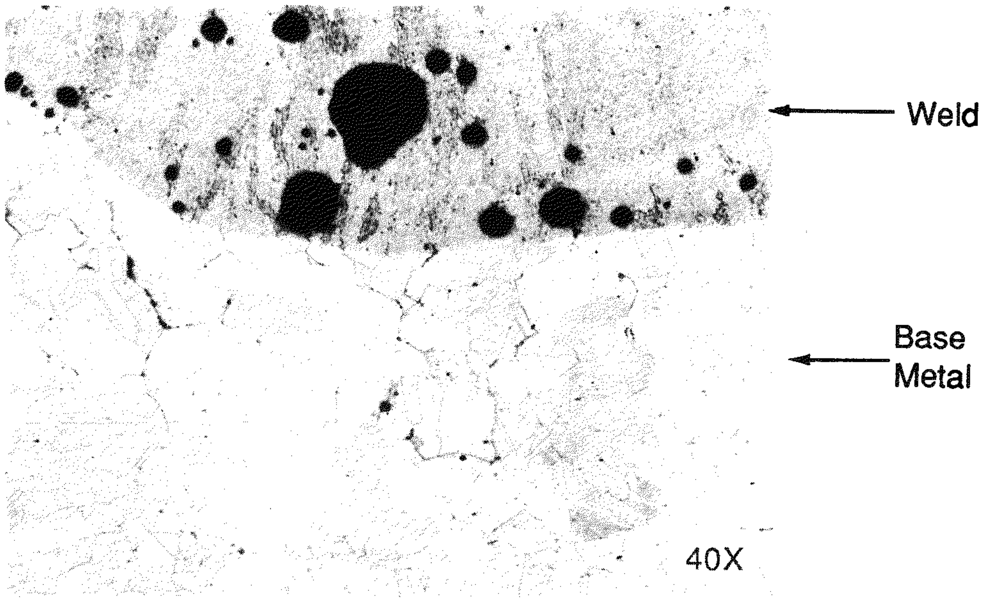

FIGURE 8. A Network of Cracks Under a High Heat Input Stringer Bead on a Sample with 85 Appm Helium