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HELIUM-INDUCED WELD CRACKING IN IRRADIATED 304 STAINLESS STEEL (U)

by

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A paper proposed for presentation at a meeting
of the Metallurgical Society of AIME
at Indianapolis, IN
on October 3, 1989

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Research Associate

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AIME Presentation on Helium Weld Cracking

The following sections are submitted for approval as slide notes for presentation to The Metallurgical Society of the American Institute of Mining, Metallurgical and Petroleum Engineers (AIME). The meeting in question will be held October 3, 1989 in Indianapolis. An abstract of this talk has been previously approved by DOE.

This presentation will be the second of three consecutive talks contributed by SRL personnel dealing with helium-induced weld cracking. A copy of the agenda is attached. An earlier talk by W. R. Kanne will review the history of the C-reactor repair effort. This talk will cover the results of the program, largely conducted at the Westinghouse Research and Development Center, to diagnose the cause of the weld toe cracking observed in C-tank. The third talk will cover subsequent work at SRL investigating low penetration/heat input welds.

Slide 1 - Dye Penetrant Examination of In Reactor Weld Beads
This slide recapitulates the important results of the in-reactor weld studies reported by the previous speaker. The slide shows dye penetrant indications along the fusion line of two parallel, autogeneous GTA welds that were placed on the wall of the C-tank. The indications are in the same location relative to the weld as leaks in the acceptance pressure test of the patch repair of the C-tank knuckle.

Slide 2 - Montage of Boat Sample Metallography
We removed thin, lenticularly-shaped "boat" samples from the knuckle region of the C-reactor. The samples had to be kept small and thin in order to preserve the option to repair the reactor. They were 0.25" at the thickest location. For the sample shown, the right most edge of the sample was adjacent to the knuckle-to-bottom plate fabrication weld. The two intergranular cracks toward the right edge of the micrograph are

stress corrosion cracks such as those that originally necessitated the repair of the vessel. On the left side of the montage is the cross section of an autogeneous GTA weld applied to the knuckle as part of the diagnostic program. Intergranular cracks can be seen in the heat-affected zone of the base metal several grains away from the fusion line of the weld. These are the cracks responsible for the penetrant test indications and for the leaks in the pressure test of the repair patch described in the previous talk.

Slide 3 - Toe Cracking Mechanisms

The program to diagnose the cause of this "toe" cracking began by constructing a list of all imaginable causes of the cracking phenomena. For example, it was considered that pre-weld intergranular attack (IGA) or stress corrosion cracking could open under the stresses imparted by welding. In the course of the study, evidence for or against a mechanism was collected. In the case of IGA, a similar form of toe cracking was observed. However, examination and sampling of the tank failed to show the IGA was present. Toe cracking was independant of weld location and persisted even after removal of up to 0.080" of sample surface.

In the course of the study, a solid case for helium embrittlement as the cause of the toe cracking phenomenon was established. Welding on material with IGA did induce a similar phenomenon, but the toe crack indicates were not as sharp as those observed in tank. Subsequent metallography showed this reflected multiple crack mouths at the metal surface with IGA as opposed to singular crack mouths in the case of helium cracking. This difference in phenomena was supported by welding on an earlier reactor patch which was made of 304L and not likely to be subject to IGA. These test welds also cracked. This suggested that irradiation-induced helium (or interactions of helium and hydrogen) might be responsible for toe cracking. Hydrogen alone was ruled out when welds on hydrogen charged 304 did not crack. Irradiated charpy bar halves with very low helium contents (0.07 appm) did not crack. The case for helium as the cause of cracking was greatly strengthen when welds on tritium-charged and aged 304L exhibited identical toe cracking. Tritium is a radioactive isotope of hydrogen which can be charged into austenitic stainless steel. In solution in the steel, the tritium decays into helium which is, in turn, essentially insoluable and precipitates as fine (10 angstrom diameter) bubbles. Samples prepared in this fashion are unexposed to neutrons nor have they been in the reactor chemical environment. Possible interactions between helium and hydrogen were excluded when tritium-charged, aged, and tritium outgassed samples cracked.

Slide 4 - Effect of Helium on Ductility of Stainless Steel

Helium drastically reduces the elevated temperature ductility of austenitic stainless steels. In this figure, Curves A, B, and C are from published results from several austenitc stainless steel with helium contents derived from ion implantation. The correspondingly-lettered, primed curves are the helium-free control samples which show increasing ductility at elevated temperature. At around 550 C (823 K), the helium-bearing samples experience a strong reduction in elevated temperature ductility. Identical temperature dependance of ductility reduction, accompanied by a transition to intergranular fracture, can be seen in Curve D obtained from samples cut from the vessel sidewall of Savannah River Site's shut down R Reactor. The similarity of curve D with curves A, B, And C supports the identification of helium as the cause of weld cracking and helps clarify the cracking mechanism. In the heat-affect zone of the base metal adjacent to a weld, the ductility of the irradiated, helium-bearing stainless steel is reduced while the weld cools. The solidification of the weld generate the stresses at elevated temperature necessary to produce the cracking.

Slide 5 - Electron Microscopy of Helium Bubbles

This micrograph was taken from the unstrained head of a tensile bar of 304 stainless steel that was removed from the R reactor sidewall with 34 appm helium. It had been annealed 15 minutes at 816 C. A grain boundary decorated with approximately 80 Angstrom-diameter bubbles is shown. In the as-irradiated condition, a uniform distribution of finer bubbles (20 Angstrom in diameter) is observed. The annealing of this tensile bar (or alternatively the thermal cycle in the heat-affected zone of a weld) promotes grain boundary helium bubble formation. Additionally, a few bubbles can be observed in the bulk along with defect clusters known as "black dots" (after their appearance). The black dots arise from the fast portion of the neutron spectrum and contribute to irradiation hardening as they impede dislocation motion. The black dot concentration is also reduced by annealing.

Slide 6 - Ductility After Post Irradiation Annealing
In view of the presence of helium bubbles on the grain boundaries after annealing, one might inquire into the resulting ductility of the heat-affected zone of a weld on helium-bearing material after cooling to ambient temperature. The room temperature ductility of samples with a small range of helium contents is shown. With increasing temperature (15 minutes soak at temperature), the elongation of failure increases. By 2200 F, the ductility is indistinguishable from unirradiated 304 stainless steel (approximately 85% elongation to failure). Clearly the low area fraction of grain boundary occupied by the helium bubbles (at these bulk helium concentration) is insufficient to effect the room temperature fracture properties. This suggests that, if cracking can be avoided in the weld heat-affected zone during solidification, the residual mechanical properties of the joint should be excellent.

Slide 7 - Irradiated Fracture Toughness Test Results
Since thick (through wall) sections of vessel material could not be removed from the reactor to be repaired (C reactor), it was decided to study fracture toughness using material from the vessel sidewall of the R-reactor which had been shut down in 1964. Four six-inch-diameter, through-wall disks were cut. These provided material for fracture toughness specimens as well as the previously-reported tensile data. Two sizes of samples were tested - large (2T plan form except the thickness which was the service thickness of the reactor wall,0.5") and small (1 cm T). At room temperature and 125 C (the maximum anticipated service temperature), the fracture toughness ranges from about 900 to 1700 in.-lbs/in.^{2} . This compares with unirradiated fracture toughness values of 3000 to 8000 reported for 304 stainless steel. The reduction is ascribed to fast neutron damage. Despite this damage, significant toughness is retained and translates into tolerance of long flaws for the case of the low pressure Savannah River Reactors. When tested at 816 C, nil fracture toughness was observed. However as seen with the tensile results, a recovery of properties is seen in the sample tested at low temperature after an elevated temperature anneal. This recovery is due to annihilation of fast neutron-induced defect clusters. Taken together the data show that helium embrittles only at elevated temperature.

Slide 8 - Bend Bars From Magnetic Oscillation Welds
To avoid the elevated temperature cracking, magnetic oscillation of the

Gas Tungsten-Arc welds was investigated. This spread the 40 Kj/in. heat input over a wider area and was successsful in reducing the tendency toward toe cracking. However some underbead cracking was observed. Bend bars were cut to characterize the welds. Bars from material with about 10 appm helium were cut from the base metal unaffected by the weld and could be bent into a "horseshoe" without cracking. However bars located transverse to the weld fusion line and longitudinally under the bead exhibited intergranular cracking in the heat-affected zone.

Slide 9 - Fracture Surface From Longitudinal Bend Bar

The faces of the exposed grain boundaries were decorated with fine dimples spaced about 1 micron apart. Since no nucleating particles could be observed at 5000x in the dimples, it is likely they are nucleated by helium bubbles which disperse upon fracture. However the spacing of the dimples is much coarser than that of the grain boundary helium bubbles observed in transmission electron microscopy of annealed but unstrained samples. This indicates that helium redistribution has occurred during the weld thermal and the straining of the cracked grain boundary. This redistribution is probably stress driven and thus offers the key to avoiding cracking; through stress reduction via weld technique modification.

Slide 10 - Shear/Peel Test

To attempt to quantify joint properties, the shear/peel test was used. In this test pieces of unirradiated 304L were welded to irradiated R-reactor sidewall 304. The unirradiated material was machined to resemble the foot of the patch used in the C-reactor repair effort. Two locations of loading holes were used to obtain a shear test of thejoint or to peel the joint. In all cases, significant deformation of the test samples resulted in the weld being pulled in tension prior to failure so the location of the loading holes was not important. The load-to-failure data exhibited high scatter. More information was obtained from the location of the failure. For the magnetically-oscillated welds on irradiated material containing 3 appm helium, ductile fracture through the weld throat was observed. Since the weld throat had been chosen to accept all anticipated loads during reactor operation and accidents, failure in this location (and in load ranges used to design the weld throat) could be judged as possessing acceptable properties. For samples with 15 appm helium, failure of magnetically-oscillated welds occurred in the weld heat-affected zone.

Although this was preceded by extensive *deformation of the joint*, the properties are too uncertain are such a patch joint would be unacceptable. Since tensile tests show that embrittlement occurs only at high temperture and ambient properties are excellent, this mode of fracture is interpreted as the formation of continuous crack networks (or severely dimpled grain boundaries where the area fraction of remaining ligament is very small) around the welds. The data also shows a dependance of weldability on the helium content of the base metal in a range of helium important to the repair of C-reactor.

Slide 11 - Shear/Peel Test Heat-Affected Zone Failure
This figure shows the failure of a shear/peel test sample in the heat-affected zone. Such a joint would be undesirable for service.

Slide 12 -Model of Bead-on-Plate Welds
To make sound welds on irradiated, helium-bearing stainless steel implies avoiding stressing the material at elevated temperature. For fusion welding, temperatures approaching the melting point of the material are unavoidable in the heat-affected zone near the fusion line of the weld. Thus the stress developed in the heat-affected zone by solidification of the weld is the only variable available for manipulation. This simple model assumes a weld the shape of a half cylinder of radius r. Upon solidification, the weld contracts the distance dr. If the volume change on solidification is taken as a constant (3% for stainless steel from casting technology), then the contraction is proportional to the radius of the weld. The radius can also be identified as the penetration depth of the weld. Thus if one wants a *small contraction on solidification* (a *small* soldification stress or strain), one should make a small weld. The strain can be estimated by assuming the contraction is taken up by material in a larger concentric cylinder of radius equal to the thickness of the plate. The ligament taking up the strain is then the difference in the two radii. For the case of the C-tank configuration, the model predicts a strain of 1% which is a plastic strain for 304 stainless steel at 800 C. The helium containing material would not be expected to support such a strain under these conditions.

Slide 13 - Projected Helium Concentration Limits for Welding
If the cracking is controlled by the stress at elevated temperature, if the

solidification stress is controlled by the size of the weld and if the weldability (from the shear/peel test results) is affected by the helium content, then a plot of weld penetration versus base material helium content should delineate regions where sound welds can be made. The data obtained from R-reactor material, 304 irradiated at the University of Buffalo, and from the work of Kanne on tritium charged and aged material is ploted. Although the data is limited, it supports the premise that shallower welds on lower helium content material. This data was obtained using autogeneous GTA welding. Estimates of applicable range of helium content may be obtained from estimates of the minimum penetration depth achievable by various other welding technologies (particularly those which use addition of filler metal to the weld) and assumptions about the shape of the function controlling cracking. Additional experiments are needed to define the relationship between solidification stress, weld penetration, base metal helium content, and helium-induced cracking.

ACKNOWLEDGMENT

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WELDING OF HELIUM-CONTAINING METALS

Sponsored by: Nuclear Materials Committee.

Tuesday PM
October 3, 1989

Room: 224
Indiana Convention Center

Session Chairman: G.R.Caskey,Jr., Savannah River Site, Aiken, SC 29808.

(2:00 p.m.) Helium Embrittlement Cracking During Welding in Savannah River C-Reactor: W.R.Kanne,Jr., Savannah River Site, Aiken, SC 29808.

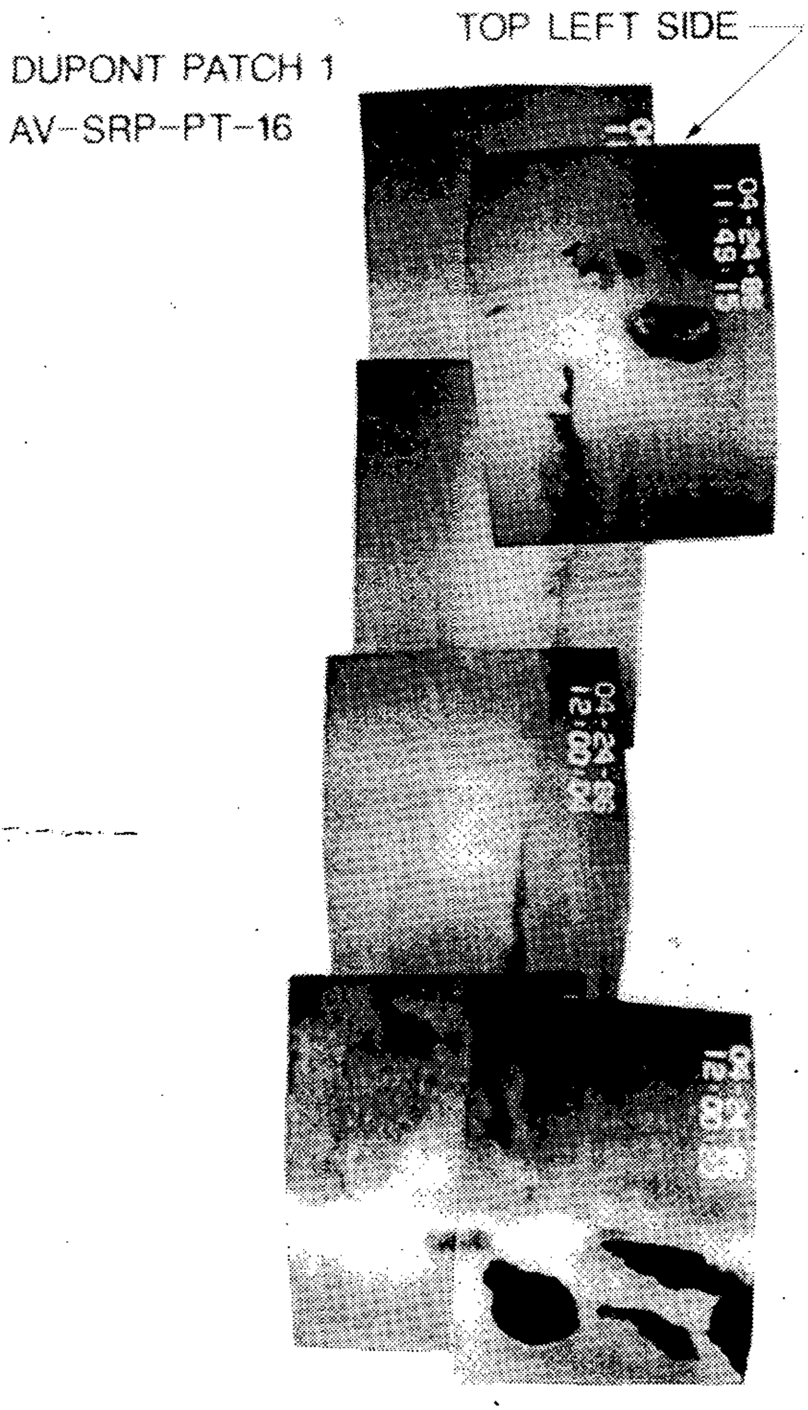
(2:30 p.m.) Helium-Induced Weld Cracking in Irradiated 304 Stainless Steel: A.K.Birchenall, Savannah River Site, Aiken, SC 29808.

(3:00 p.m.) Low Heat Input GMAW of He-Charged Stainless Steel: E.A. Franco-Ferreira Savannah River Site, Aiken, SC 29808.

(3:30 p.m.) The Feasibility of Repair Welding Irradiated Stainless Steels: H.T.Lin and B.A.Chin, Materials Engineering, Auburn University, AL 36849.

(4:00 p.m.) Rapid Heating Tensile Tests of Steels Charged with Hydrogen and Tritium: W.C.Mosley, Savannah River Site, Aiken, SC 29808.

(4:30 p.m.) Weldability of Consolidated Rapidly Solidified TYPE 304 SS Powders: D.E.Clark and G.E.Korth, Idaho National Engineering Laboratory,Idaho Falls, ID 83415.

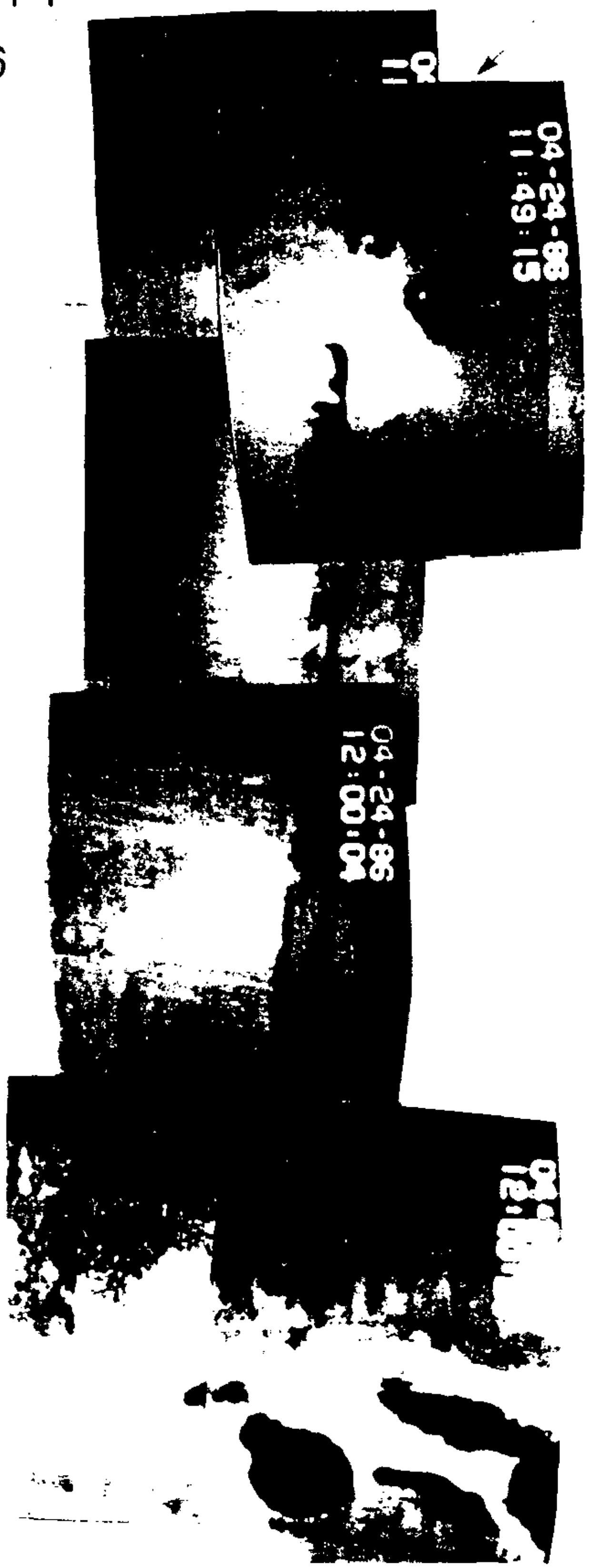


Slide 1 - Dye Penetrant Examination of In Reactor Weld Beads

DUPONT PATCH 1

AV-SRP-PT-16

TOP LEFT SIDE —



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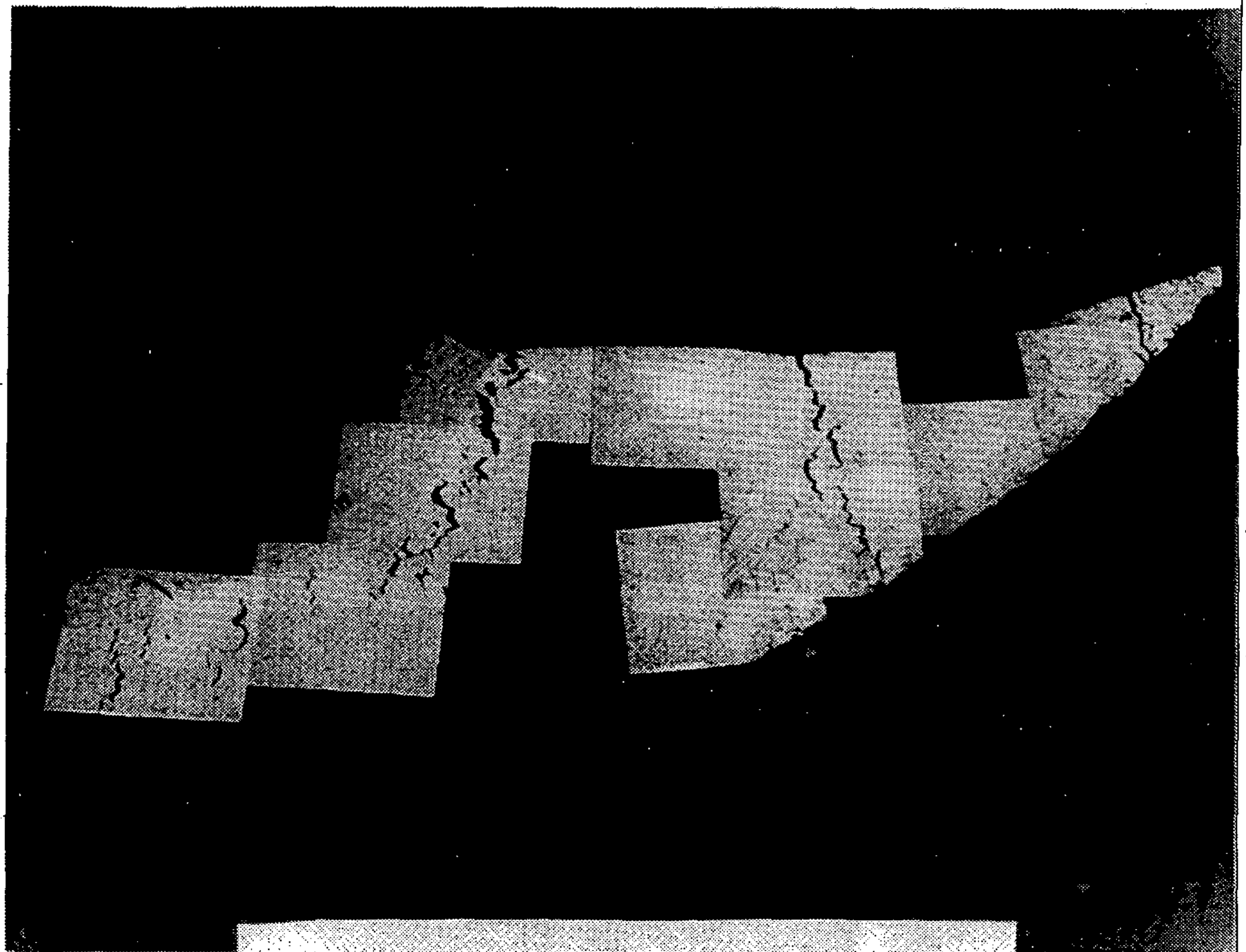
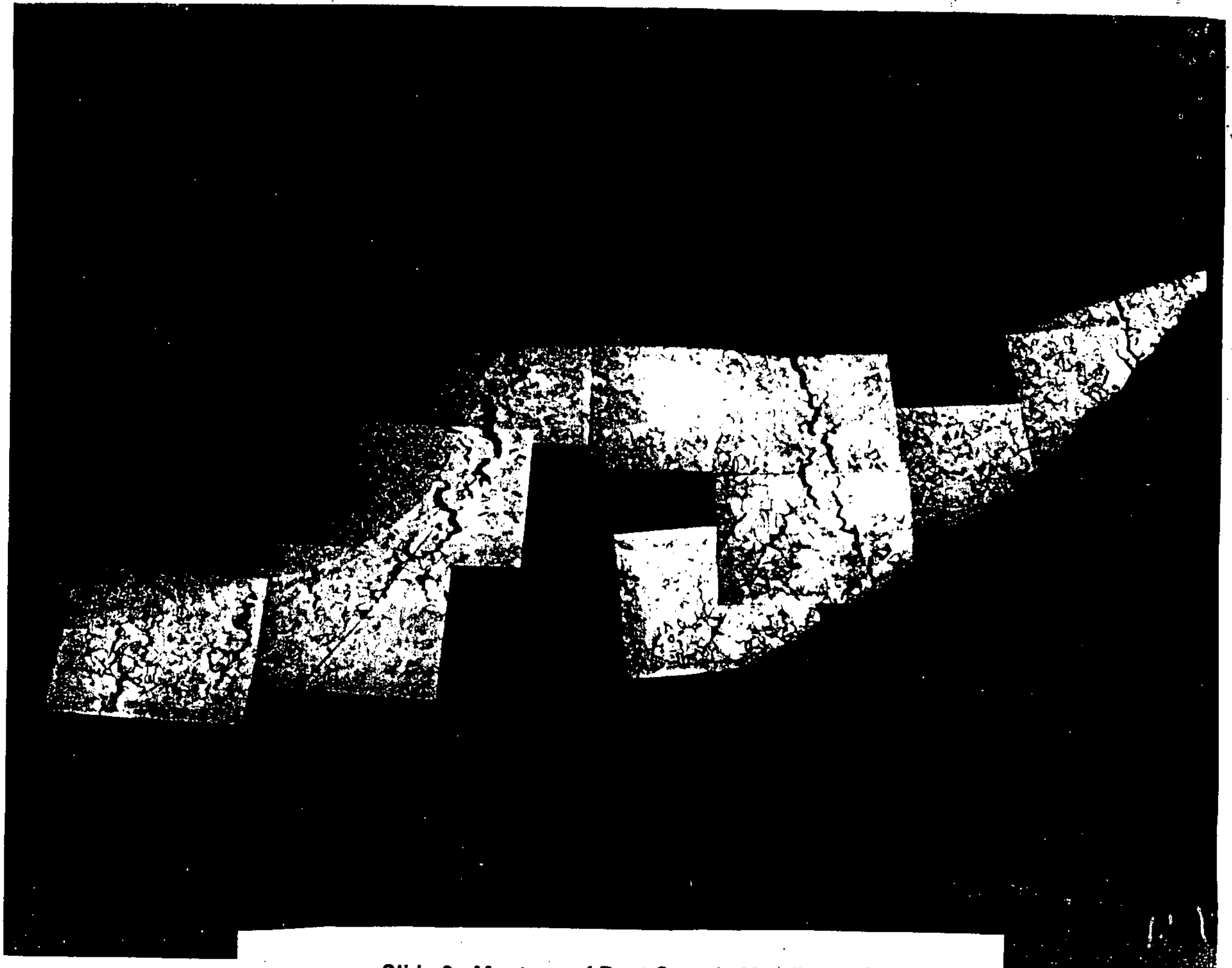


Slide 2 - Montage of Boat Sample Metallography



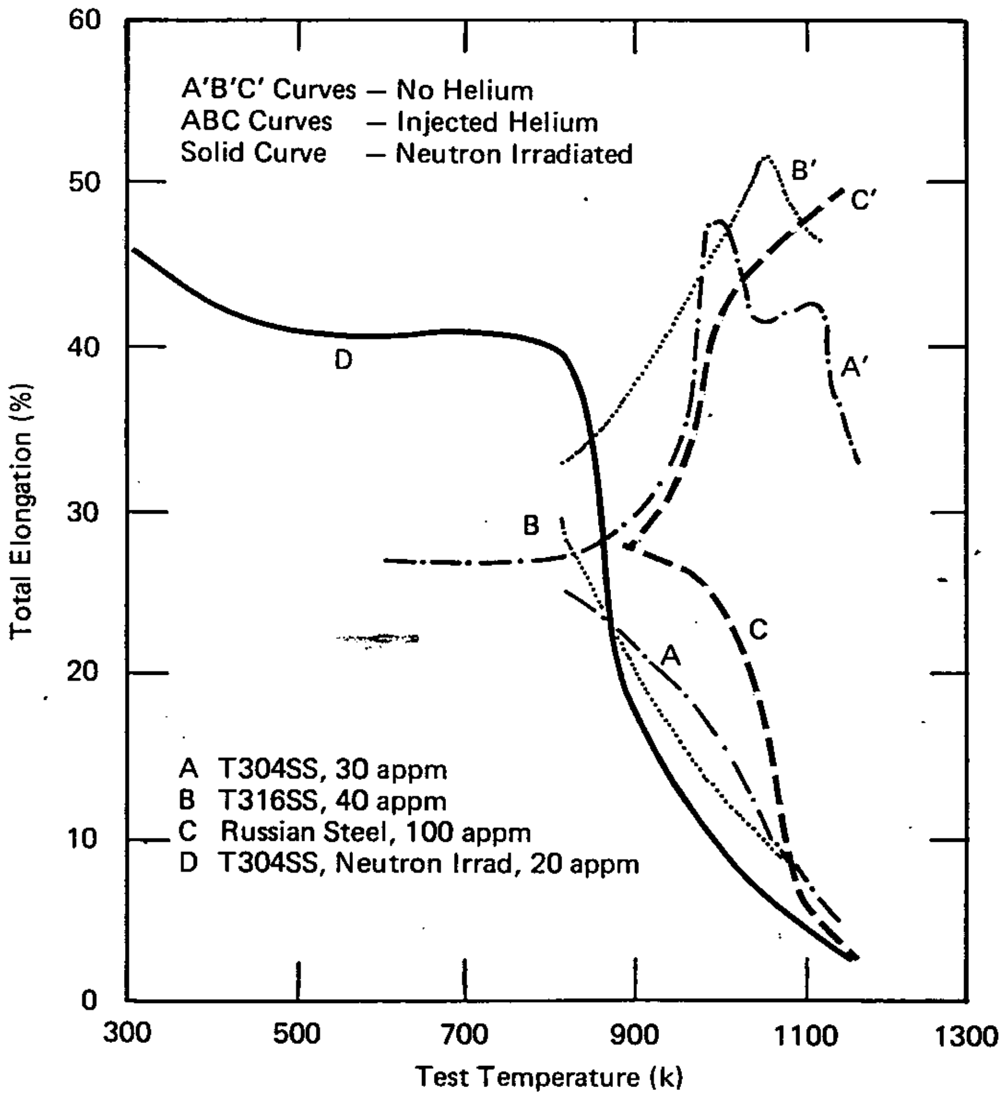
Slide 2 - Montage of Boat Sample Metallography

Slide 3 - Toe Cracking Mechanisms

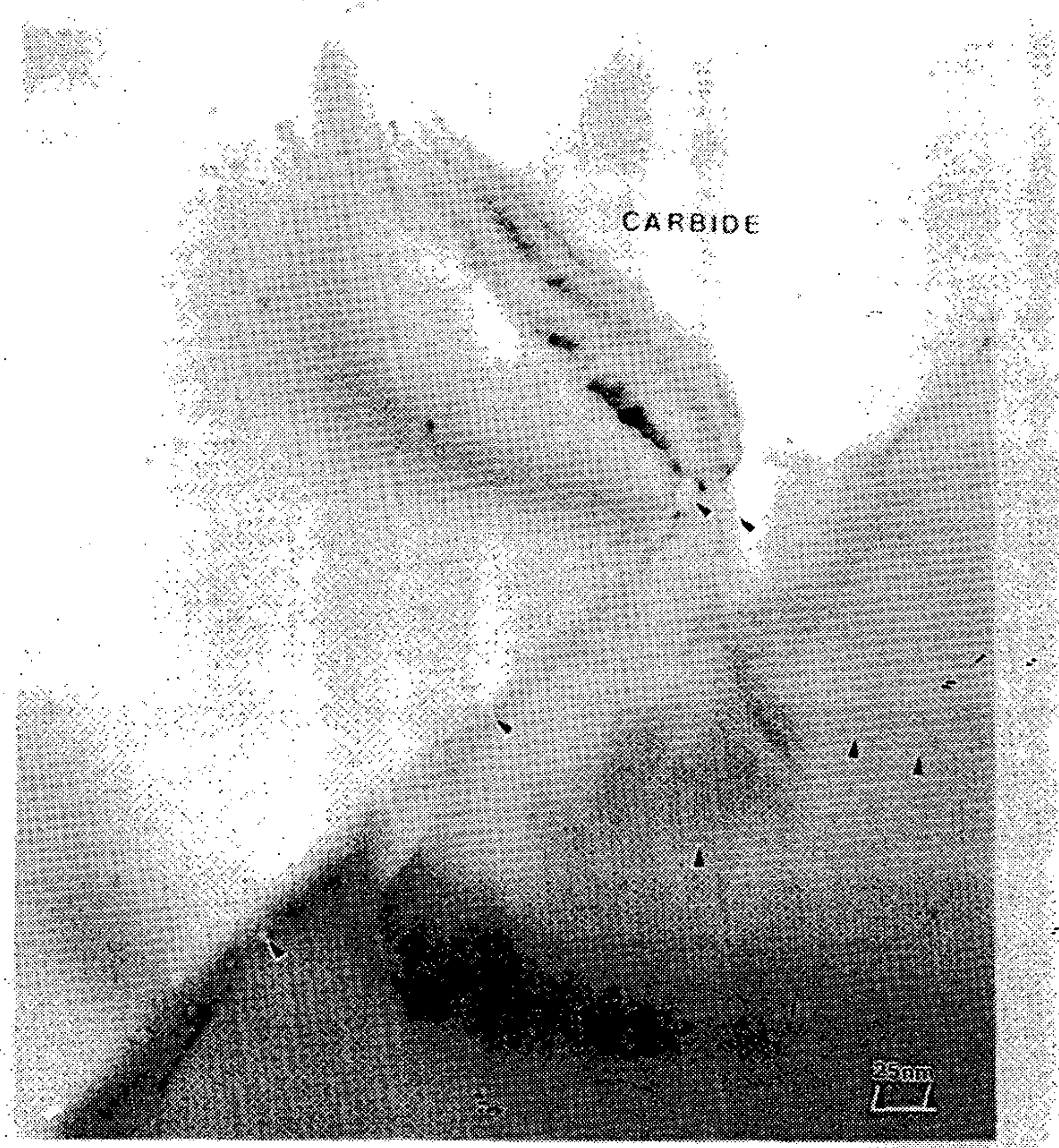
REACTOR OPERABILITY ASSURANCE PROGRAM

SUMMARY OF EXPERIMENTAL RESULTS

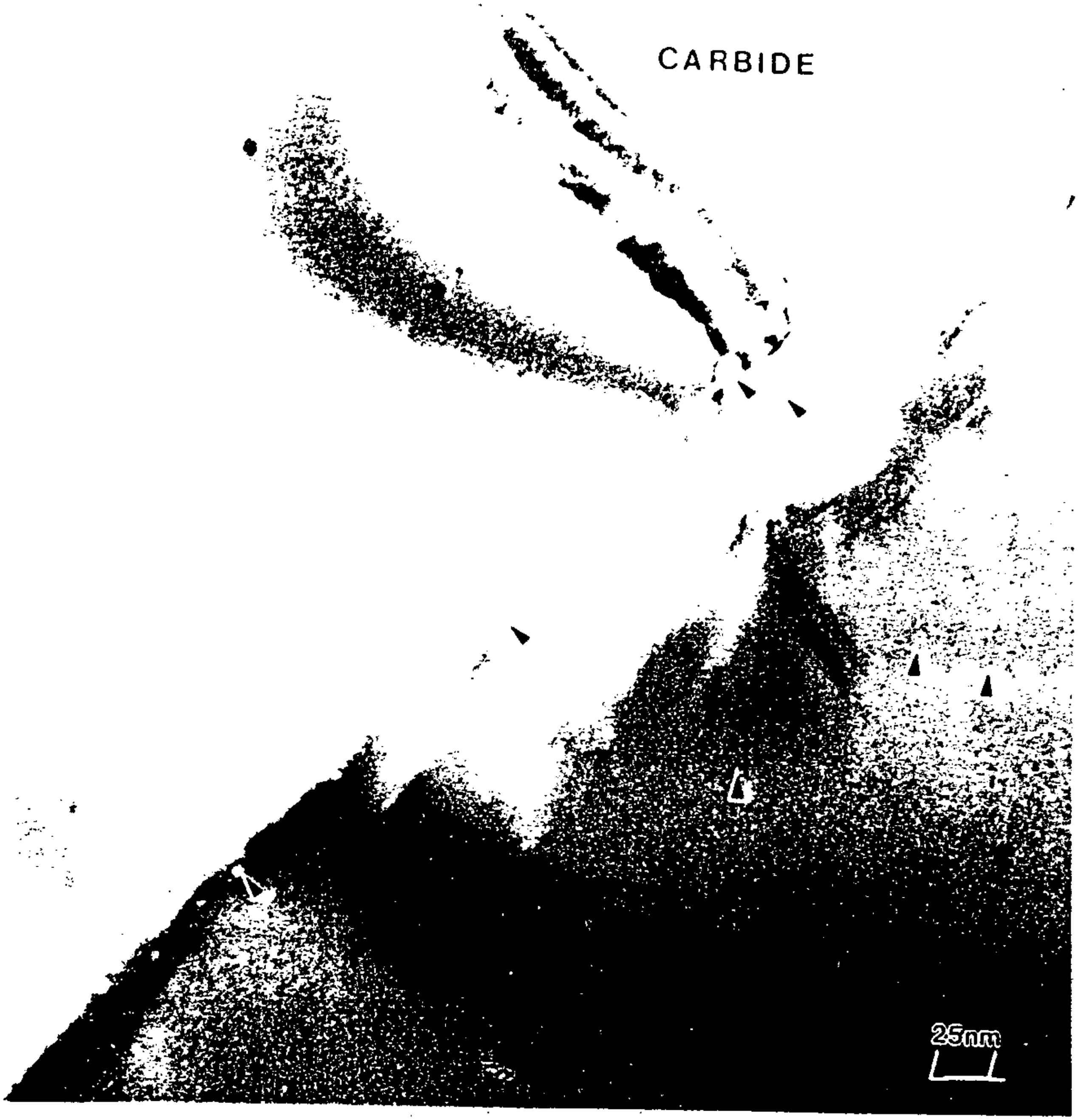
TEST	OUTCOME	CONCLUSION
WELDING ON UNIRRADIATED 304 S/S WITH IGA	WELD TOE CRACKS	IGA POSSIBLE CAUSE (IF PRESENT)
WELDING ON R-REACTOR 304 S/S	WELD TOE CRACKS	He (OR He + H) POSSIBLE CAUSE
WELDING ON '68 304L S/S PATCH	WELD TOE CRACKS	He (OR He + H) POSSIBLE CAUSE
WELDING ON H-CHARGED 304 S/S	NO CRACKING	H NOT SUFFICIENT TO CAUSE CRACKING
WELDING ON T-CHARGED 304L S/S	WELD TOE CRACKS	He (OR He + H) POSSIBLE CAUSE
WELDING ON T-CHARGED AND OUTGASSED 304L S/S	WELD TOE CRACKS	He POSSIBLE CAUSE



Slide 4 - Effect of Helium on Ductility of Stainless Steel

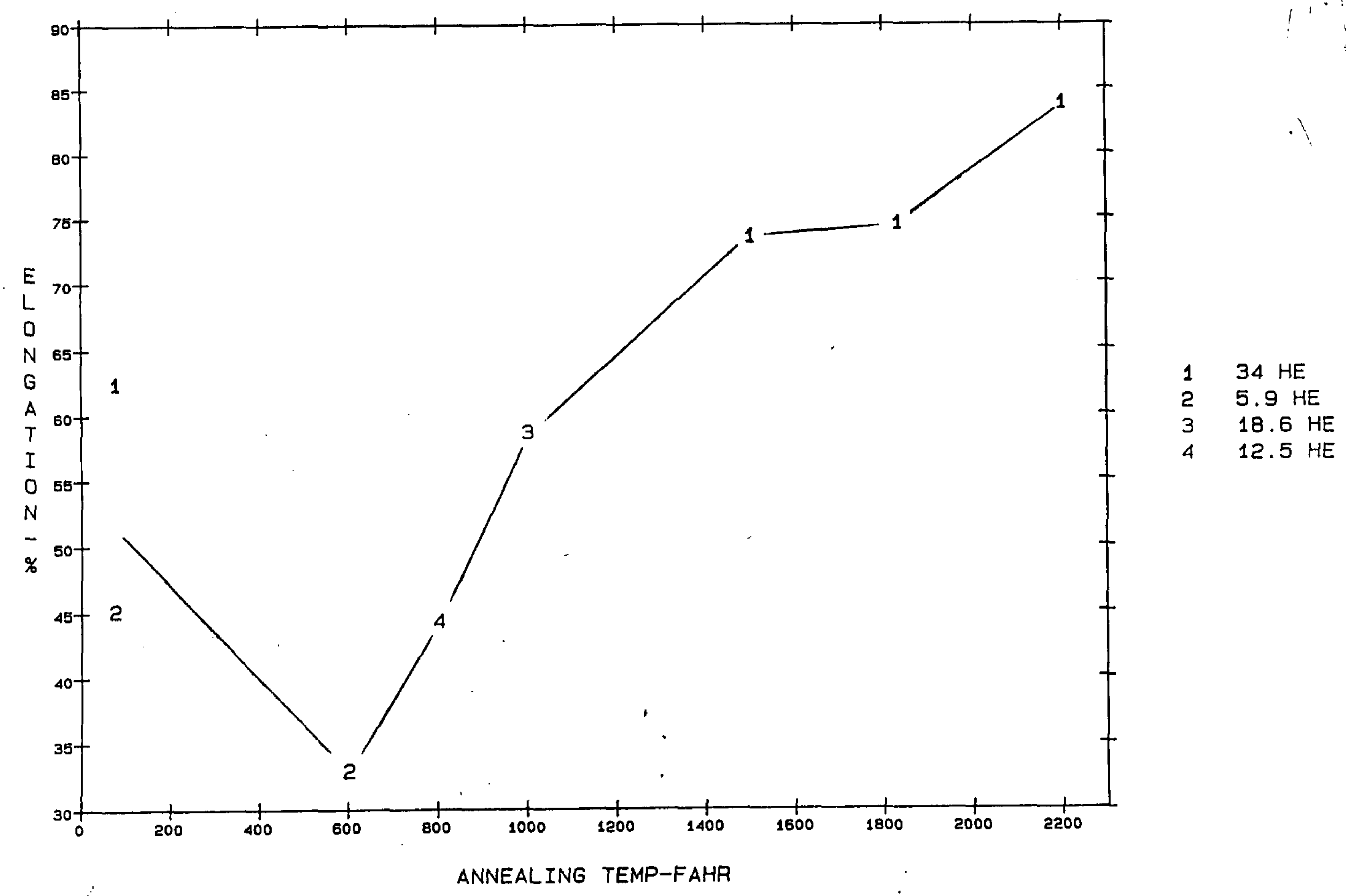


Slide 5 - Electron Microscopy of Helium Bubbles



Slide 5 - Electron Microscopy of Helium Bubbles

Slide 6 - Ductility After Post Irradiation Annealing



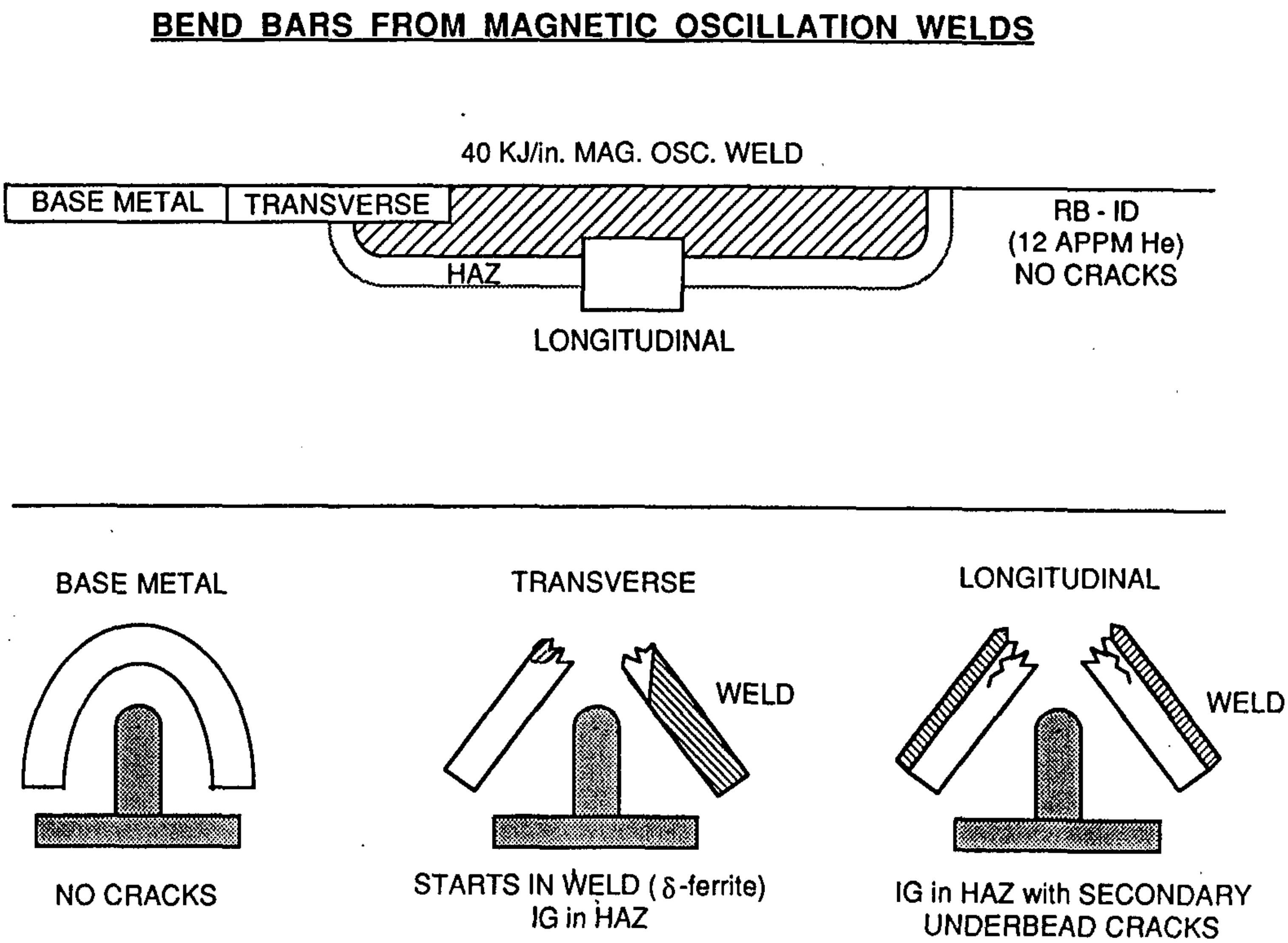
Slide 7 - Irradiated Fracture Toughness Test Results

IRRADIATED FRACTURE TOUGHNESS TEST RESULTS

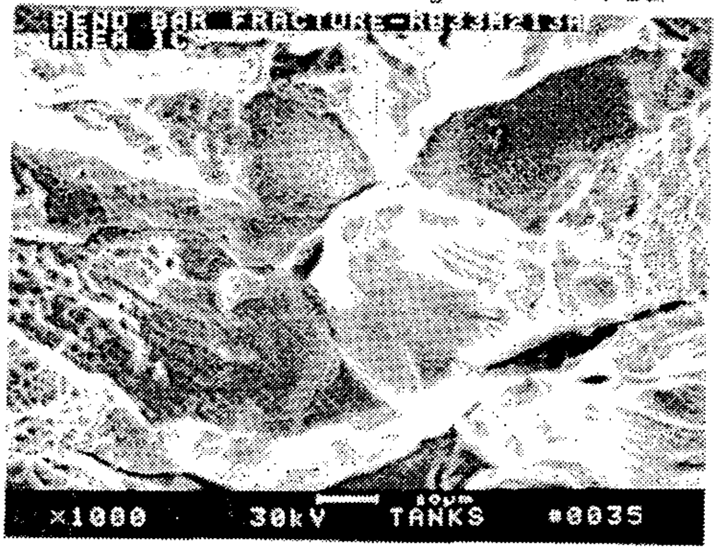
SPECIMEN	SIZE	HEAT TREATMENT	TEST TEMP.	J_{Ic} IN.-LB/IN.^{2}	TEARING MODULUS
RA37A	Large	No	RT	1663	117
RA38	Large	No	RT	1552	127
RD37	Large	No	125°C	1734	124
RD39	Large	No	125°C	1458	126
RD314	Small	No	125°C	1177	80
RD313	Small	No	125°C	895	113
RD315	Small	15 min @ 816°C	125°C	2490	117
RD320	Small	No	816°C	NIL	NIL

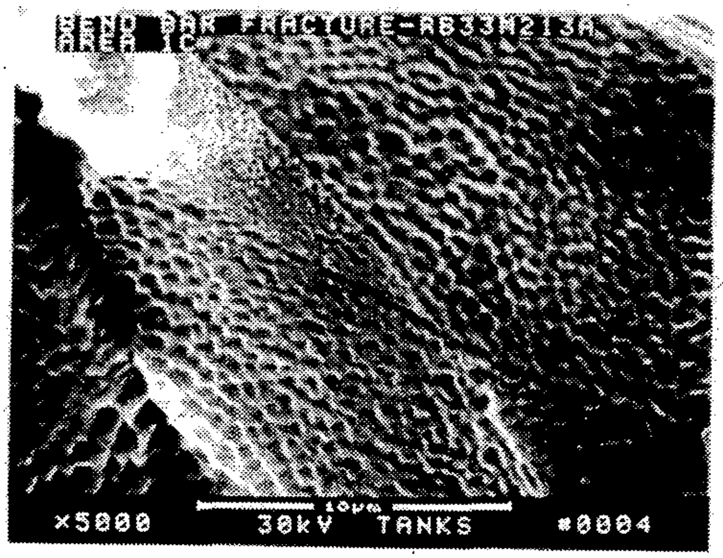
akb.11

Slide 8 - Bend Bars From Magnetic Oscillation Welds



Slide 9 - Fracture Surface From Longitudinal Bend Bar





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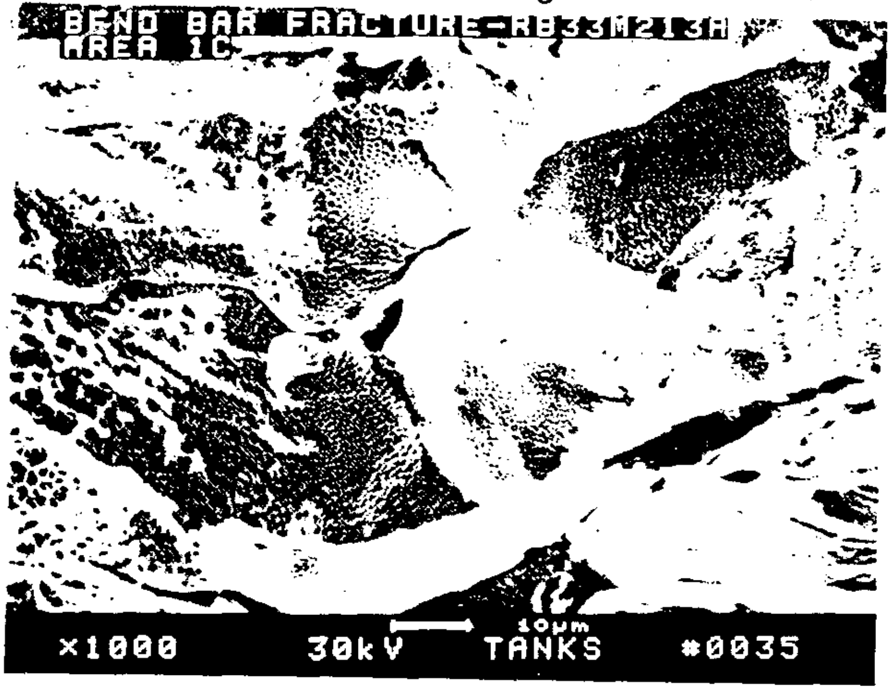
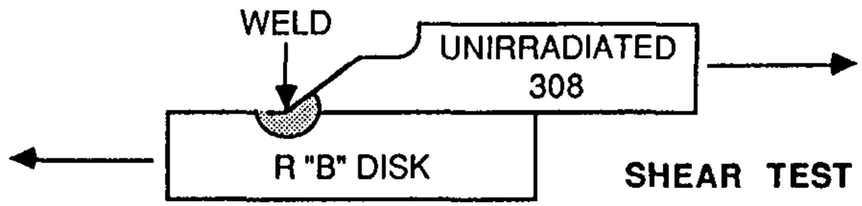


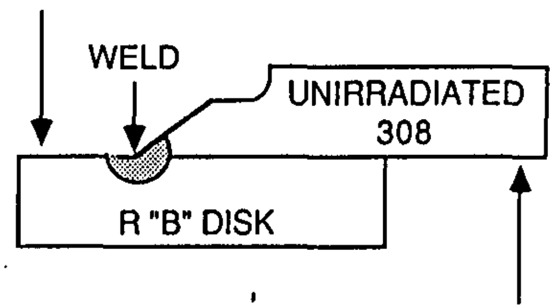
Slide 10 - Shear/Peel Test

SHEAR / PEEL TEST

JOIN SIMULATED PATCH TO R DISK USING MAGNETIC OSCILLATION WELD

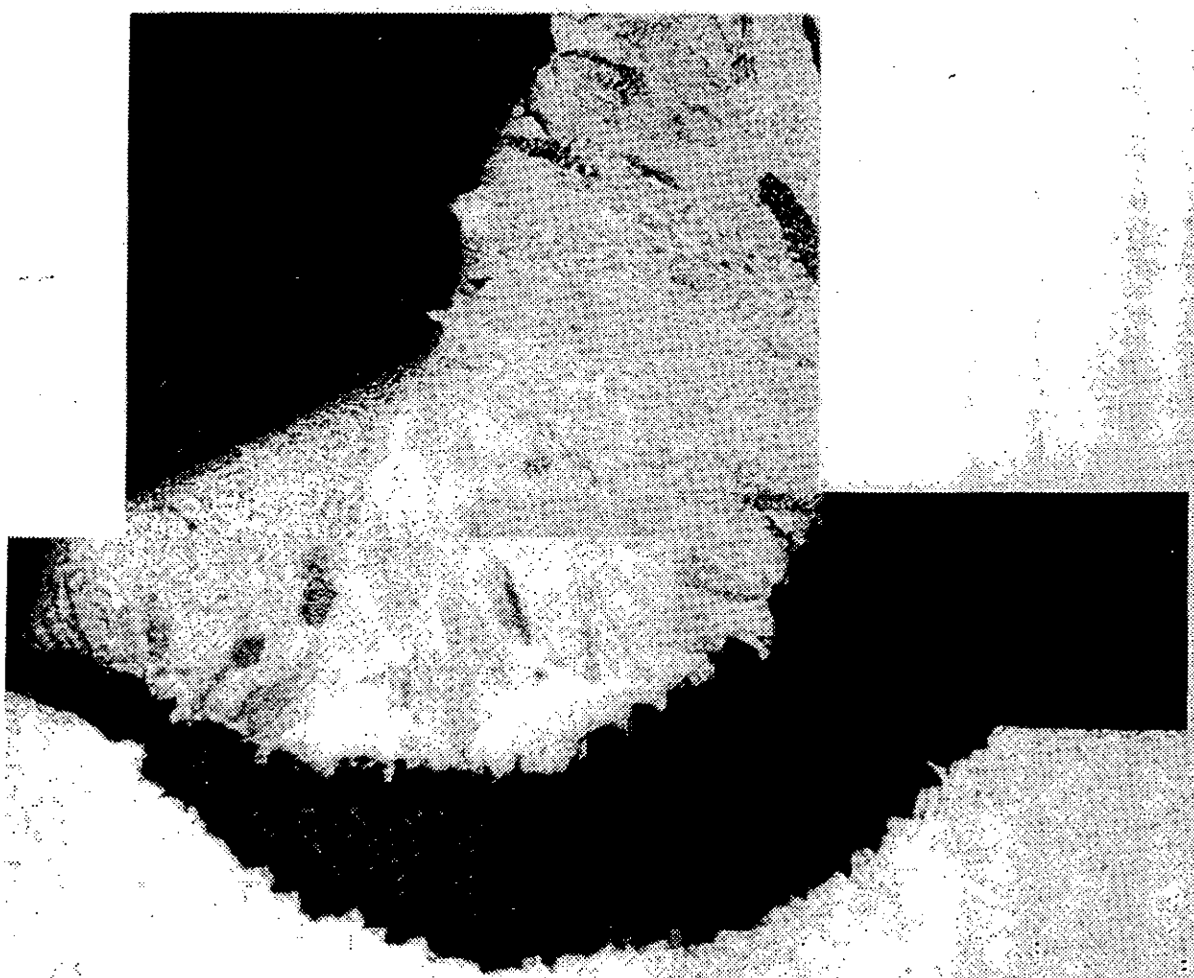


SHEAR TEST



PEEL TEST

Slide 11 - Shear/Peel Test Heat-Affected Zone Failure



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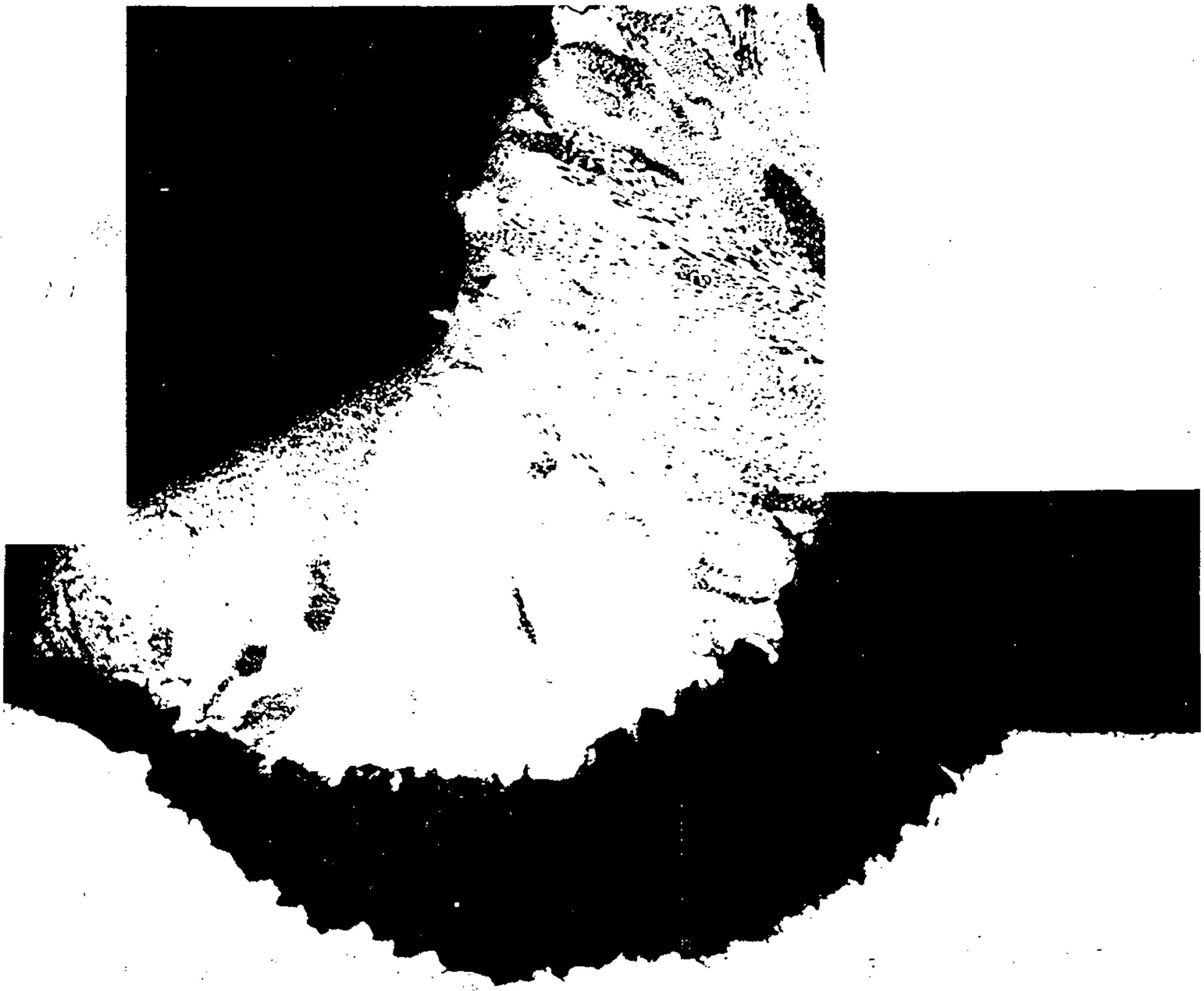
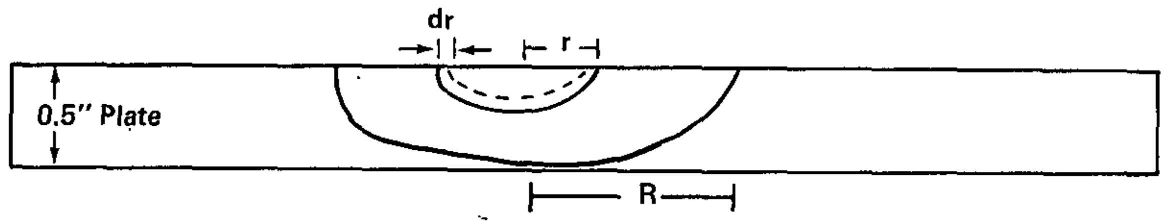


Slide 12 -Model of Bead-on-Plate Welds

Model of Bead-on-Plate Welds



- Approximate Weld as a Half Cylinder
- Allow Weld to Shrink Radially

Volume of Weld = $\frac{\pi}{2} r^2 L$

$\frac{\Delta V}{V}$ = Volume Change on Solidification ≈ 3% from Casting

$$= \frac{\pi r L dr}{\frac{\pi}{2} r^2 L} \Rightarrow \boxed{dr = \frac{r}{2}\left(\frac{\Delta V}{V}\right)}$$

- To Minimize HAZ Strain, Minimize Penetration Depth

For Penetration of r = 0.2" and R = 0.3"

dr = 0.003" Strain = $\frac{dr}{R}$ = 1 %

Slide 13 - Projected Helium Concentration Limits for Welding

Projected Helium Concentration Limits for Welding