APPENDIX B

THE EFFECTS OF ROLLER EXPANDING SLEEVES
INSIDE OTSG TUBES AFFECTED BY INTERGRANULAR CORROSION

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RESEARCH AND DEVELOPMENT DIVISION
LYNCHBURG RESEARCH CENTER

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LYNCHBURG RESEARCH CENTER
LYNCHBURG, VIRGINIA

THE EFFECTS OF ROLLER EXPANDING SLEEVES INSIDE OTSG TUBES AFFECTED BY INTERGRANULAR CORROSION

By: S. C. Inman

PROJECT SUMMARY

The purpose of this project was to determine the effects of mechanically expanding a sleeve inside an Alloy 600 OTSG tube containing shallow intergranular attack (IGA) on the outer surface. Tube samples with existing IGA were sleeved and then destructively examined using metallography and scanning electron microscopy. Results showed that the sleeve installation process induces plastic strain on the tube, causing deteriorated grain boundaries to open in the direction of highest tensile stress. No radial propagation of grain boundaries into the tubewall was observed on samples ,

a considerable margin is provided for sleeve installation in Arkansas Nuclear One Unit 1 steam generator tubing.

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Project Sponsored by Arkansas Power & Light

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1. INTRODUCTION

Steam generator (SG) tubing in the Arkansas Nuclear One Unit 1 (ANO-1) power plant has experienced secondary side corrosion in the form of intergranular attack (IGA) within the upper tubesheet crevice region.[1] This has resulted in the plugging of a number of tubes. In addition, shallow IGA has been identified on the tubing outer surfaces in the upper spans. Babcock and Wilcox (B&W) has proposed to the plant owner, Arkansas Power and Light (AP&L), that a mechanically rolled sleeve be used to extend the life of tubes exhibiting pluggable eddy current indications. The rolled sleeve technique utilizes a roller expander to expand the sleeve against the inner surface of the tube in a freespan region. Since the tubes are stressed in the hoop and axial directions due to the expansion, the question was raised as to whether radial propagation occurred to the existing shallow IGA. This program was therefore initiated to answer this question.

1.1 OBJECTIVE

The objective of this program was to determine whether the roller expansion process causes propagation of existing IGA damage present on the tubes. Sleeves were installed into three samples of tubing which were removed from an OTSG at ANO-1 in late 1982. Control specimens were sectioned from either end of the tube samples prior to sleeve installation to determine the amount of IGA present. A series of examinations including eddy current testing, diameter measurements, metallography, and scanning electron microscopy were used to characterize the effects of sleeve installation on the existing IGA. This report documents the results of this project, followed by recommendations concerning the roller expansion process.

2.0 METHODS AND RESULTS

2.1 SAMPLE PREPARATION

Three 7-inch samples were selected from tubes B73-8 and B112-19 which were in storage at the B&W Lynchburg Research Center (LRC). Sample designations and their origin are listed below:

Tube Sample Number	Origin*
B73-8-3RET	Tube B73-8 piece 3, 33 to 40 inches
B73-8-3REB	Tube B73-8 piece 3, 40 to 47 inches
B112-19-2RE	Tube B112-19 piece 2, 11-3/4 to 18-3/4 inches

*Axial location, referenced from top of tubesheet.

A 1/2-inch ring was cut from both ends of each tube sample to be used as control specimens.

Personnel from the B&W Special Products and Integrated Field Services (SP&IS) department installed a sleeve inside each tube sample at the LRC using the procedure qualified during the sleeve qualification project.[2] The procedure and data sheets are contained in Appendix A.

- - Diameter values are discussed in detail in Sections 2.3 and 2.4. Figure 2-1 shows the sleeved tube sample configuration and photographs of each sample are shown in Figure 2-2.

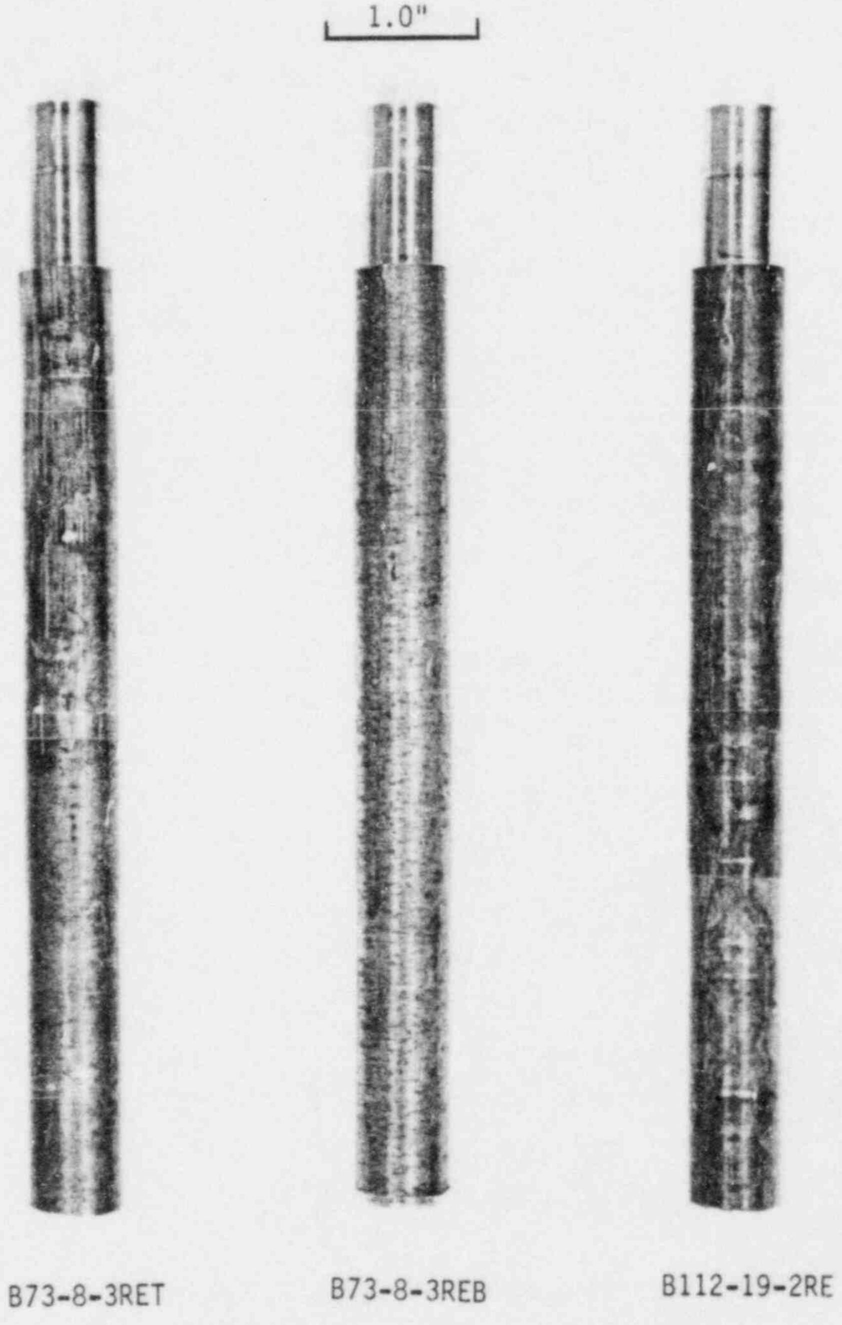


Figure 2-2. Photographs of Sleeved Tube Samples

2.2 EDDY CURRENT TESTING

Each tube sample and sleeve were eddy current inspected prior to and after sleeve installation by personnel of the SP&IS department. Details of the equipment and inspection parameters are contained in Appendix B.

Two anomalous signals were observed on the inside diameter (ID) of sample B73-8-3RET and a small ding was observed in B73-8-3REB. The anomalous signals were most likely related to the ID decrease over a 4-inch length, which was measured on the inside and outside diameters during the 1983 tube examination.(1) The ding may have been due to inadvertent handling damage to the tube and was not measured previously. After sleeve installation, one anomalous signal was again observed in sample B73-8-3RET, while the other tube samples and all sleeves were free of indications.

In summary, no significant through-wall defect indications were observed during the eddy current inspection of the tube samples and sleeves either before or after sleeve installation. In addition, no indications of shallow IGA was observed on the tube outer surfaces.

2.3 DIAMETER MEASUREMENTS

Inside and outside diameter (ID and OD) measurements were taken on the tube samples and sleeves prior to and after sleeve installation. An Intrimik (three point contact) was used to measure the ID, while a dial caliper and laser telemetric system were used on the OD. Measurements were taken at the locations of roll transitions and roll centers as designated in Figure 2-1. Diameter data and other pertinent calculated values are listed in Table 2-1.

Columns 1-7 are data obtained prior to sleeve installation. The sleeves were all fairly uniform size;

The tube samples, on the other hand, varied between 0.529-and 0.552-inch on the ID and 0.601-and 0.629-inch on the OD. Both tube samples from OTSG tube B73-8 were unintentionally selected from a region of the tube which was below the specification minimum ID value of 0.542-inch.[2] Sample B112-19-2RE had diameters within the specified range.

In an attempt to obtain a better diameter representation after sleeving, the ID was measured at the 0 and 60° orientations and the OD at 0, 45, 90, and 135° orientations. These data were averaged and are listed in columns 8 and 10 in the table. The increases in sleeve ID and tube OD due to sleeve installation are listed in columns 9 and 11, respectively. Of principle interest are the increases in the rolled regions, locations C1 and C2. As expected, the maximum increases occurred on the sleeve ID in the rolled regions

Three OD decrease values were calculated at lower transition regions and were due to either slight variations in measurement location (and/or technique) or an inward displacement of tube material due to the rolling operation.

2.4 STRAIN CALCULATIONS

By dividing the ΔID values in columns 9 and 11 by the initial measurements in columns 1 and 5, the amount of hoop strain induced on the sleeve inner and

tube outer surfaces were calculated. These values are listed as percent strain in columns 13 and 14 on Table 2-1.

Shown in Figure 2-3 is a stress-strain curve for Alloy 600 material thermally treated similar to that which a tube experiences during OTSG manufacture. Since plastic strain occurs above approximately 0.35 percent, strain values experienced by the sleeve and tube samples were well into the plastic regime.

Tube outer surface strain values are shown plotted as a function of gap in Figure 2-4 for each tube sample. These data indicate that the tube samples with the larger values of initial tube-to-sleeve gap were subjected to smaller amounts of strain on the tube outer surface, and vice versa.

This plot includes data on hypothetical situations of strain values which would not occur in situ and, therefore, is provided for information purposes only.

2.5 SECTIONING

Specimens were sectioned from each sleeved tube sample according to the diagram in Figure 2-5. This scheme was devised so that the center and one transition of each roll could be examined using both SEM and metallographic tech-

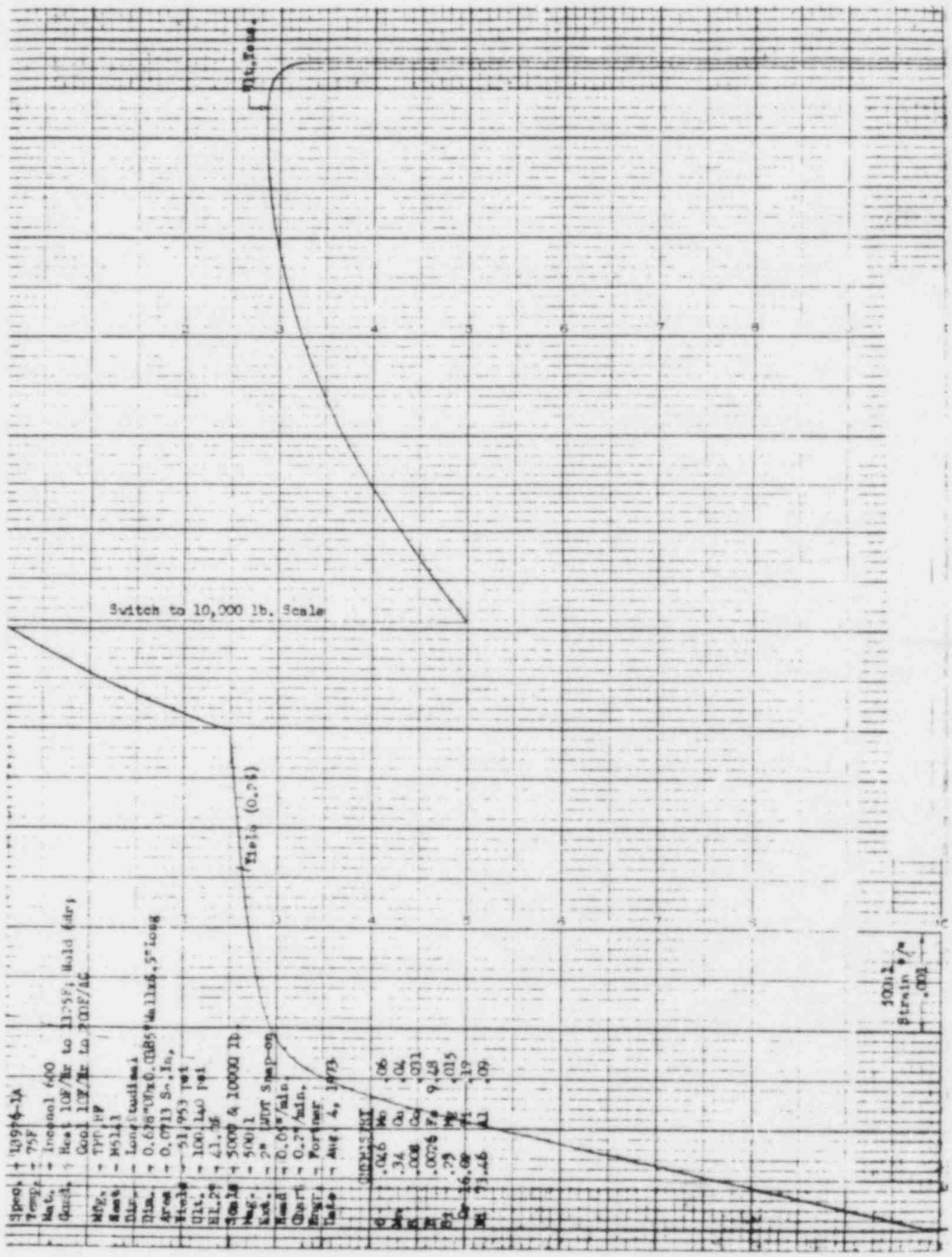


Figure 2-3. Stress-Strain Curve for OTSG Tubing

Table 2-2

LIST OF TUBE SPECIMENS AND EXAMINATION TECHNIQUE

Specimen Designation	Origin	Examination Technique Used: Metallography Longitudinal	Examination Technique Used: Metallography Transverse	SEM	Descale[1]	Bend[1]
Control Specimens						
CT-A	Top	X	X		X	X
CT-B						X
CB-A	Bottom	X	X		X	X
CB-B						X
Sleeved Tube Specimens						
UT-1	Upper Transition - Roll 1		X			
C-1	Center - Roll 1		X	X	X	
LT-1	Lower Transition - Roll 1	X		X		
UT-2	Upper Transition - Roll 2	X		X		
C-2	Center - Roll 2		X	X	X	
LT-2	Lower Transition - Roll 2		X			

[1] SEM used to examine specimens after descaling and bending.

niques. All sectioning was performed using a high speed abrasive cut-off saw and no allowances were made on the diagram for saw blade kerf. Control specimens obtained in Section 2.1 were longitudinally split in half so that both transverse and longitudinal cross sectional views could be obtained. Table 2-2 lists the specimen designation and the examination techniques used to examine them. The following sections of this report describe in detail these examinations.

2.6 METALLOGRAPHY

Standard laboratory practices were used to prepare and examine metallographic specimens. Two incremental grind-and-polish routines were performed on each specimen to obtain better representation of surface condition. Photomicrographs were taken at 200X at each increment to document the results. An 8:1 orthophosphoric acid electroetch was used to delineate grain boundaries.

Photomicrographs of the control specimens in the "as-received" condition were compared to those of the sleeved tube samples to determine the effects of the roll expansion on existing IGA.

2.6.1 Control Specimens

Transverse and longitudinal views were used to inspect each control specimen in the as-received condition. Typical photomicrographs of the outer surface of the control specimens from each tube sample are shown in Figures 2-7, 2-8, and 2-9. While no excessive IGA was observed on any specimen, grain boundary penetrations were present, to some extent, on each specimen. In all cases, penetrations were less than 0.001-inch in depth. During the 1983 tube examination, the shallow penetrations became more pronounced only after bending the specimens with the tube outer surface in tension.(1) Therefore, it is not expected that these unstressed control specimens would exhibit more than that observed previously. Additional characterization of the control specimens was performed using scanning electron microscopy and is presented in Section 2.7.1.

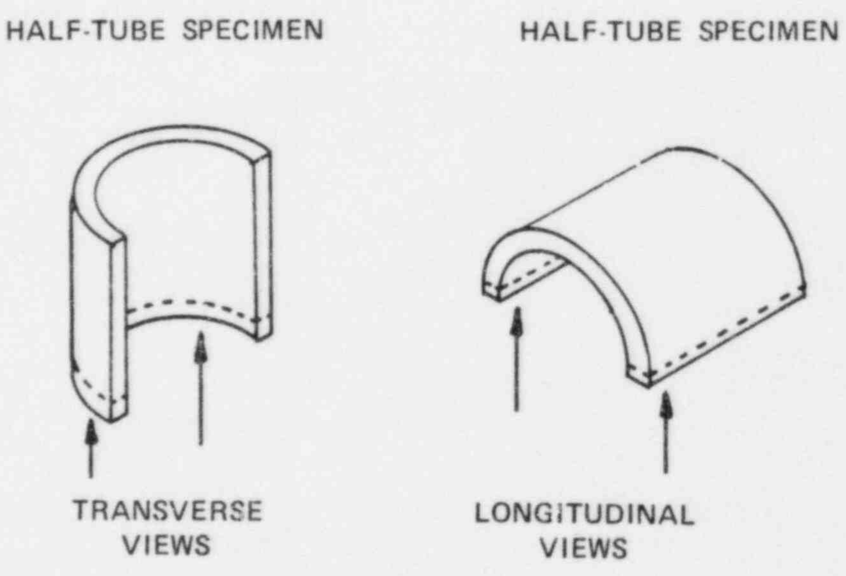


Figure 2-6. Metallograph Examination Techniques

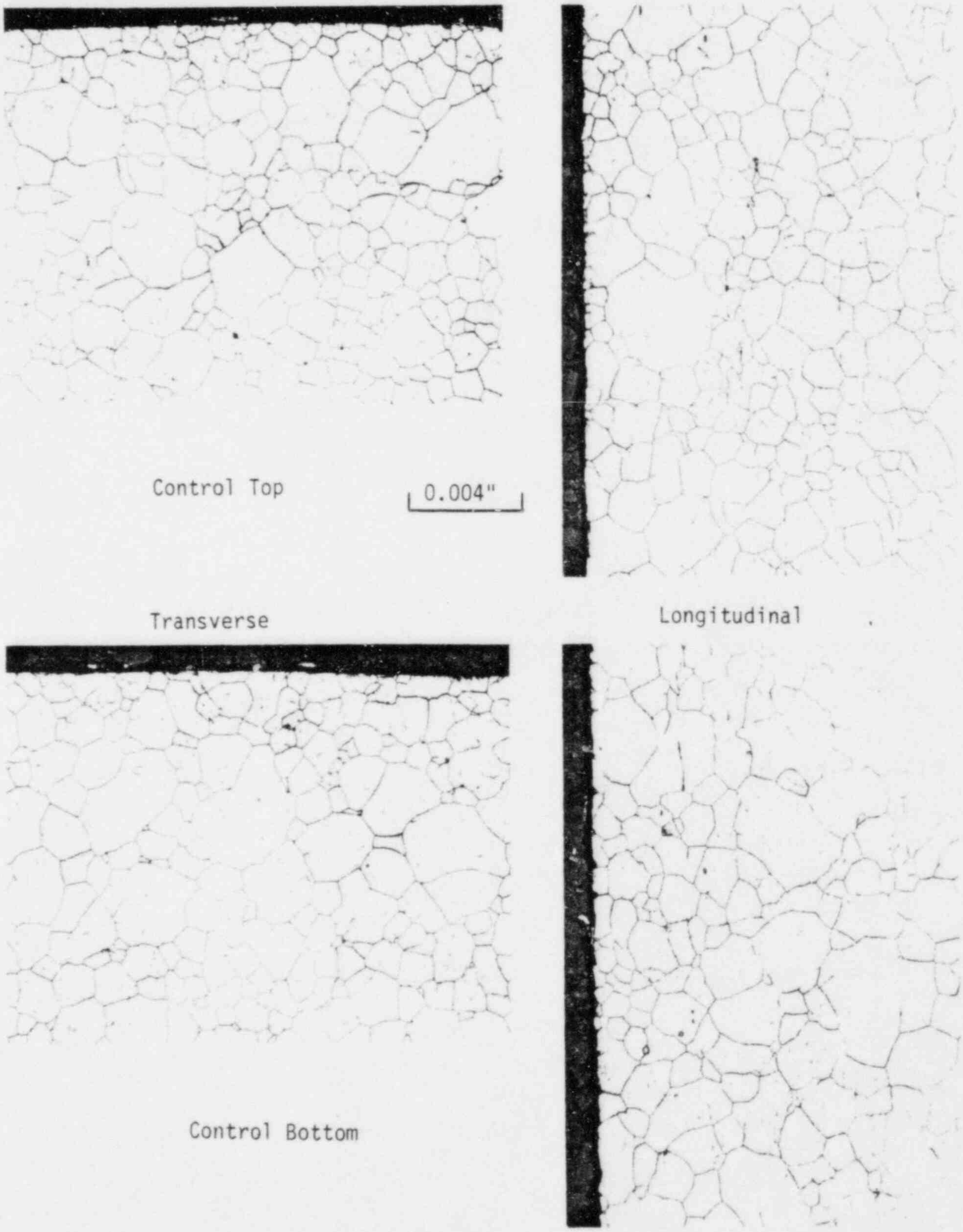


Figure 2-7. Photomicrographs of Tube Sample B73-8-3RET Control Specimens - Outer Surface

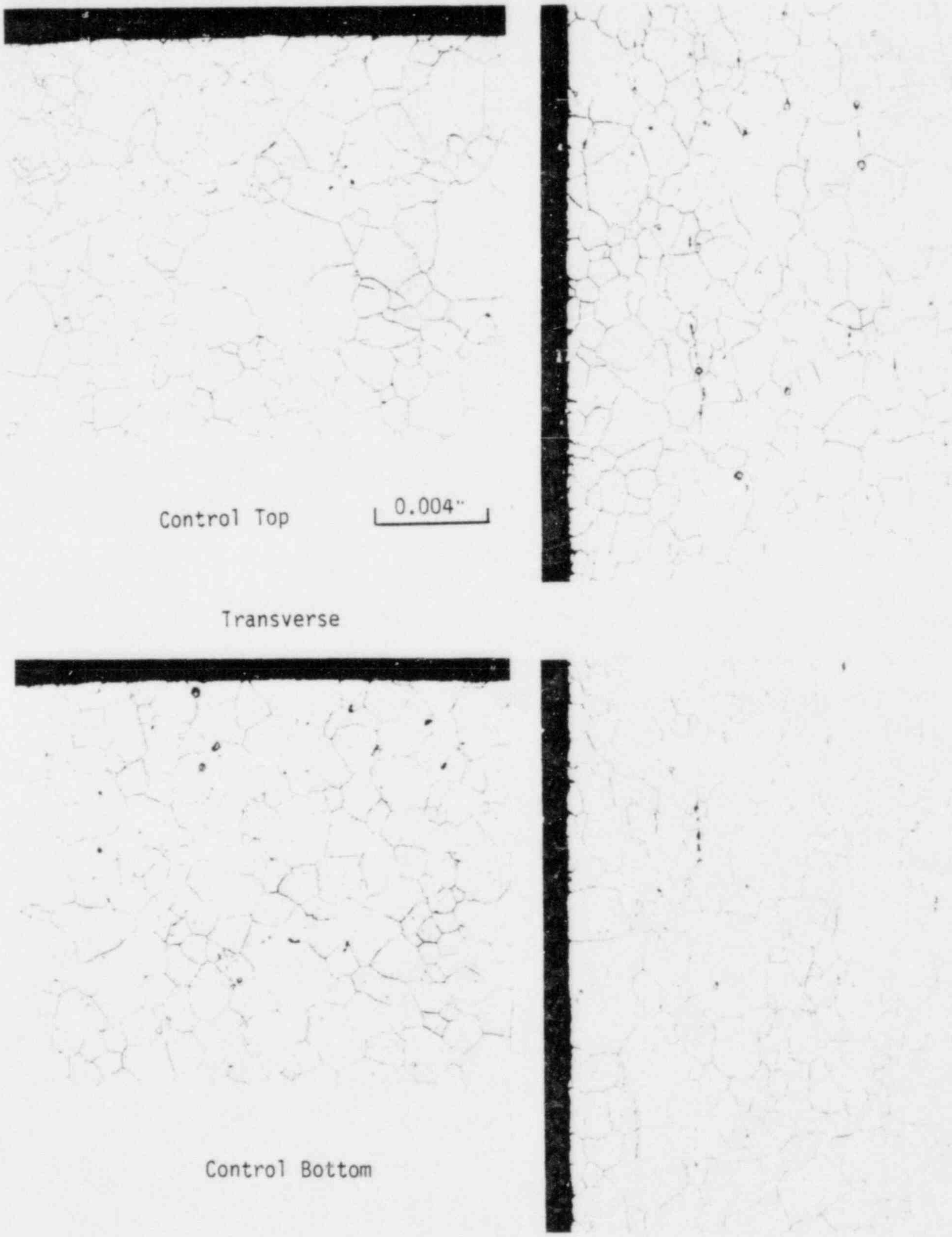


Figure 2-8. Photomicrographs of Tube Sample B73-8-3REB Control Specimens - Outer Surface

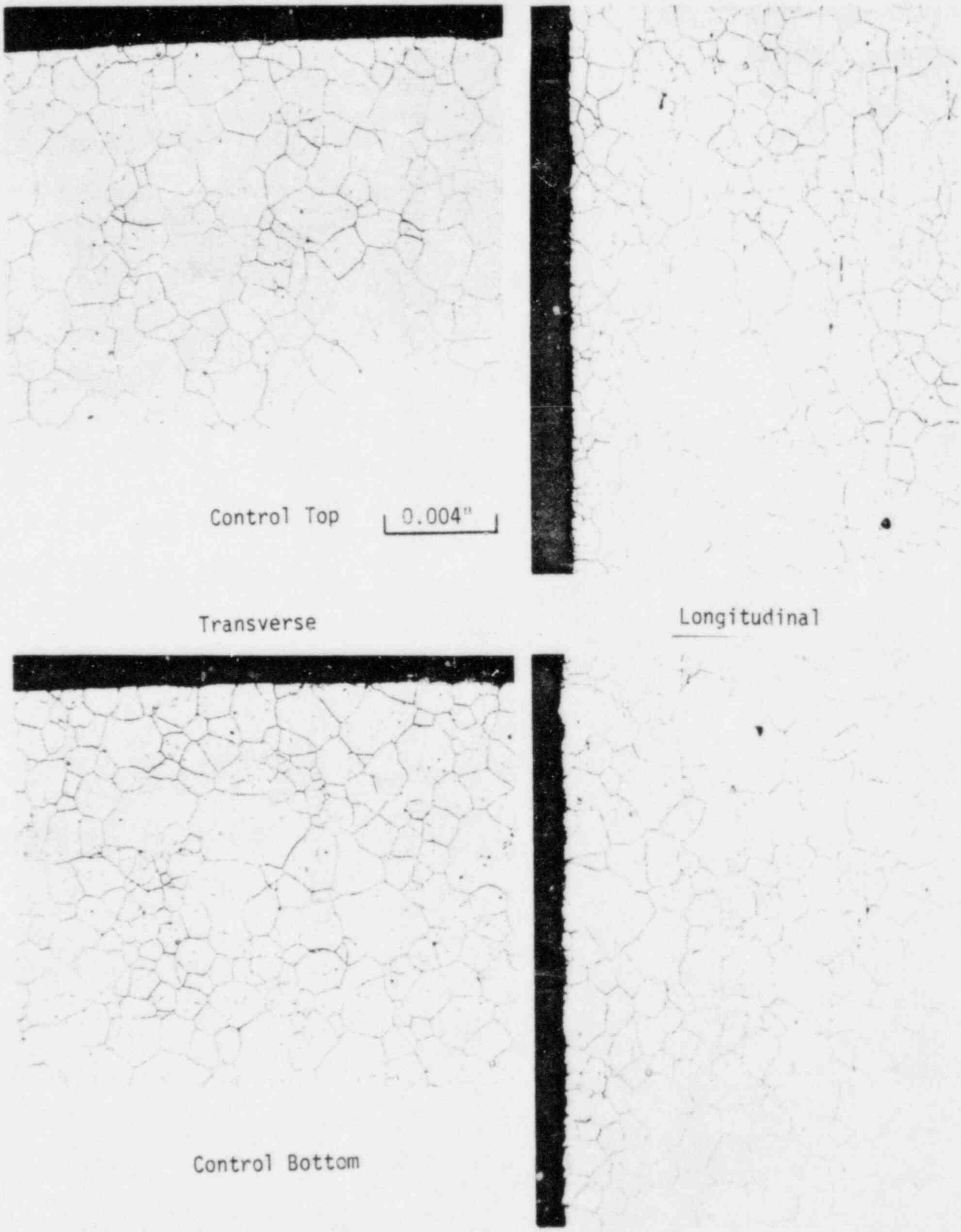


Figure 2-9. Photomicrographs of Tube Sample BII2-19-2RE Control Specimens - Outer Surface

Shown in Figure 2-10 are typical photomicrographs of the inner surface of the control specimens depicting the mill-pickled condition of the tubes. Grain boundary penetrations of approximately 1 grain diameter or less were present on each specimen.

2.6.2 Sleeved Tube Specimens

2.6.2.1 Roll Centers. Transverse photomicrographs taken of the outer surface of the roll center regions are shown in Figures 2-11 through 2-16. Upon comparing these photomicrographs to those from the control specimens, no measurable amount of grain boundary inward radial propagation was observed. A slight amount of grain boundary opening in the circumferential direction, however, was observed on specimens from tube samples B73-8-3RET and B73-8-3REB, Specimens from tube sample B112-19-2RE were the photomicrographs in Figures 2-15 and 2-16 of which exhibited little, if any, difference in grain boundary opening compared to those of the control specimens shown in Figure 2-9.

Figures 2-12 and 2-16 also include photomicrographs of the sleeve inner surface showing the cold-worked layer caused by the rollers contacting the sleeve during sleeve installation.

2.6.2.2 Roll Transitions.

Longitudinal photomicrographs were taken in the rolled and unrolled regions of each roll transi-

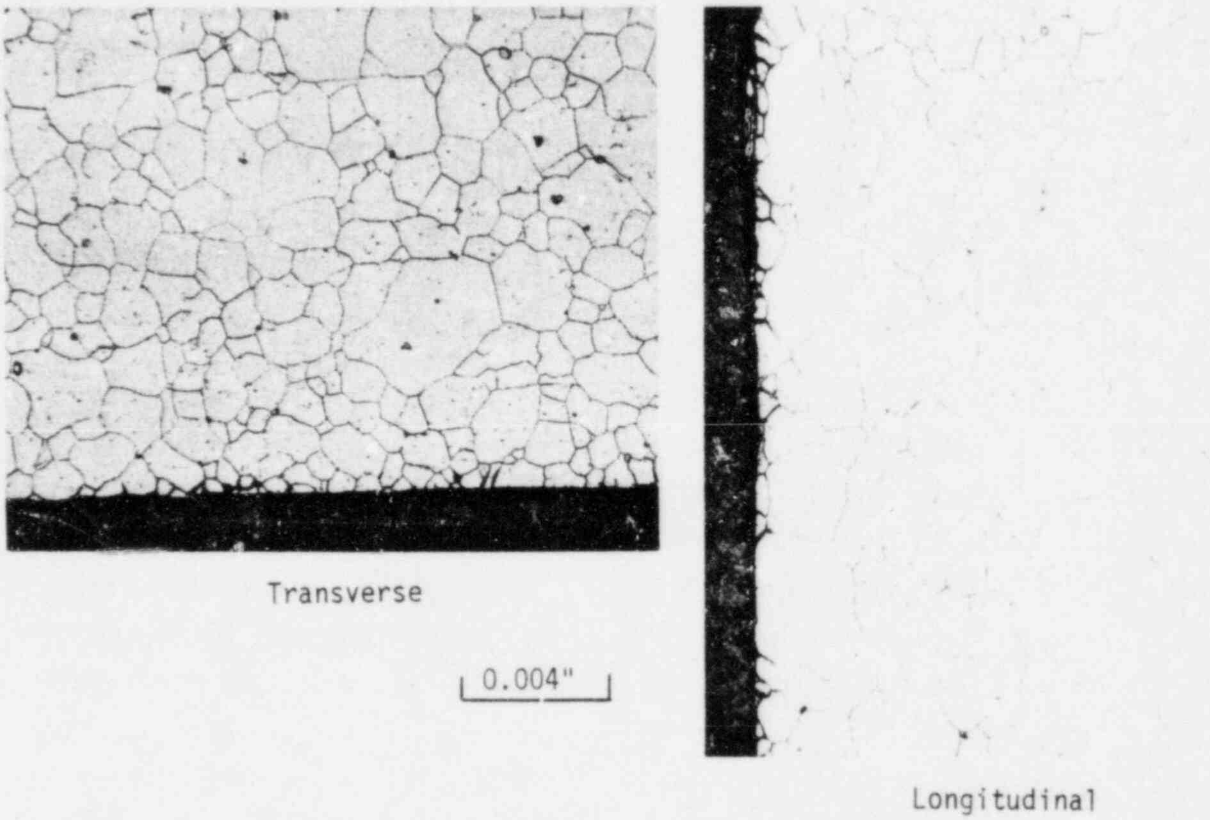


Figure 2-10. Typical Photomicrographs of Control Specimen Inner Surface

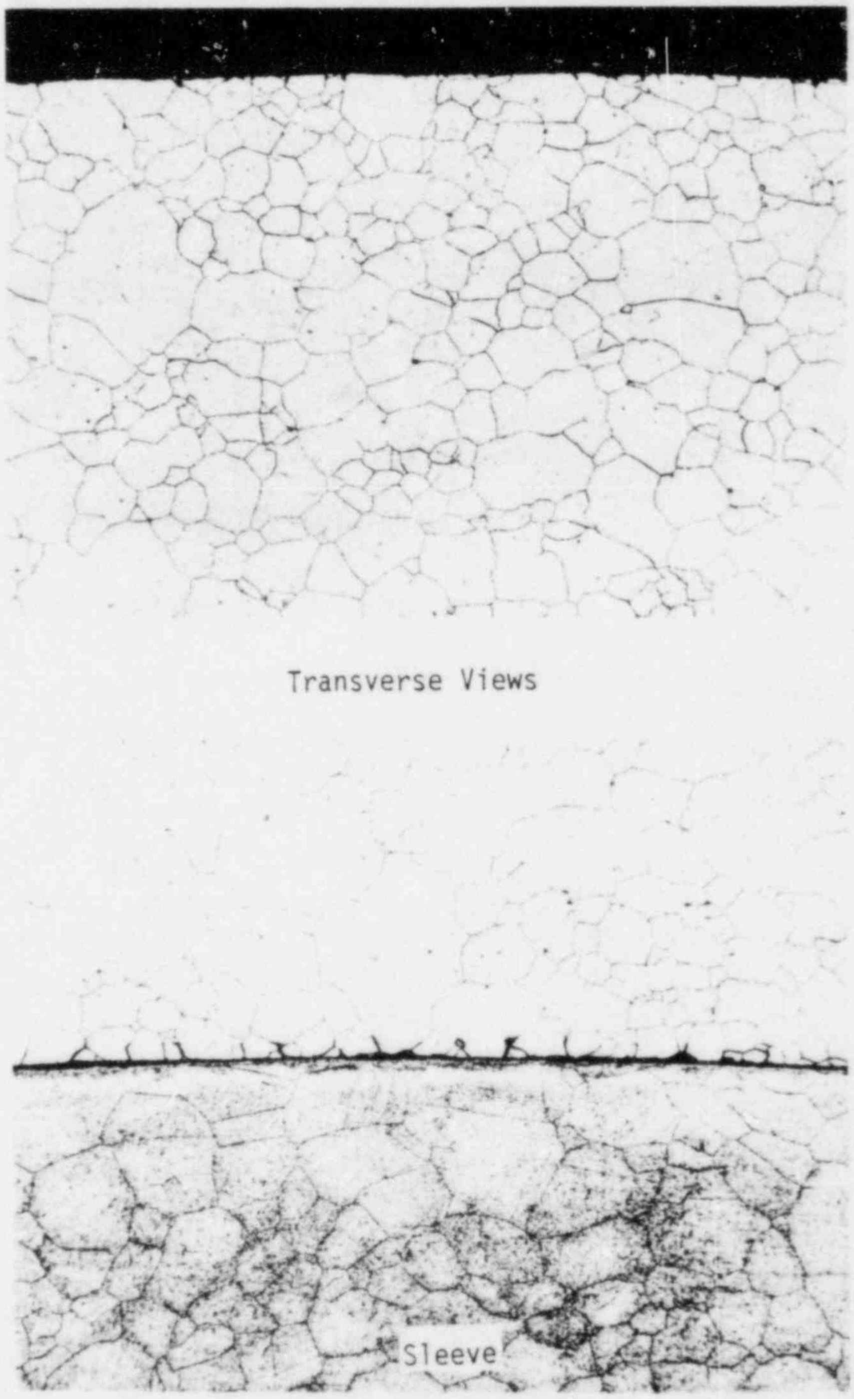


Figure 2-11. Photomicrographs of Tube Sample B73-8-3RET Specimen C-1

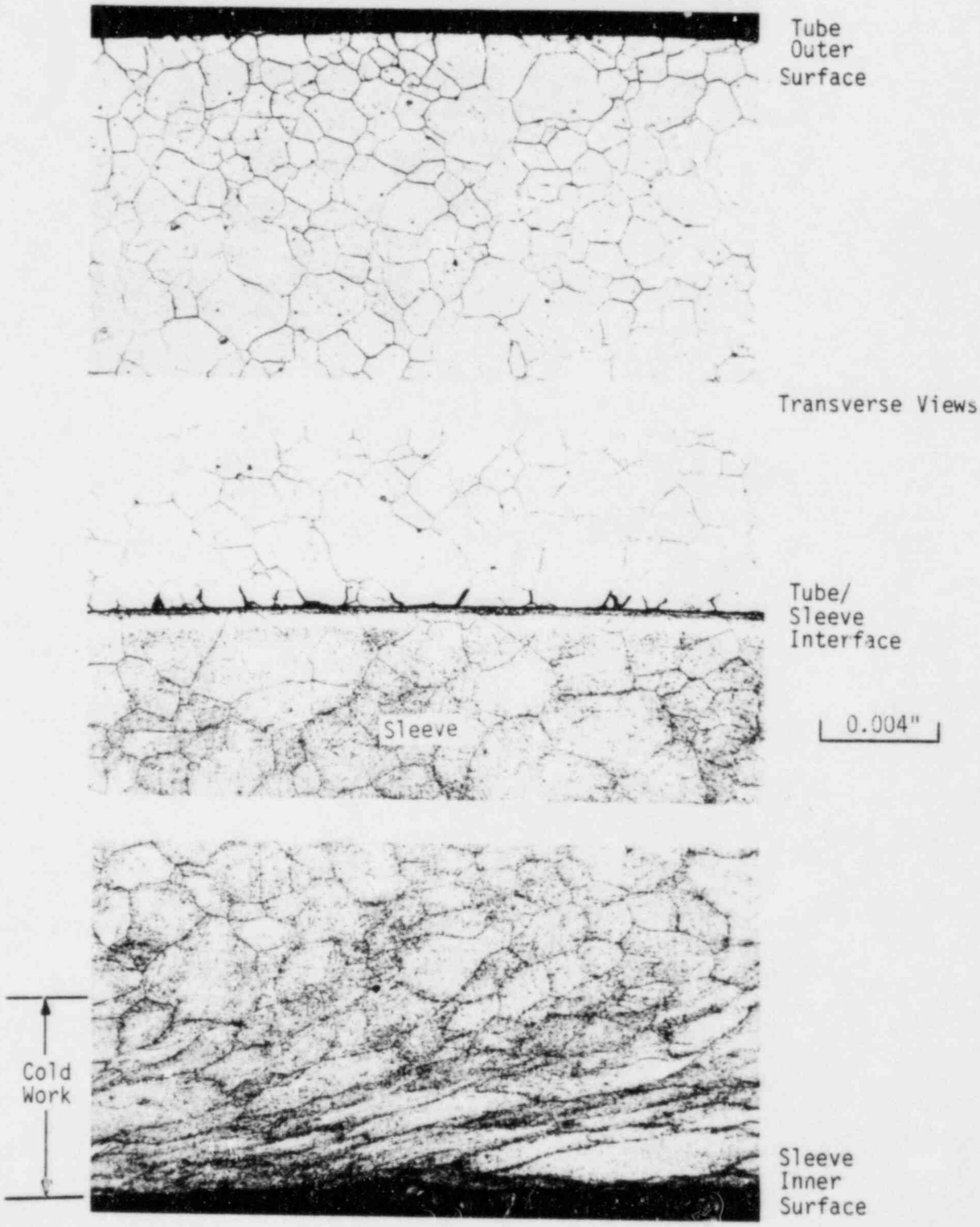


Figure 2-12. Photomicrographs of Tube Sample B73-8-3RET Specimen C-2

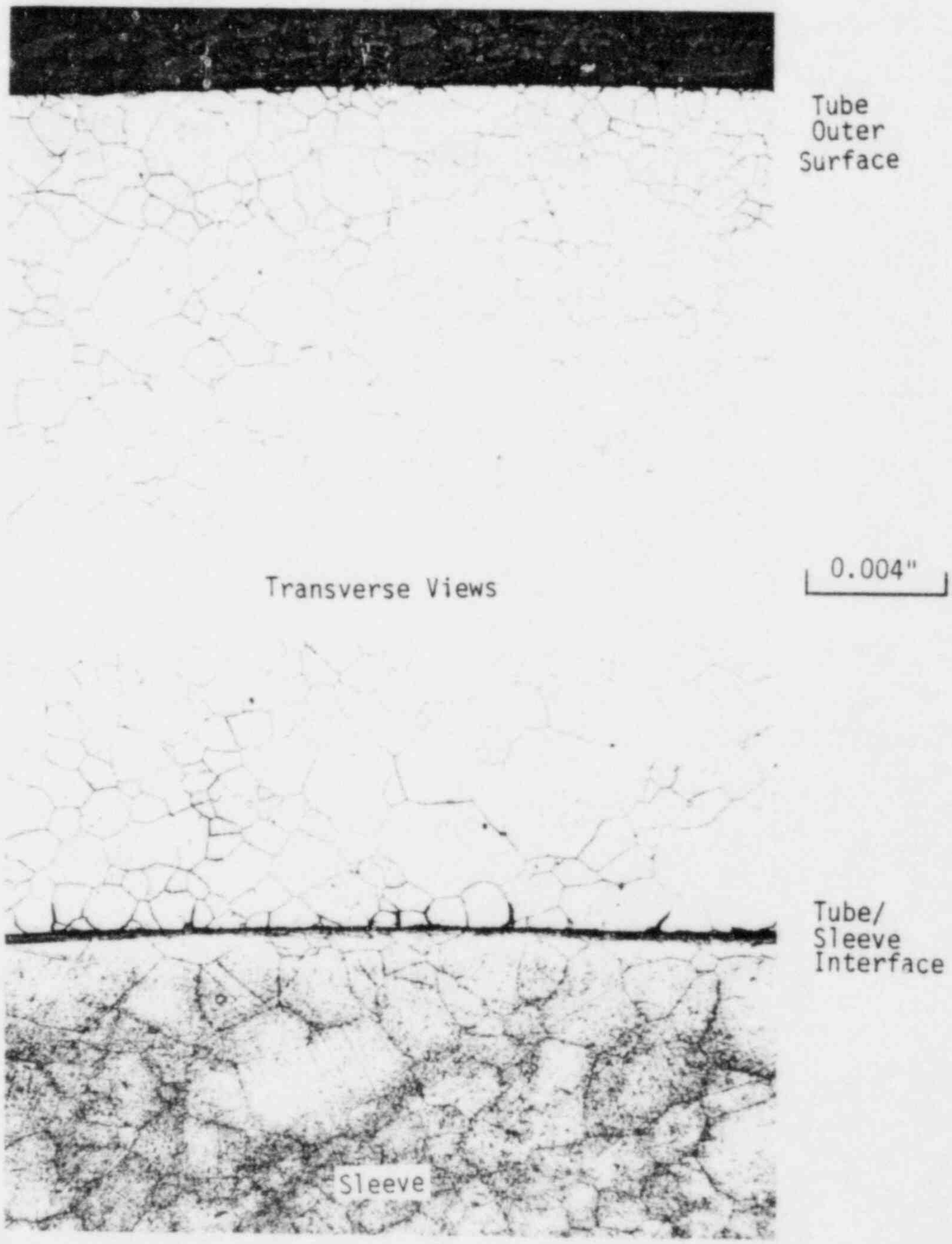


Figure 2-13. Photomicrographs of Tube Sample B73-8-3REB Specimen C-1

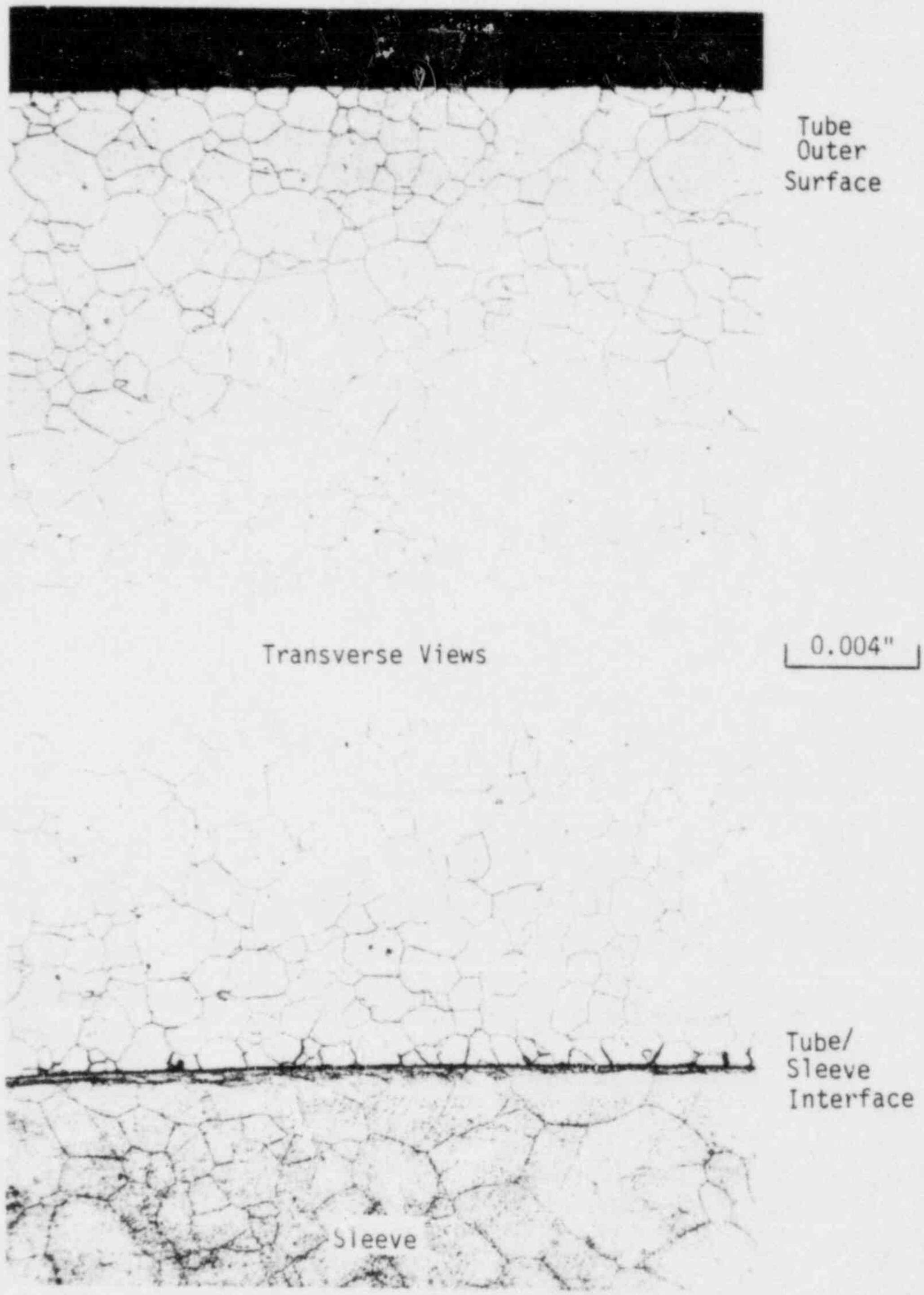


Figure 2-14. Photomicrographs of Tube Sample B73-8-3REB Specimen C-2

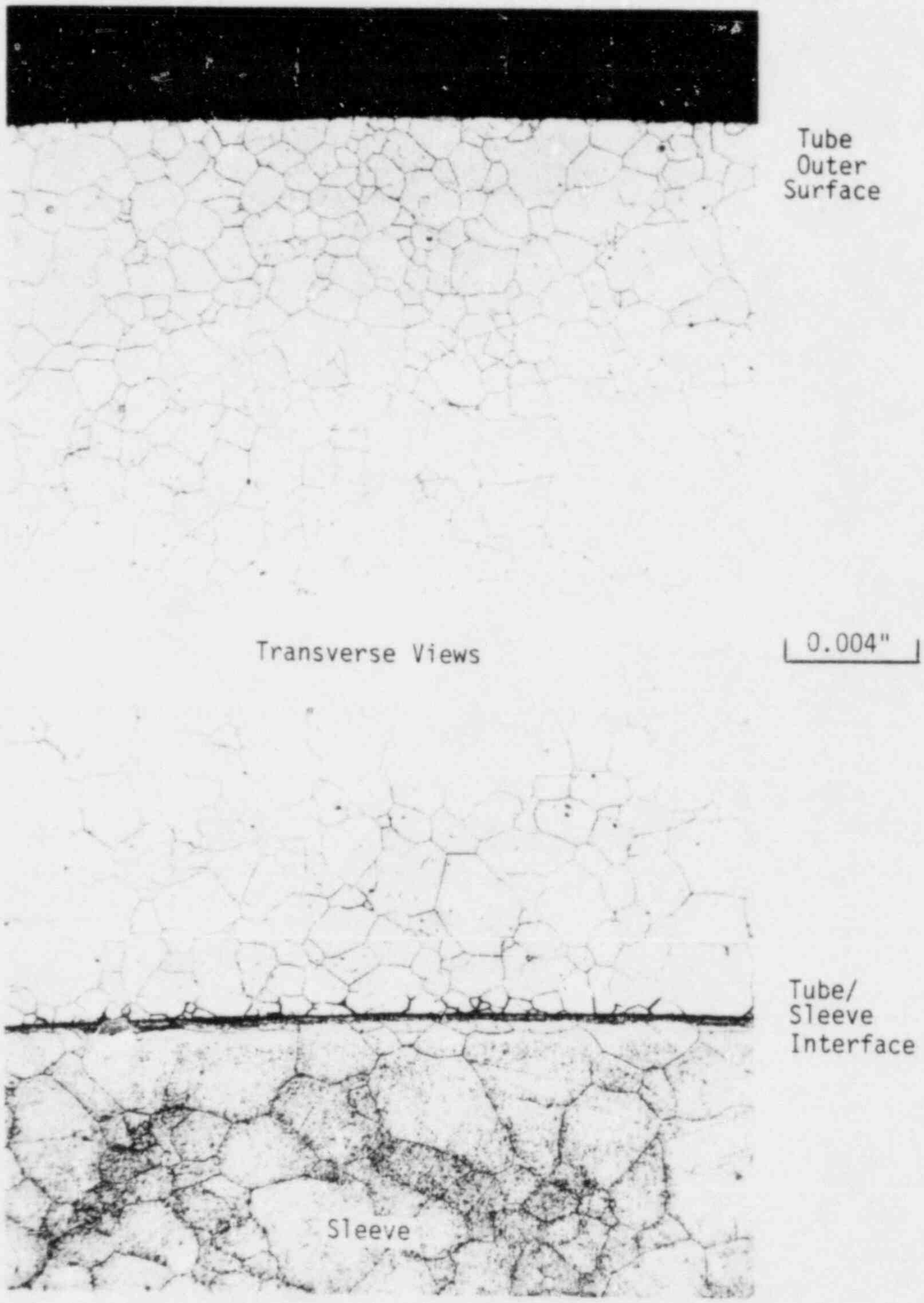


Figure 2-15. Photomicrographs of Tube Sample B112-10-2RE Specimen C-1

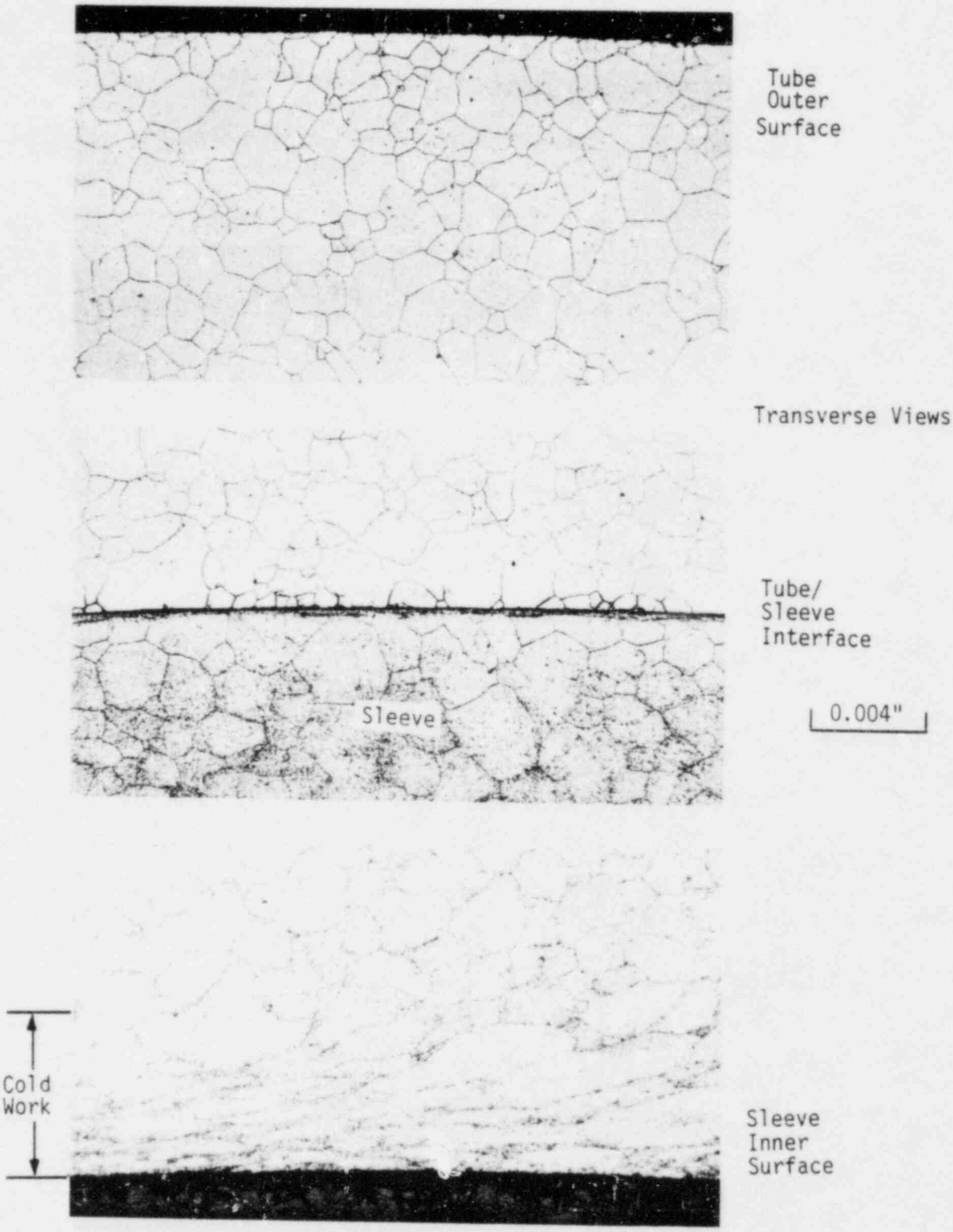


Figure 2-16. Photomicrographs of Tube Sample B112-19-2RE Specimen C-2

tion specimen and are shown in Figure 2-17, 2-18, and 2-19. The results were consistent with those observed previously in the roll centers; i.e., higher strains resulted in more grain boundary separation. The unrolled regions of specimens LT-1 and UT-2 from sample B73-8-3RET (shown in Figure 2-17) exhibited the most obvious axial separation due to the higher hoop strain values in the roll center regions. Little, if any, separation was observed on specimens from tube samples B73-8-3REB and B112-19-2RE.

An unrolled region adjacent to each roll was examined transversely to detect any circumferential grain boundary opening which may have occurred. The photomicrographs looked identical to those of the control specimens, indicating that no separation occurred in this region. The photomicrographs are not included in the report to prevent redundancy.

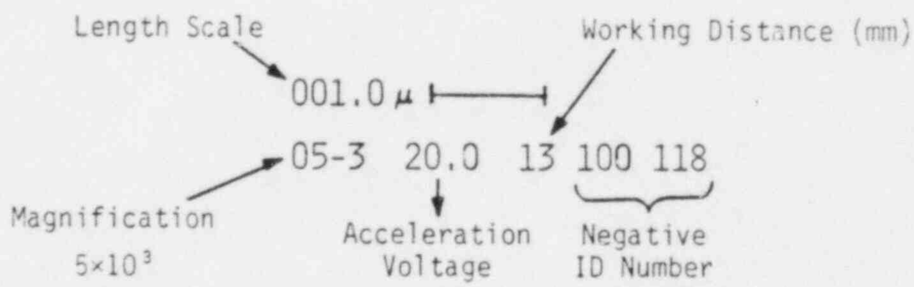
2.7 SCANNING ELECTRON MICROSCOPY

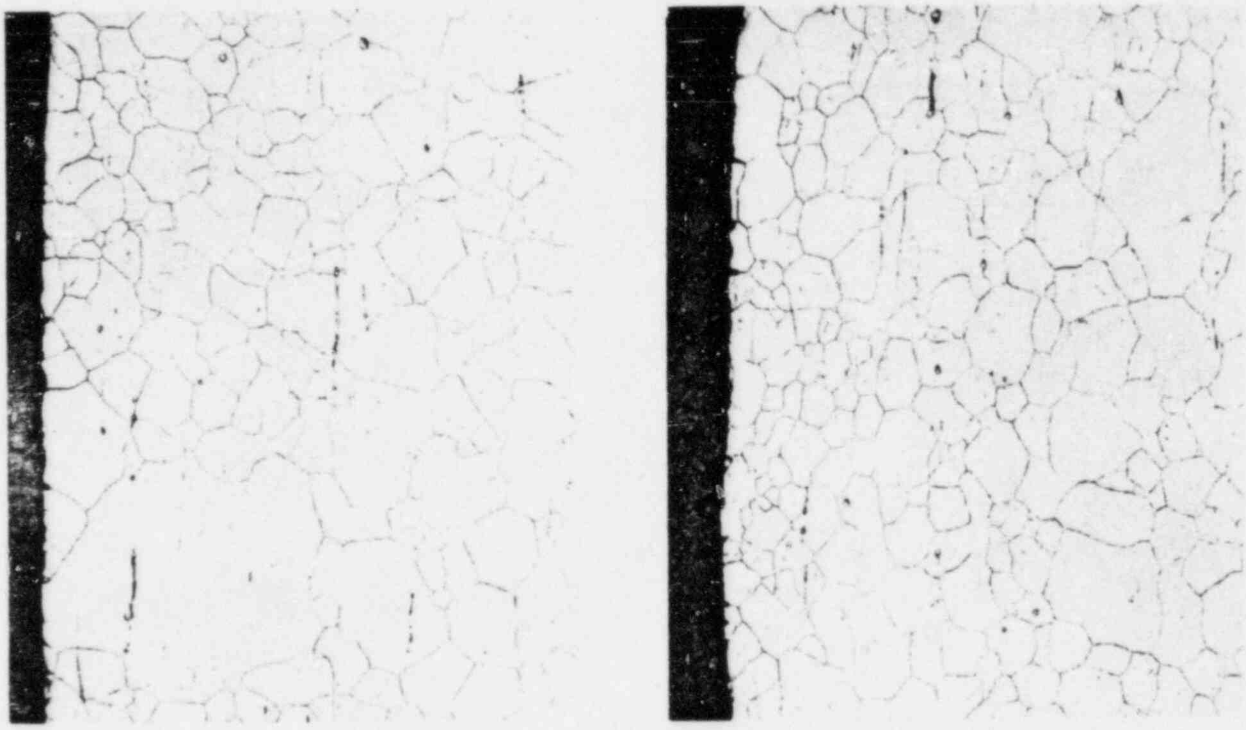
Control specimens and specimens from each sleeved tube sample were examined on the outer surface at high magnifications using an ETEC Autoscan microscope* at the intervals of descaling and bending (see Table 2-2). Results are presented in the same format as was used previously in Section 2.6, i.e., each type specimen described separately.

- - - - -

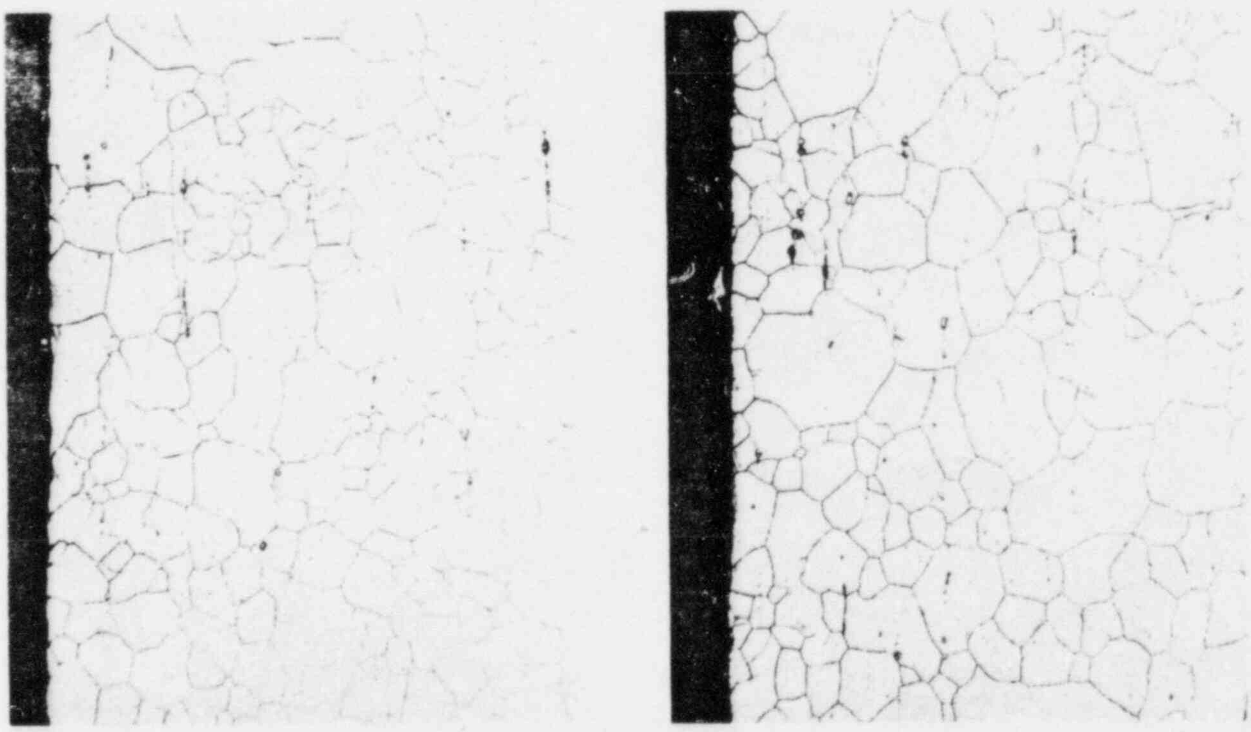
*The ETEC Autoscan microscope used automatically records pertinent data on the micrographs.

Example:





LT-1 Unrolled End UT-2 0.004"
Longitudinal Views



Rolled End

Figure 2-17. Photomicrographs of Tube Sample B73-8-3RET Specimens LT-1 and UT-2

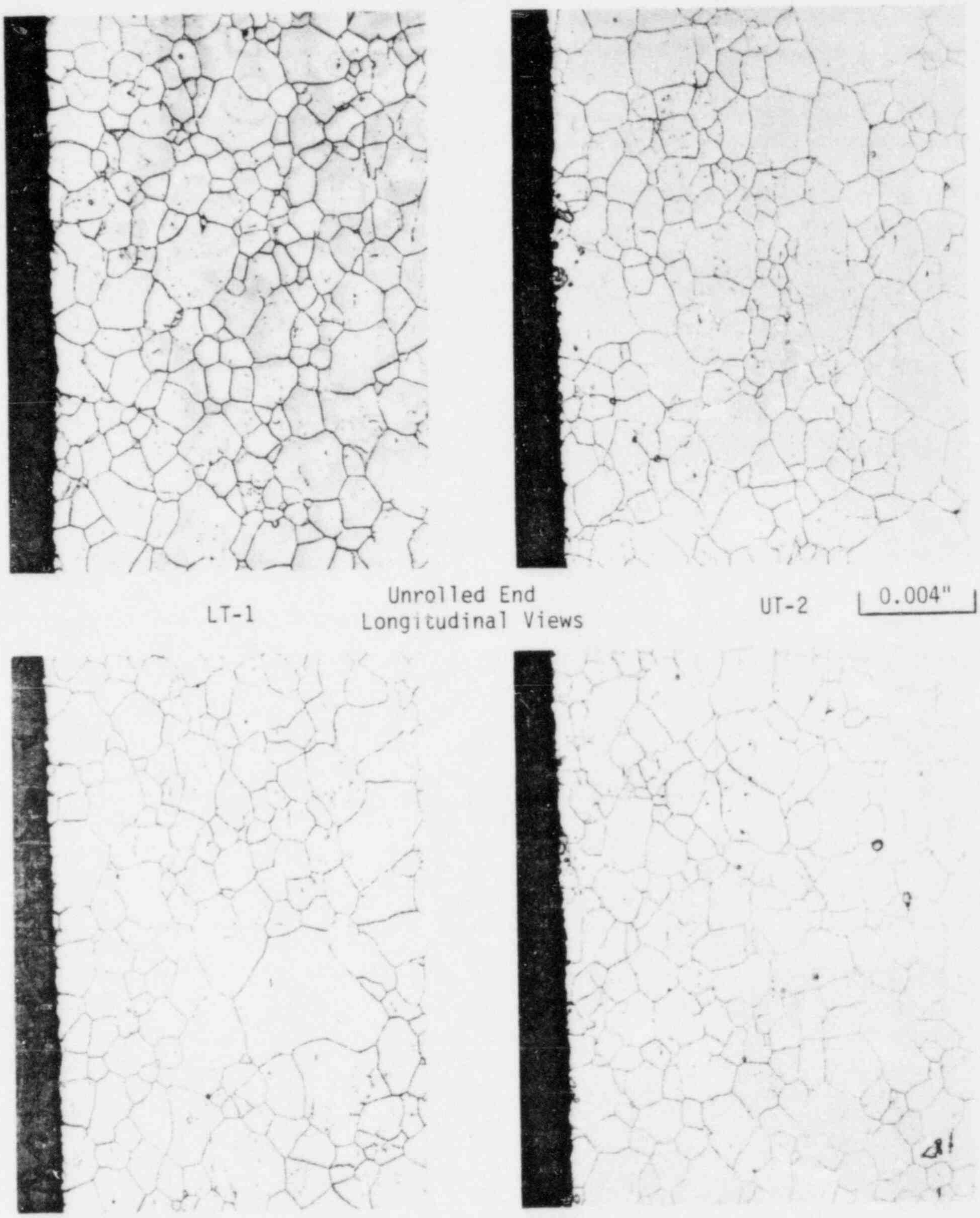
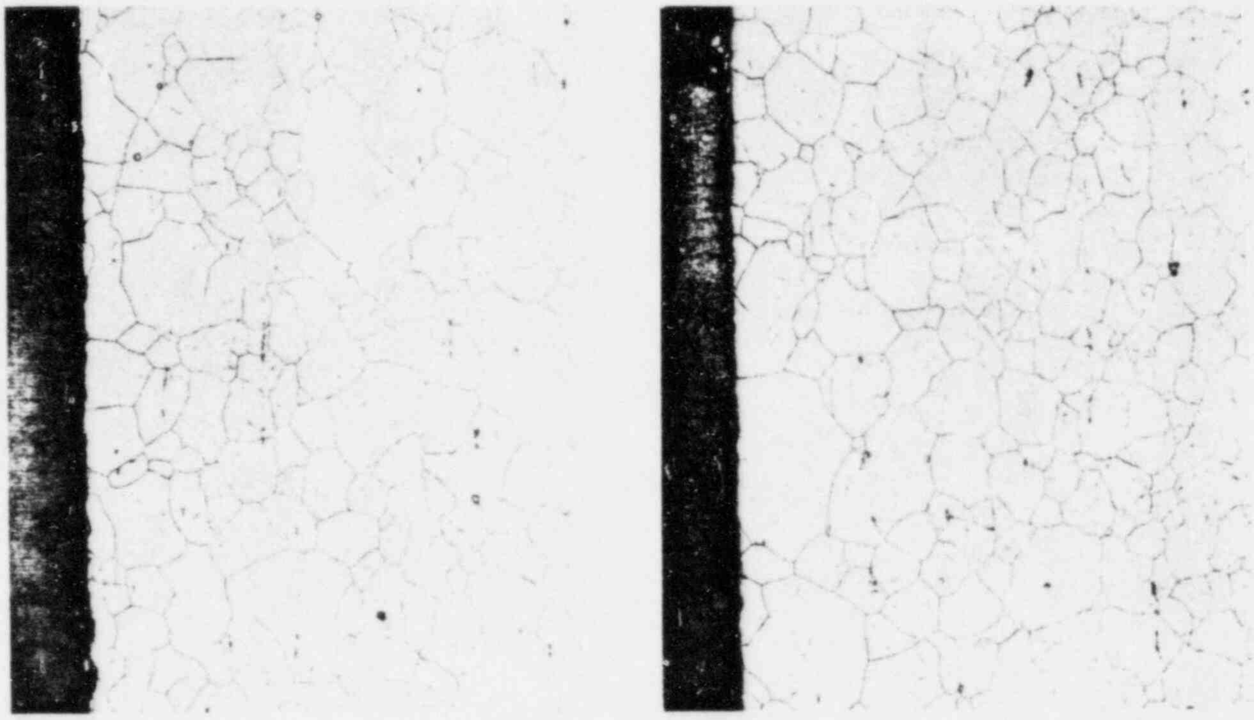
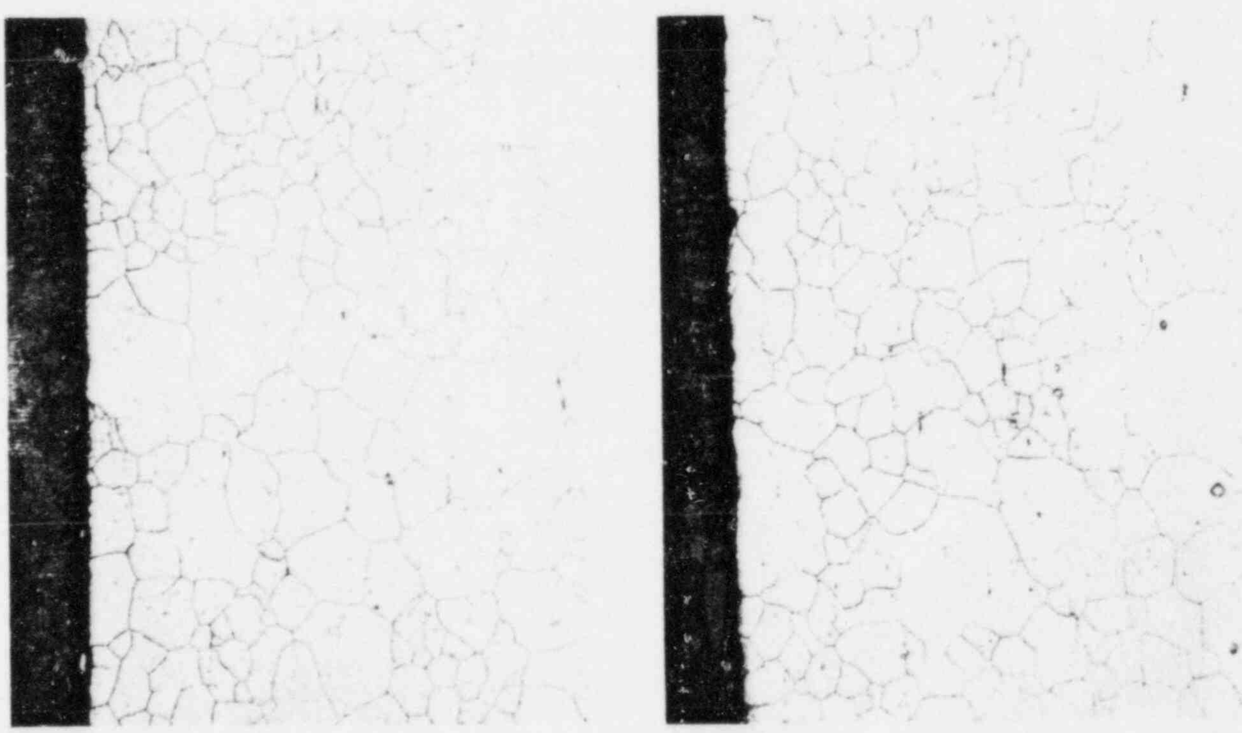


Figure 2-18. Photomicrographs of Tube Sample B73-8-3REB Specimens LT-1 and UT-2



LT-1 Unrolled End Longitudinal Views UT-2 0.004"



Rolled End

Figure 2-19. Photomicrographs of Tube Sample B112-19-2RE Specimens LT-1 and UT-2

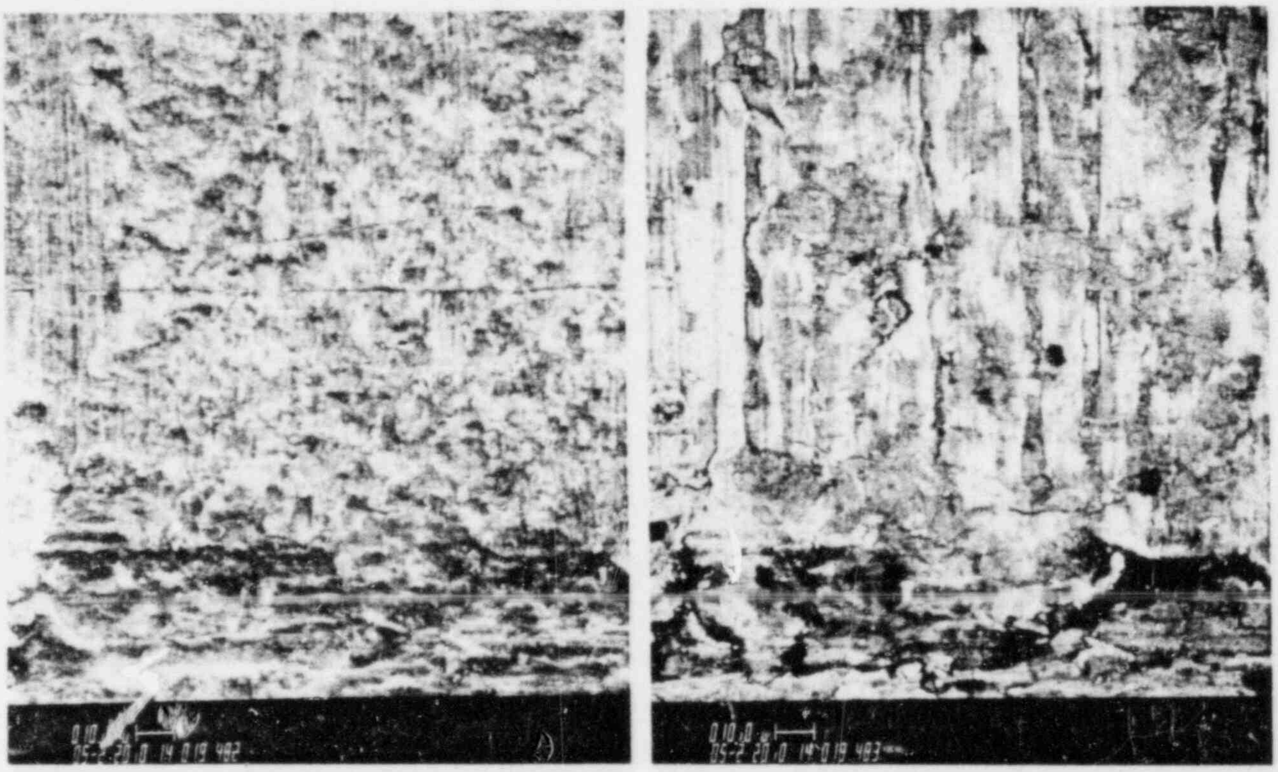
2.7.1 Control Specimens

A control specimen from tube sample B112-19-2RE was initially examined in the SEM to document the "as-received" condition of the tube outer surface. As seen in the photomicrographs in Figure 2-20, the surface was covered with deposit which prevented inspecting the tube material. Therefore, it became necessary to descale the specimens in order to proceed with the inspection. A descaling procedure using an ultrasonic bath of inhibited hydrochloric acid (500 ml 6N HCl + 1g hexamethylene tetramine) is commonly used on Alloy 600 tubing at the LRC. To insure that this solution would not attack the base material of ANO-1 OTSG tubes, a small piece of archive OTSG tubing was descaled for 15 minutes at 140° F. Photomicrographs of this piece before and after descaling are shown in Figure 2-21, which illustrates that the solution had no effects on the base tube material. The contrast difference between photomicrographs is a result of exposure time and not related to the procedure.

To expedite inspection of the control specimens, one half of each specimen was descaled using the above procedure and then examined in the SEM. These specimens were labeled "A" control specimens. Figures 2-22, 2-23, and 2-24 show SEM photomicrographs of the outer surface of each of the "A" specimens. Deteriorated grain boundaries were visible on each specimen, similar to that observed on descaled specimens examined during the 1983 tube examination.[1] Therefore, it appears that the tube samples selected for sleeve installation were from areas containing representative amounts of IGA damage.

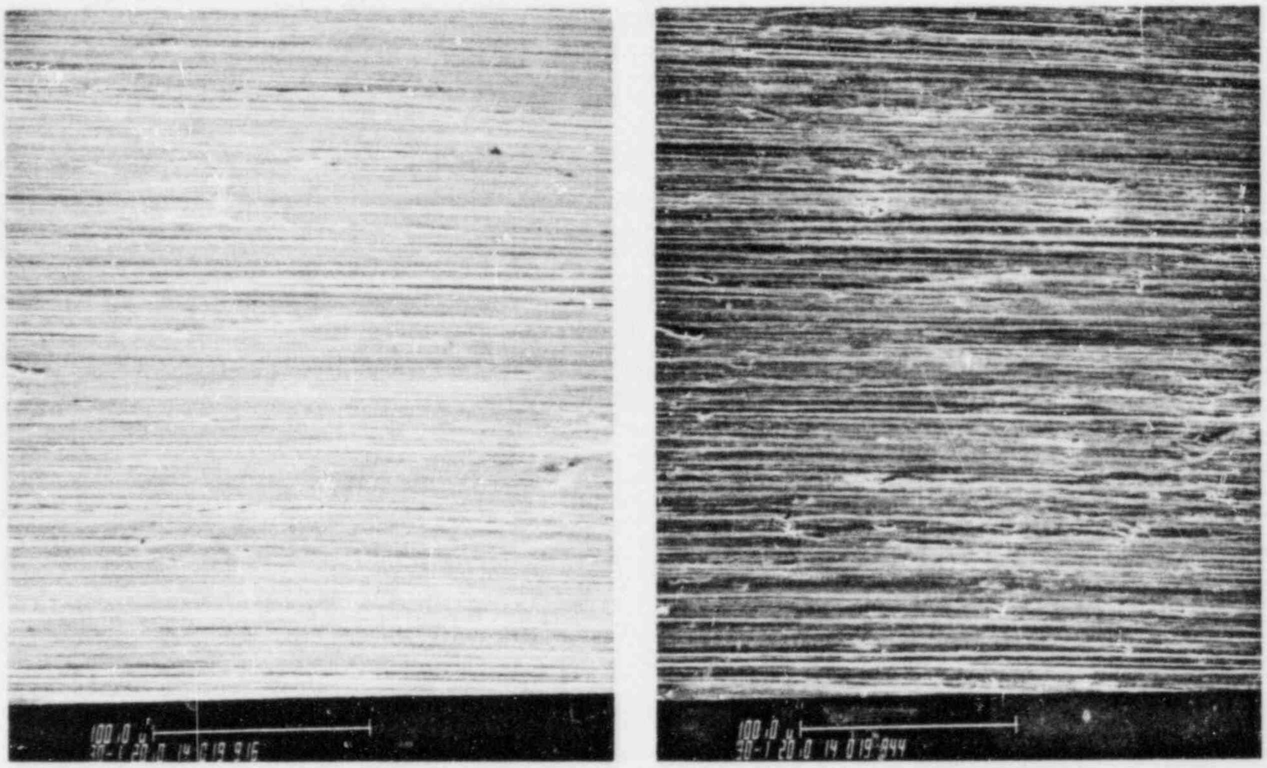
For further comparison, each of the "A" control specimens was bent inward about the tube axis, placing tensile stress on the tube outer surface, and re-examined in the SEM. Photomicrographs of the bent specimens are also shown in Figures 2-22, 2-23, and 2-24. Bending caused grain boundaries to open primarily in the direction of highest tensile stress; i.e., parallel to the tube axis. These photomicrographs appear almost identical to those of specimens bent and examined during the 1983 examination.[1] Additional photomicrographs of descaled and bent control specimens are presented in Figures C-1, C-2, and C-3 in Appendix C.

The other half of each of the control specimens, labeled "B" specimens, was bent and not descaled. Photomicrographs of these specimens in Figures 2-25, 2-26, and 2-27 simply confirm that bending the tube causes the outer surface deposit to split along underlying grain boundaries, much the same as that observed during the 1983 examination.[1]



Tube Axis

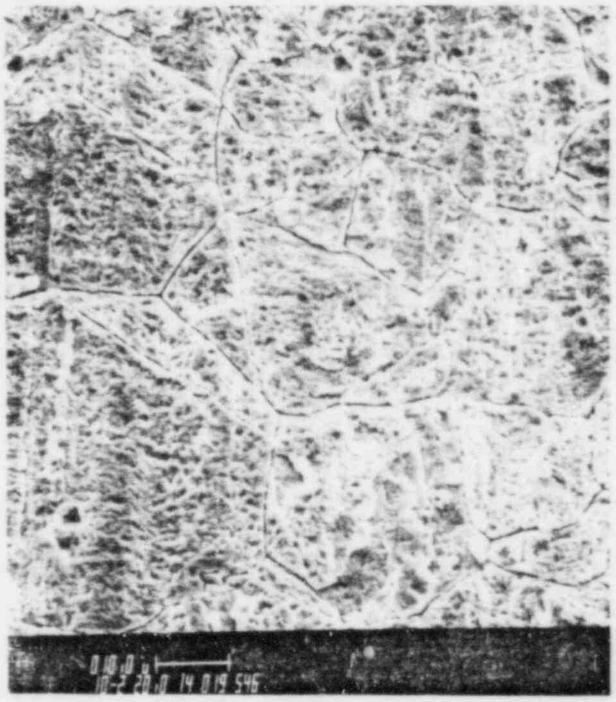
Figure 2-20. SEM Photomicrographs of Tube Sample B112-19-2RE Outer Surface Deposit

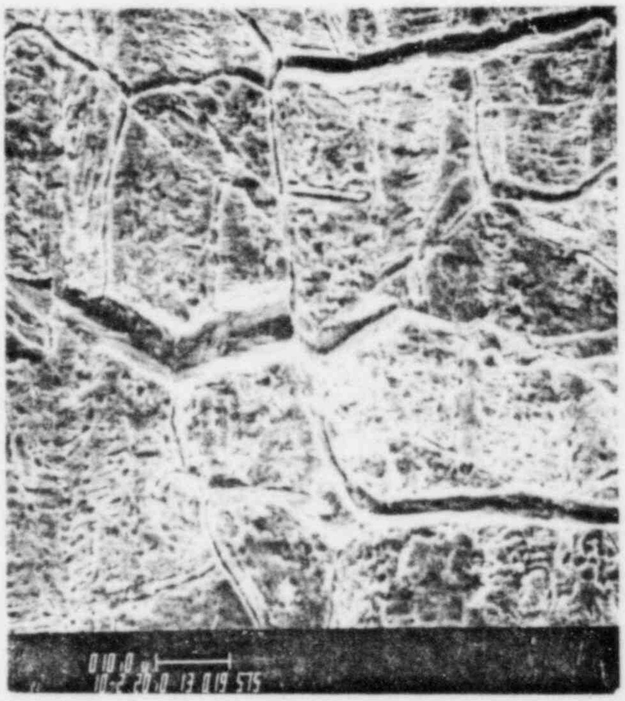


As-received   Descaled

Tube Axis

Figure 2-21. SEM Photomicrographs of Descaled Archive OTSG Tube Sample



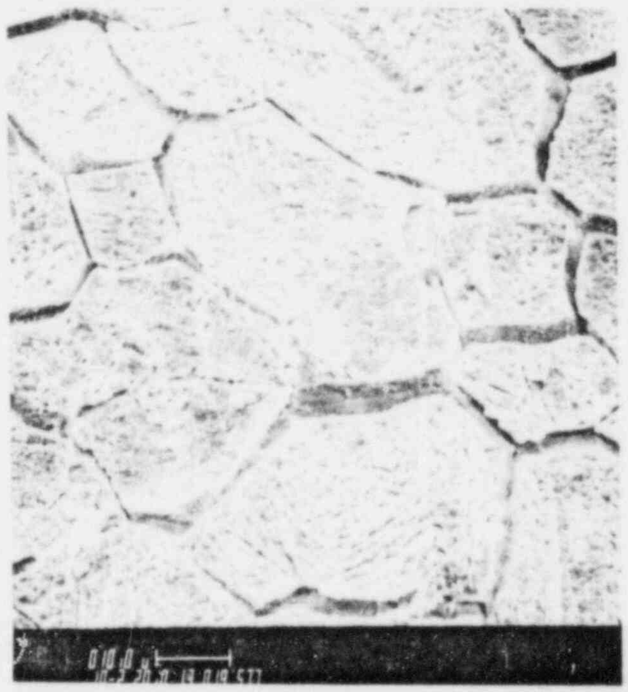


Control Top

Descaled

Bent

Tube Axis →



Control Bottom

Figure 2-22. SEM Photomicrographs of Tube Sample B73-8-3RET "A" Control Specimens

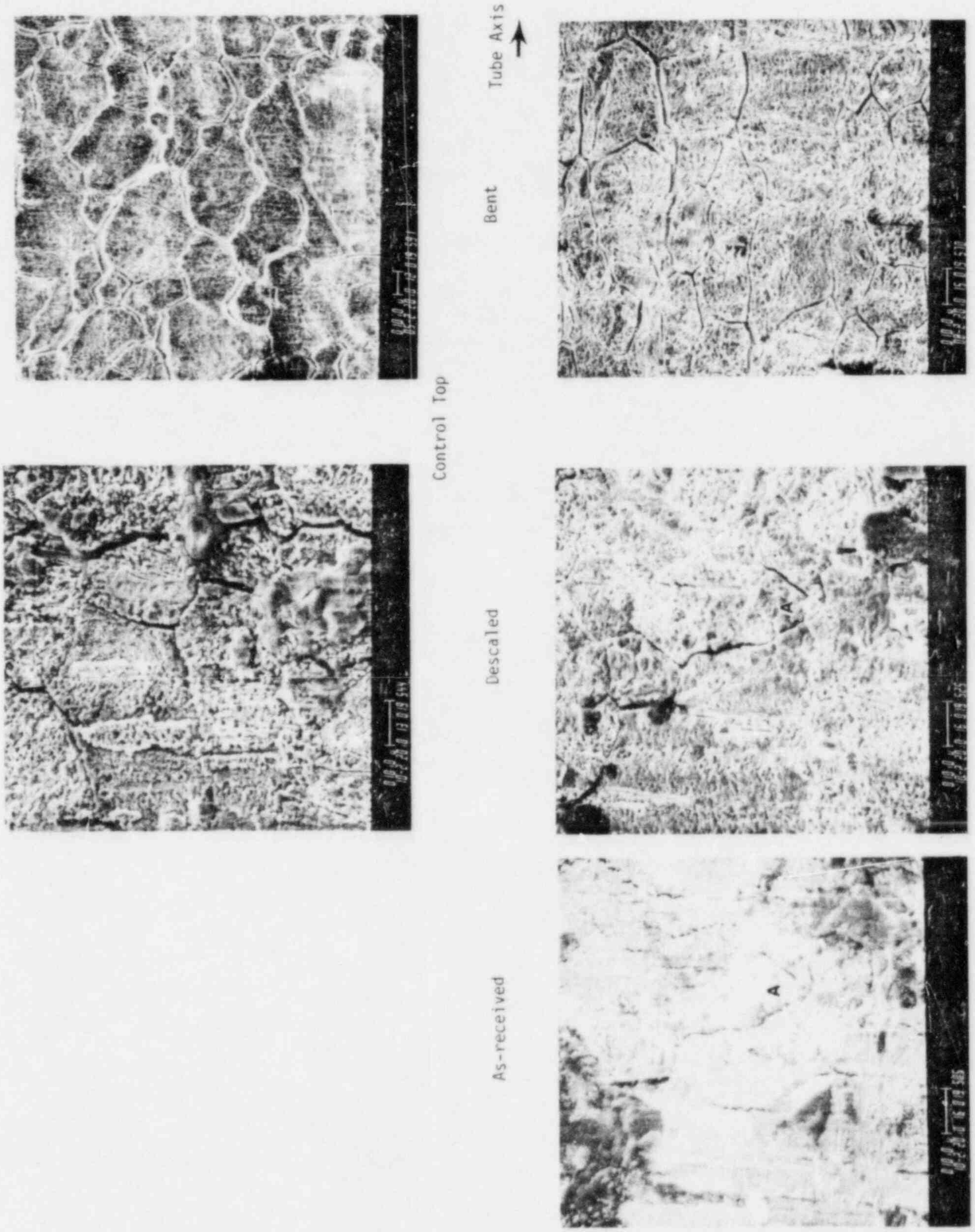


Figure 2-23. SEM Photomicrographs of Tube Sample B73-8-3REB "A" Coontrol Specimens

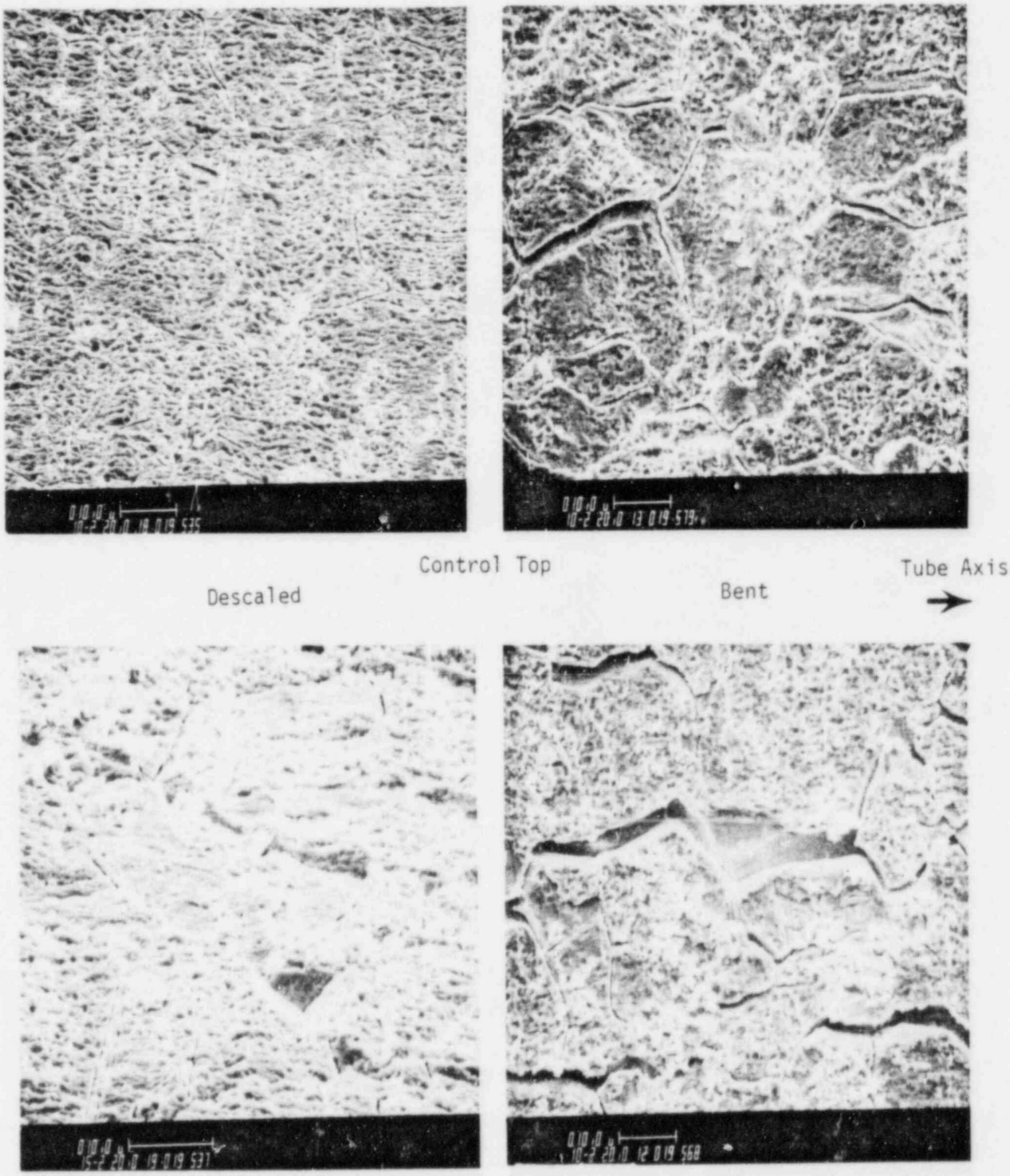
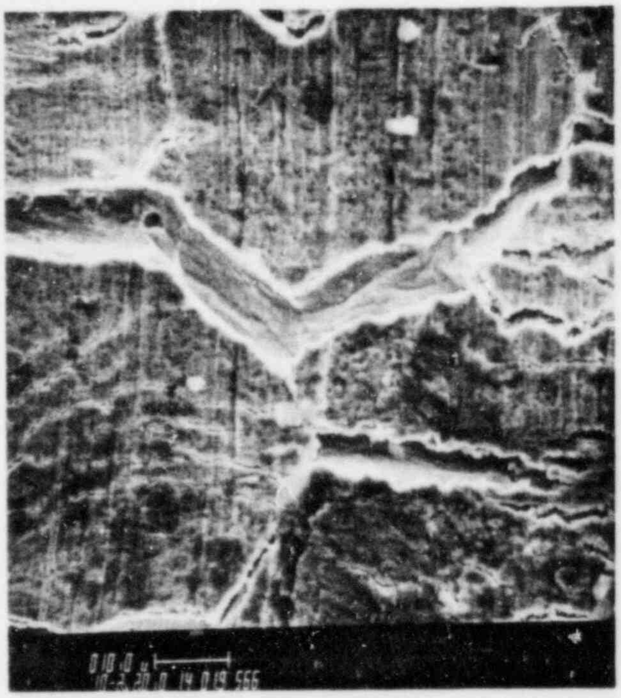
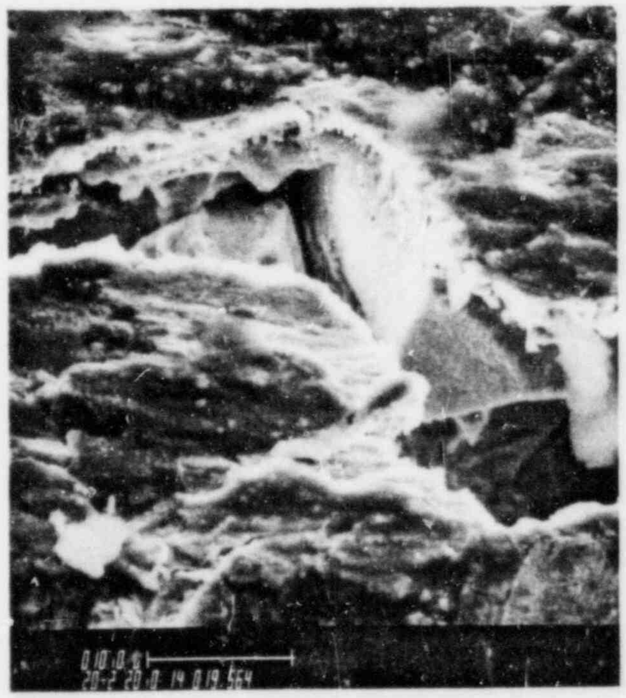


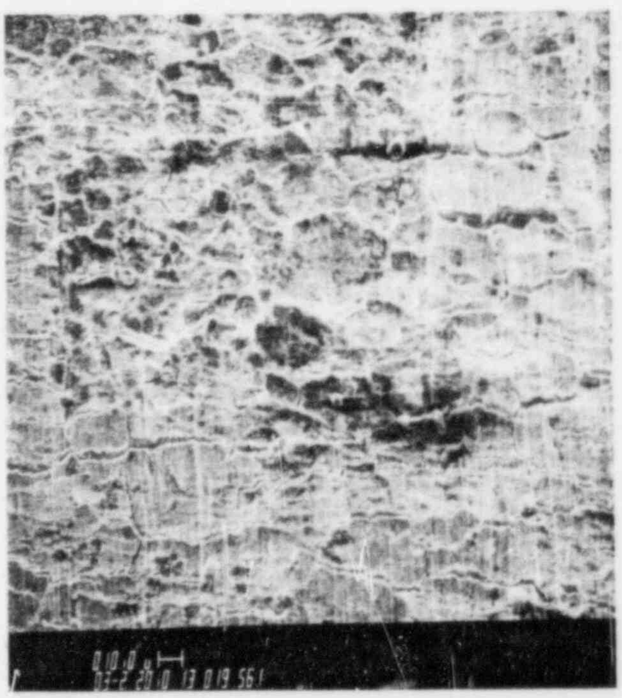
Figure 2-24. SEM Photomicrographs of Tube Sample B112-19-2RE "A" Control Specimens





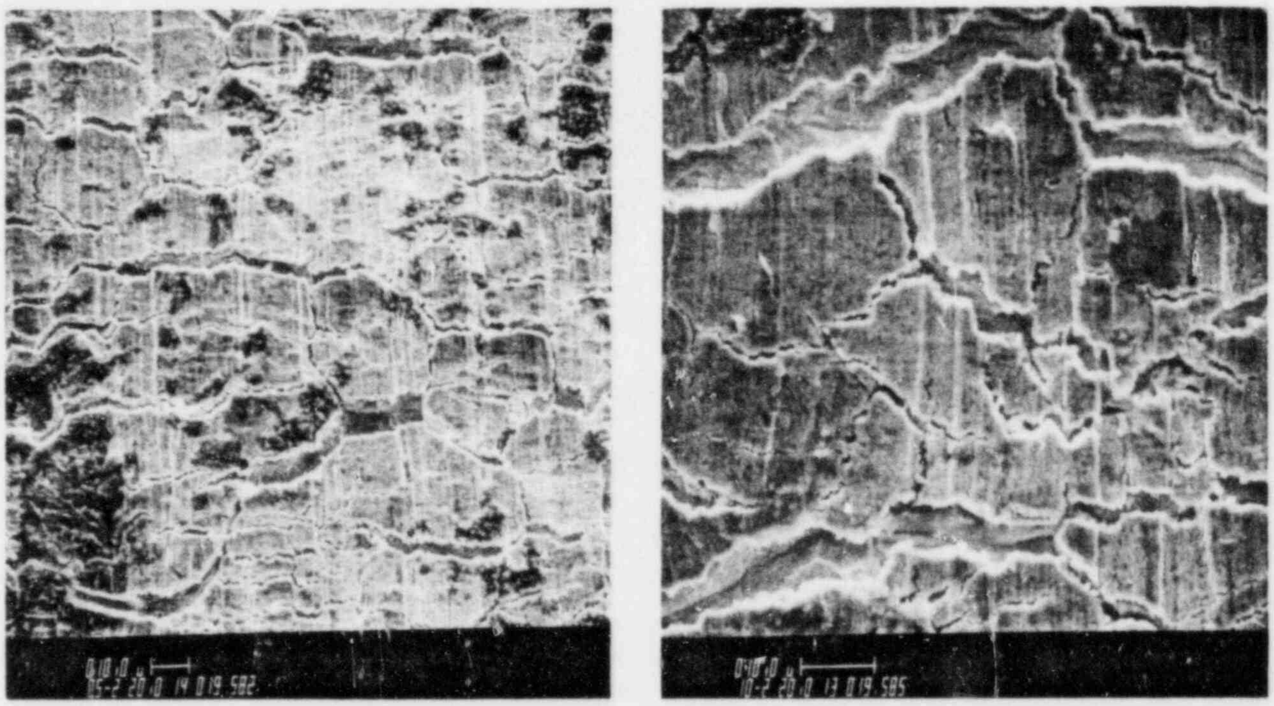
Control Top

Bent Bent Tube Axis →



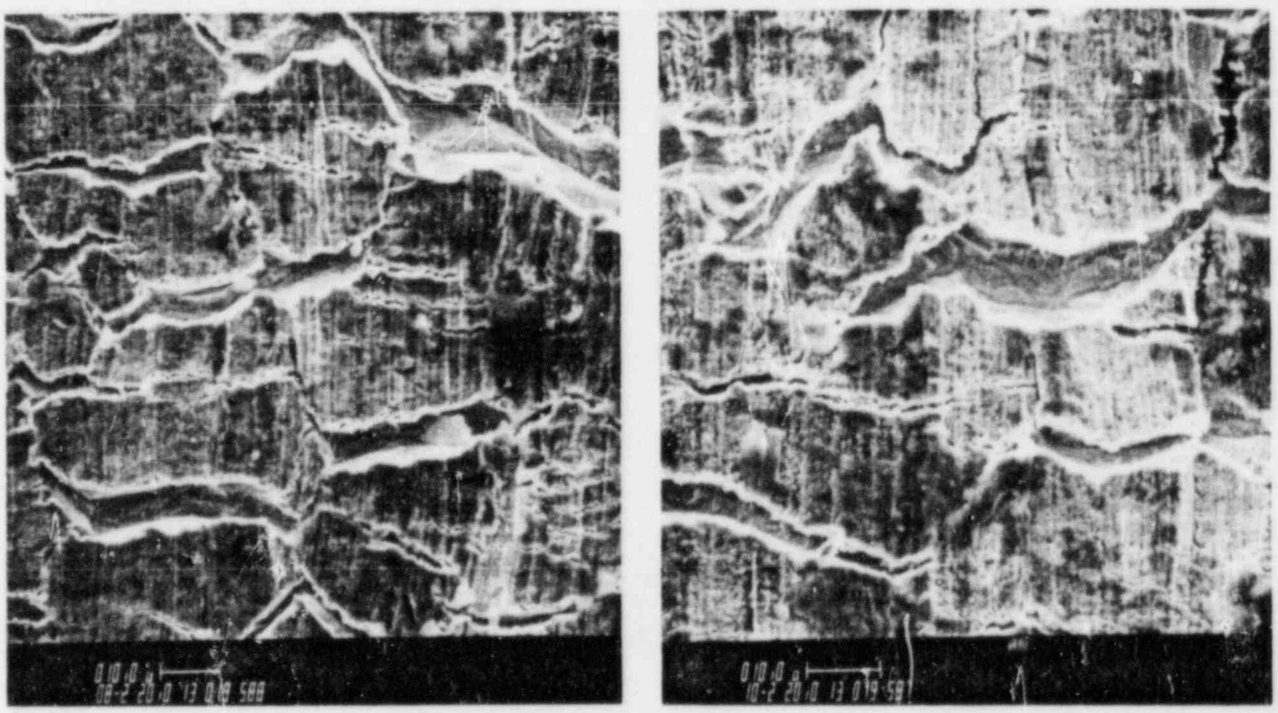
Control Bottom

Figure 2-25. SEM Photomicrographs of Tube Sample B73-8-3RET "B" Control Specimens



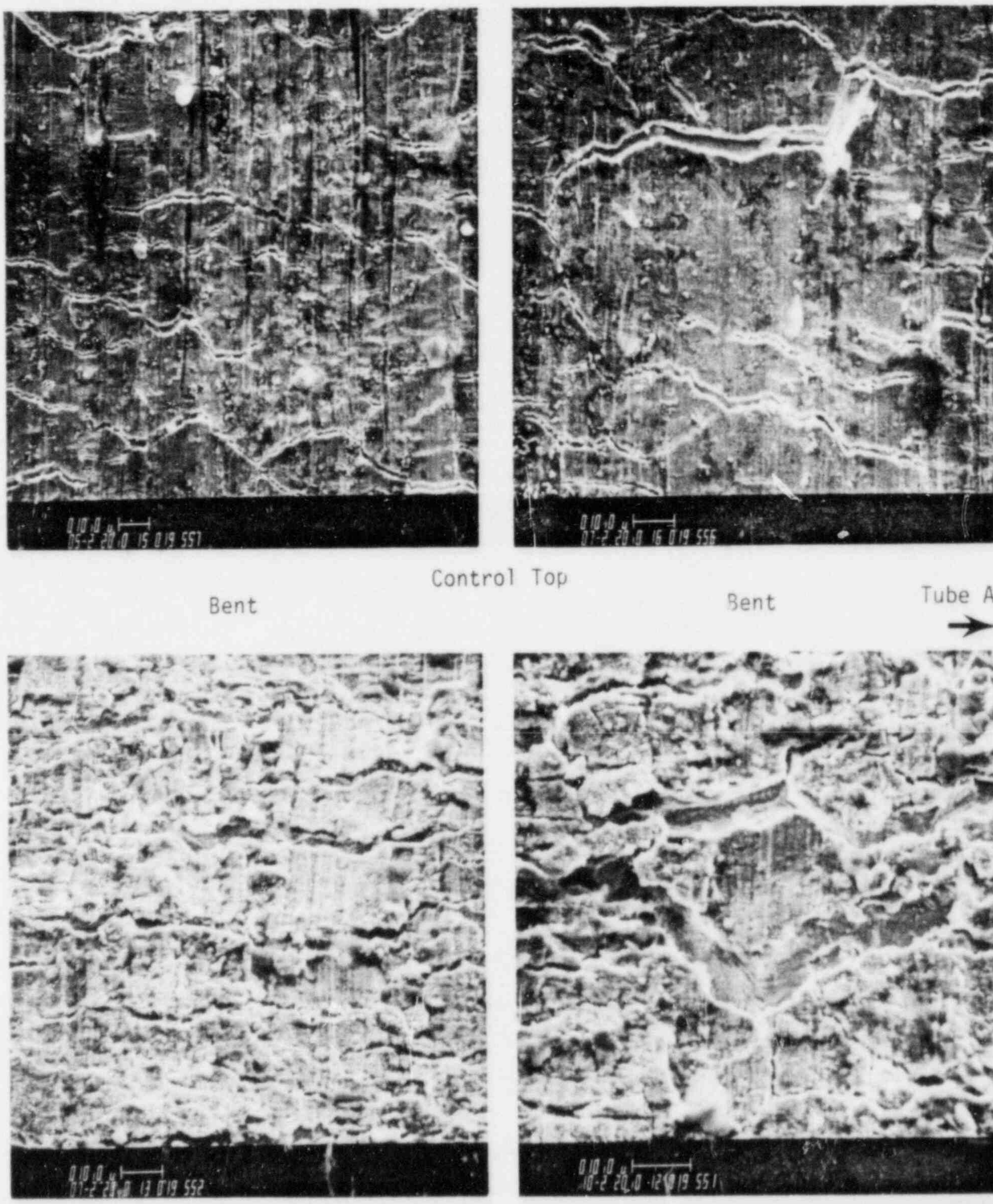
Control Top

Bent Bent Tube Axis →



Control Bottom

Figure 2-26. SEM Photomicrographs of Tube Sample B73-8-3REB "B" Control Specimens



Control Top

Bent

Bent

Tube Axis →

Control Bottom

Figure 2-27. SEM Photomicrographs of Tube Sample B112-19-2RE "B" Control Specimens

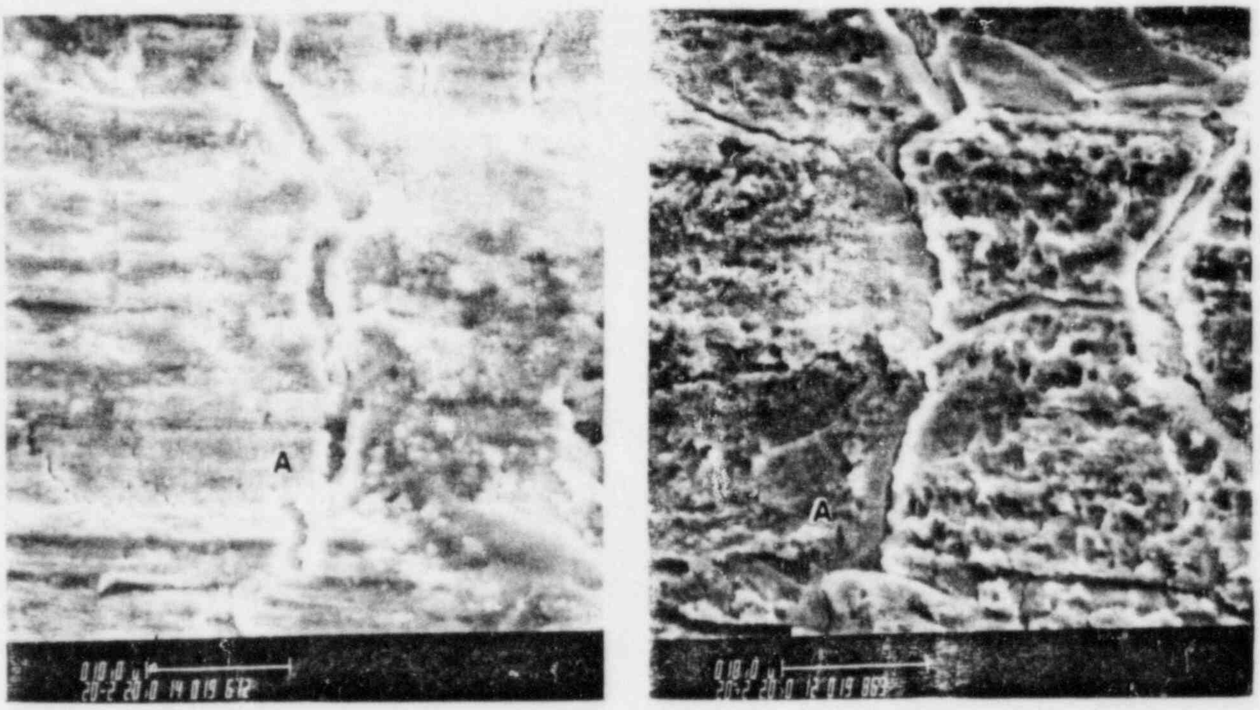
2.7.2 Sleeved Tube Specimens

2.7.2.1 Roll Centers. Specimens from the roll centers were inspected using the SEM to determine the effects of the rolling operation in regions of highest hoop stress. A scribe mark was placed on the specimen outer surface to be used as a locator. After an initial SEM characterization of deposit appearance, each specimen was descaled using the same procedure as described in Section 2.6.1. Re-examination of the specimens in the SEM at the same location as before using the locator permitted complete characterization of deposit splitting along grain boundaries.

The results are clearly depicted in the photomicrographs shown in Figures 2-28, 2-29, and 2-30. When comparing photomicrographs of the roll center specimens in the "as-rolled" and descaled conditions, it becomes obvious that deposit splitting occurred along grain boundaries due to sleeve installation. Strain induced during sleeve installation causes displacement of the tube material and deposit layer(s) in the direction of least resistance; i.e., along axially oriented deteriorated grain boundaries intersecting the tube outer surface.

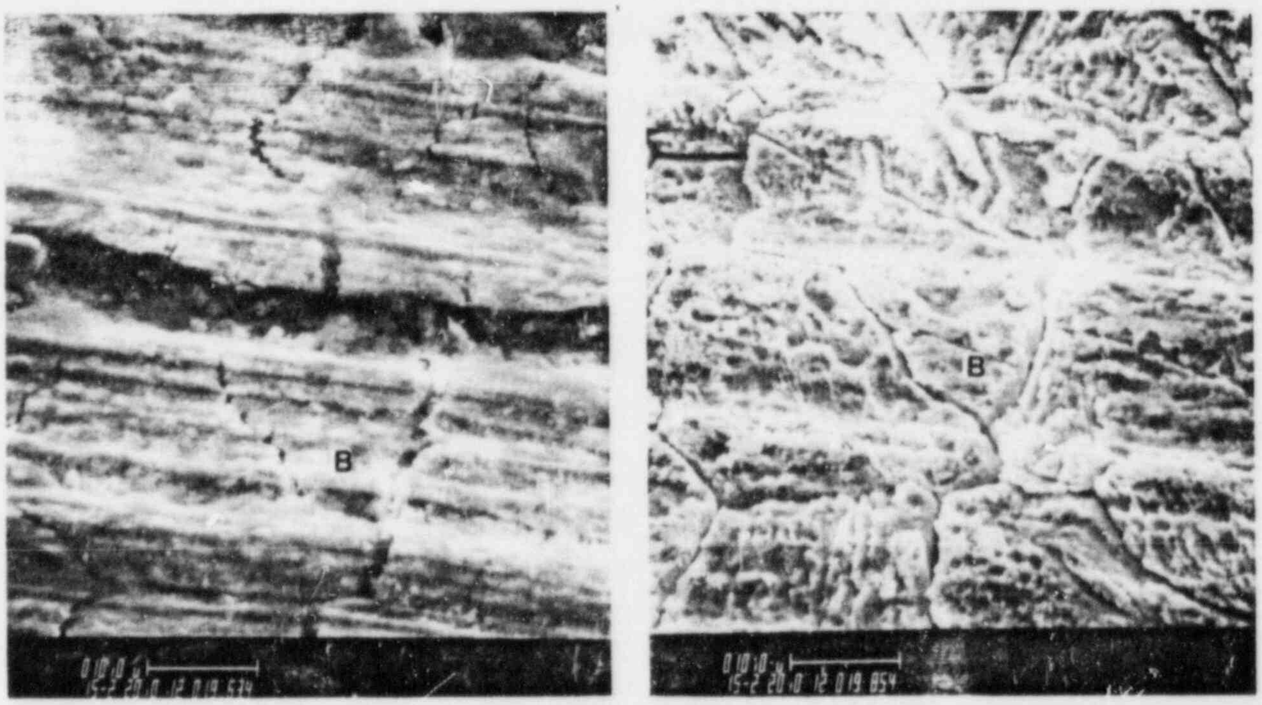
Horizontal lines visible in the "as-rolled" photomicrographs represent tube surface grinding marks caused during a manufacturing process. These lines become less obvious upon descaling, when slightly etched grain matrices and stretched grain boundaries become visible.

2.7.2.2 Roll Transitions. For each tube sample, regions encompassing the lower transition of Roll 1 and the upper transition region of Roll 2 were examined in the SEM. Photomicrographs of these specimens in the "as-rolled" condition are shown in Figures 2-31, 2-32, and 2-33. The results are consistent with those presented throughout this report; i.e., outer surface deposit splitting occurred along grain boundaries oriented perpendicular to the direction of highest tensile stress. On the rolled end of the roll transition specimens where tensile stress was in the hoop direction, splitting occurred axially. On the opposite end of the specimen adjacent to the roll transition, stresses were in the axial direction which caused circumferential splitting. Vertical lines in the deposit layer on these specimens represent the surface grinding marks caused during manufacture. It was not deemed necessary to descale and re-examine these specimens since the previous roll center specimens clearly showed that deposit splitting occurred along grain boundaries.



C-1

As-rolled Descaled Tube Axis



C-2

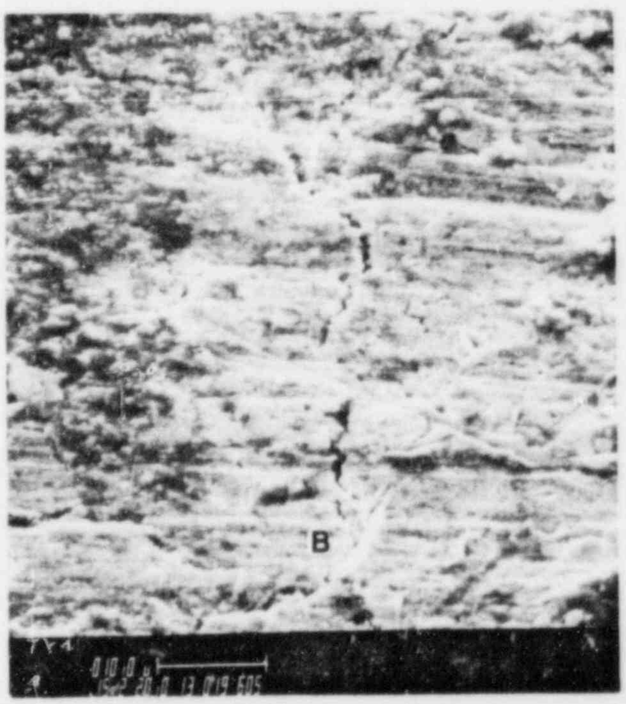
Figure 2-28. SEM Photomicrographs of Tube Sample B73-8-3RET Roll Center Specimens

C-1

As-rolled

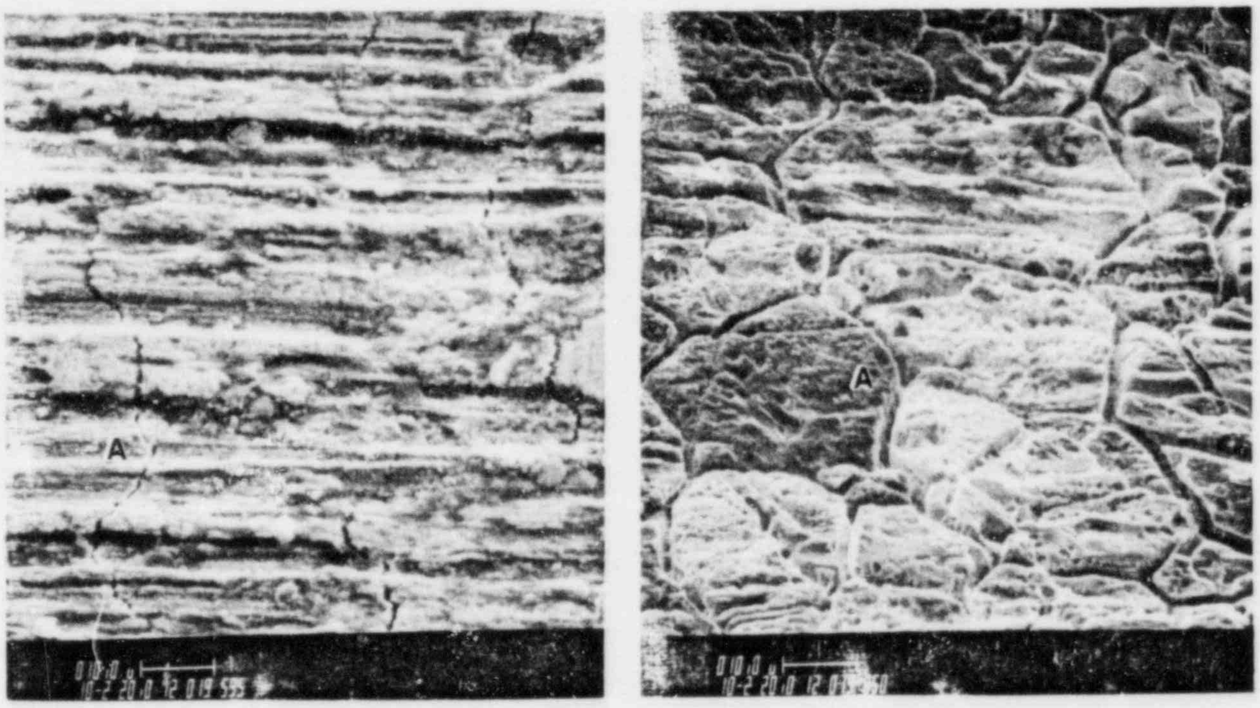
Descaled

Tube Axis ↑



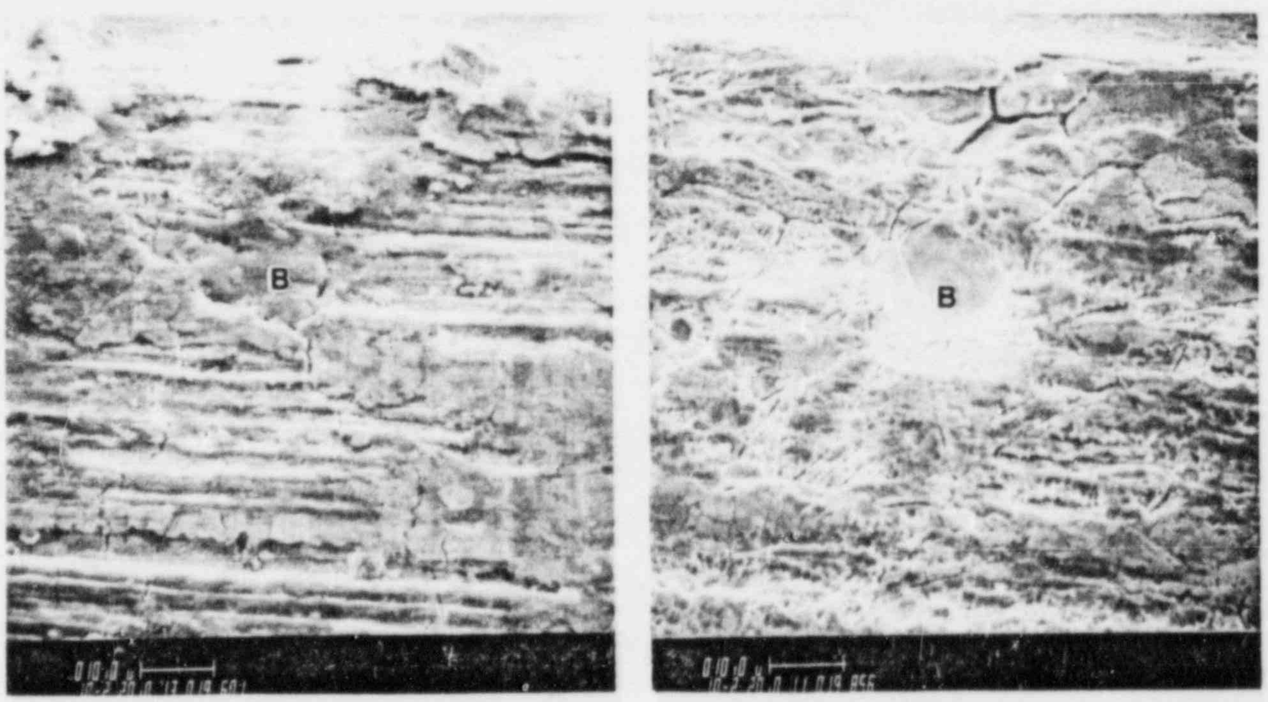
C-2

Figure 2-29. SEM Photomicrographs of Tube Sample B73-8-3REB Roll Center Specimens



C-1

As-rolled Descaled Tube Axis ↑



C-2

Figure 2-30. SEM Photomicrographs of Tube Sample B112-19-2RE Roll Center Specimens

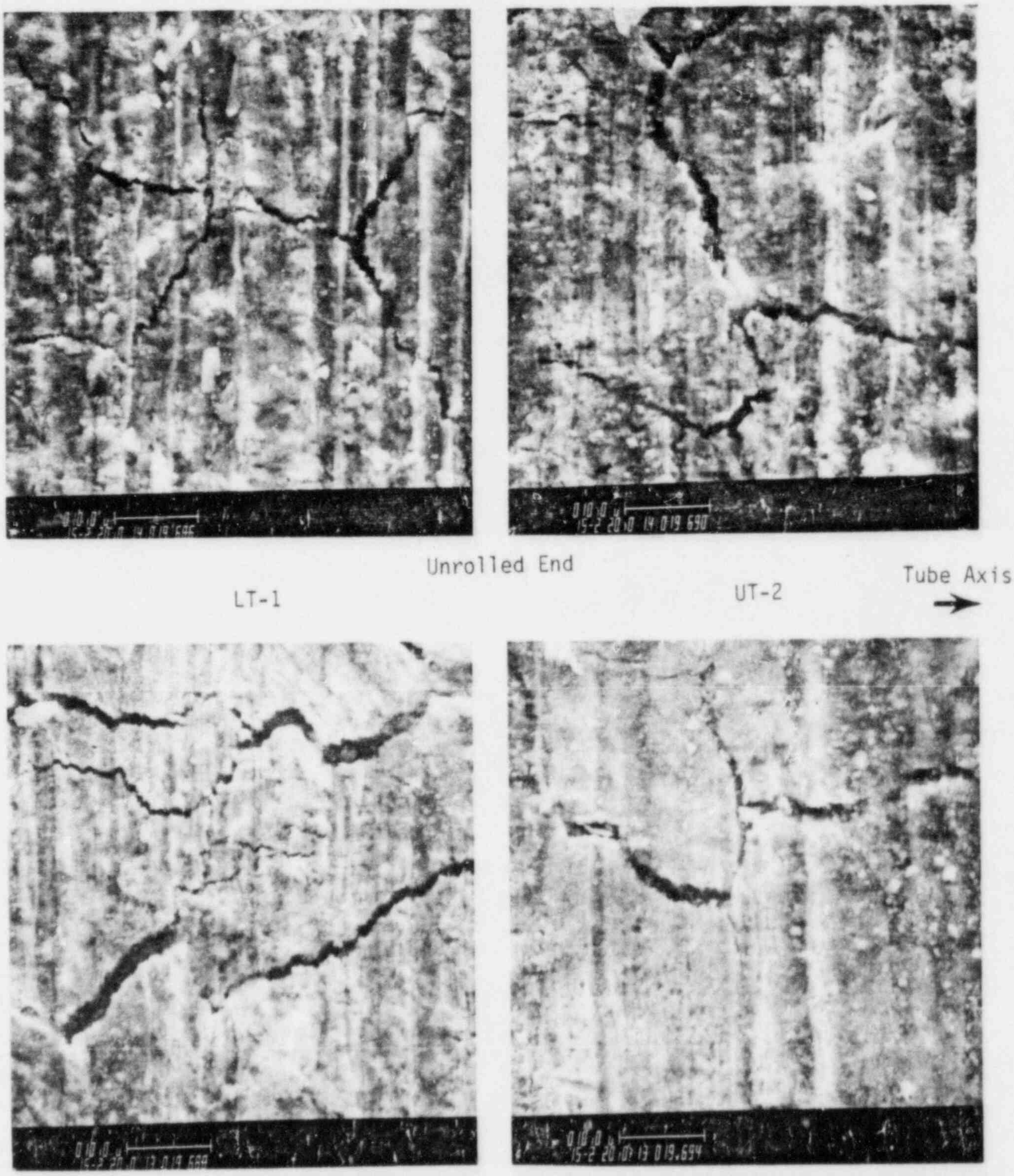


Figure 2-31. SEM Photomicrographs of Tube Sample B73-8-3RET Roll Transition Specimens

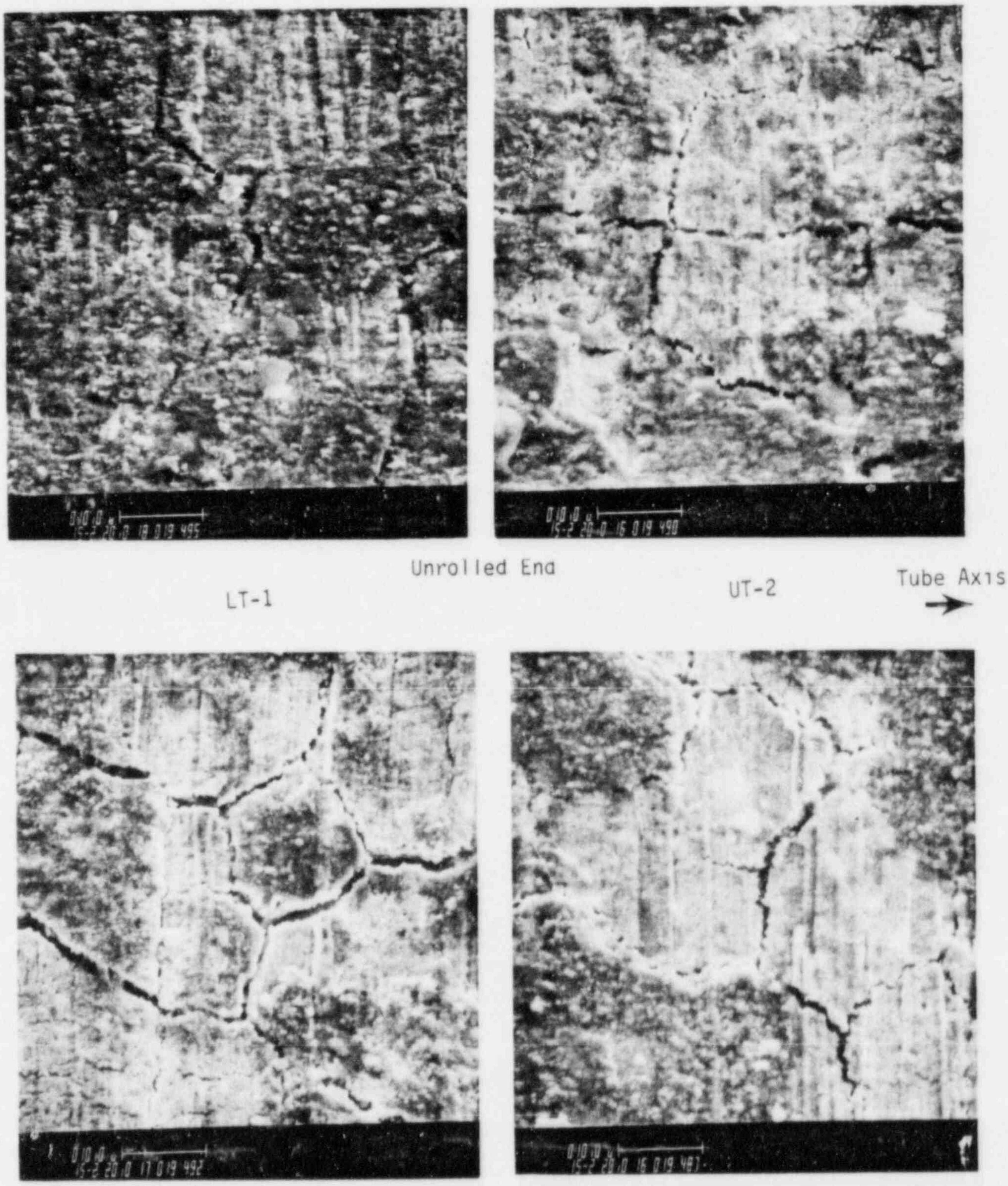


Figure 2-32. SEM Photomicrographs of Tube Sample B73-8-3REB Roll Transition Specimens

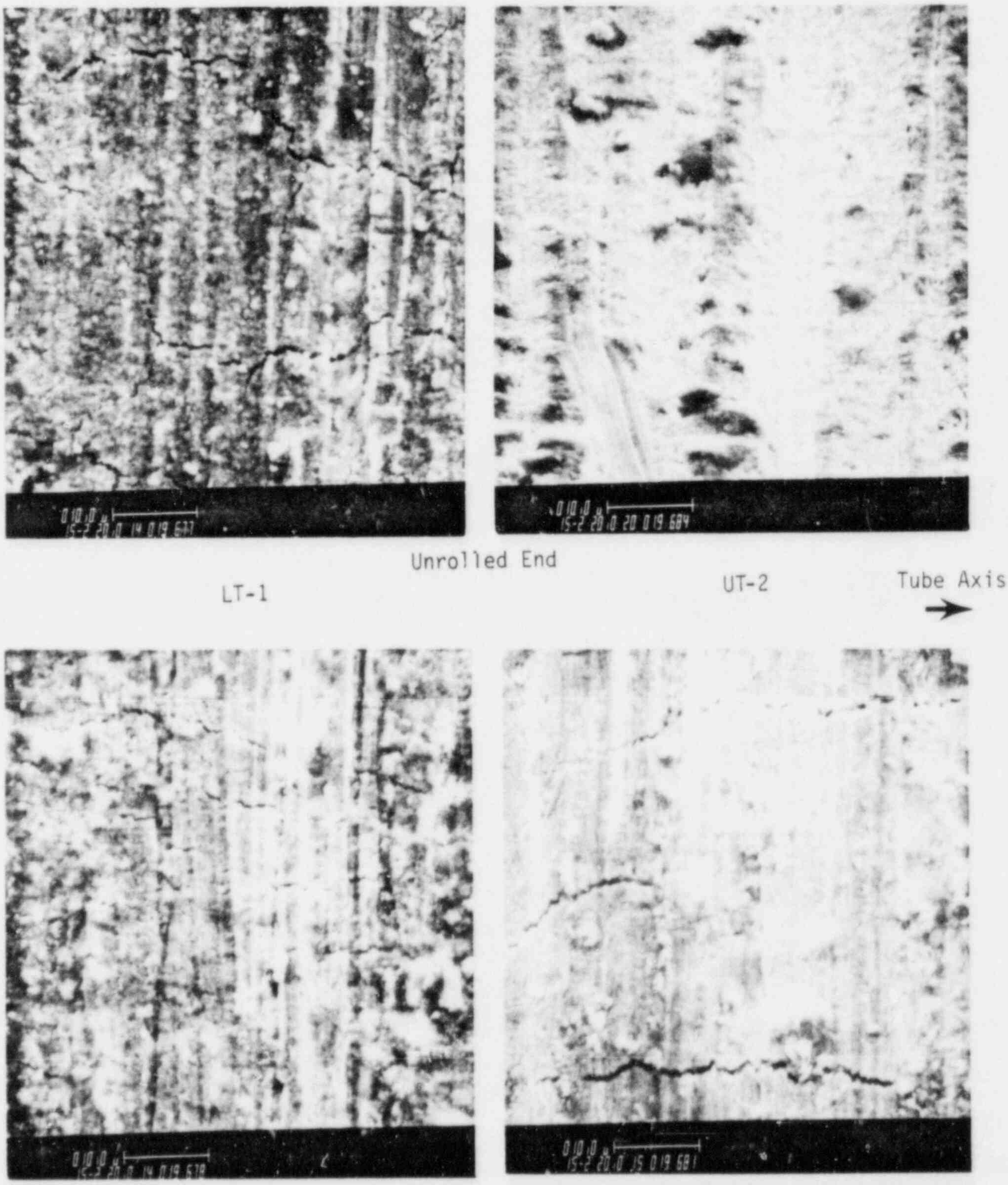


Figure 2-33. SEM Photomicrographs of Tube Sample B112-19-2RE Roll Transition Specimens

3.0 DISCUSSION

3.1 EDDY CURRENT TESTING

The shallow intergranular penetrations observed on the tube outer surface are too shallow for ECT detection. Results of this investigation showed that sleeve installation causes no inward radial propagation of deteriorated grain boundaries on the tube outer surface. Accordingly, ECT did not detect a change in the tube as a result of sleeving.

3.2 EFFECTS OF SLEEVE INSTALLATION

Roller expanding a sleeve inside an OTSG tube obviously results in an increase in sleeve ID and tube OD in the rolled regions.

A layer of cold work also was produced on the sleeve inner surface due to roller contact. The effects of the cold working on sleeve performance was evaluated in another project and was found to be acceptable.[2]

Results of this investigation show that existing deteriorated grain boundaries on the tube outer surface are opened in the circumferential, or hoop, direction during the sleeve installation process, with no inward radial propagation. The tube samples which experienced OD increases larger than those expected to occur in situ showed more grain boundary opening than the sample expanded the normal amount

Therefore, there exists a considerable margin for installation of sleeves in the ANO-1 OTSGs without affecting the structural integrity of the tubes.

4.0 CONCLUSIONS

Based on the results of this examination, the following conclusions have been drawn concerning the effects of roller expanding a sleeve into a tube with shallow IGA present on the outer surface.

- The sleeve installation process causes plastic strain in the tube and sleeve material.
- Deteriorated grain boundaries on the tube outer surface in the rolled regions are slightly opened in the direction perpendicular to the highest tensile stress and not radially inward into the tubewall.
- The amount of grain boundary opening is determined by the amount of OD expansion due to sleeve installation.
- Test sample B112-19-2RE was "field representative" and experienced the smallest amount of grain boundary opening.

  no structural damage was observed on the sample due to sleeve installation.
- No structural damage of the ANO-1 tube samples was observed

  there is a considerable margin for sleeve installation in the ANO-1 OTSG tubes without causing damage.

5.0 REFERENCES

1. S. C. Inman, "Examination of OTSG Tubes B73-8 and B112-19 from ANO-1 - Final Report," Babcock & Wilcox Letter Report RDD:84:5303-04:02, June 1983.

2. "Once-Through Steam Generator Mechanical Sleeve Qualification", Babcock and Wilcox BAW-1823P, June 1984.

3. S. C. Inman and J. V. Monter, "Corrosion Test of a Mechanically Sleeved ANO-1 OTSG Tube," Babcock and Wilcox RDD:85:5223-06:01, February 1985.

APPENDIX C

ADDITIONAL SEM PHOTOMICROGRAPHS OF CONTROL SPECIMENS

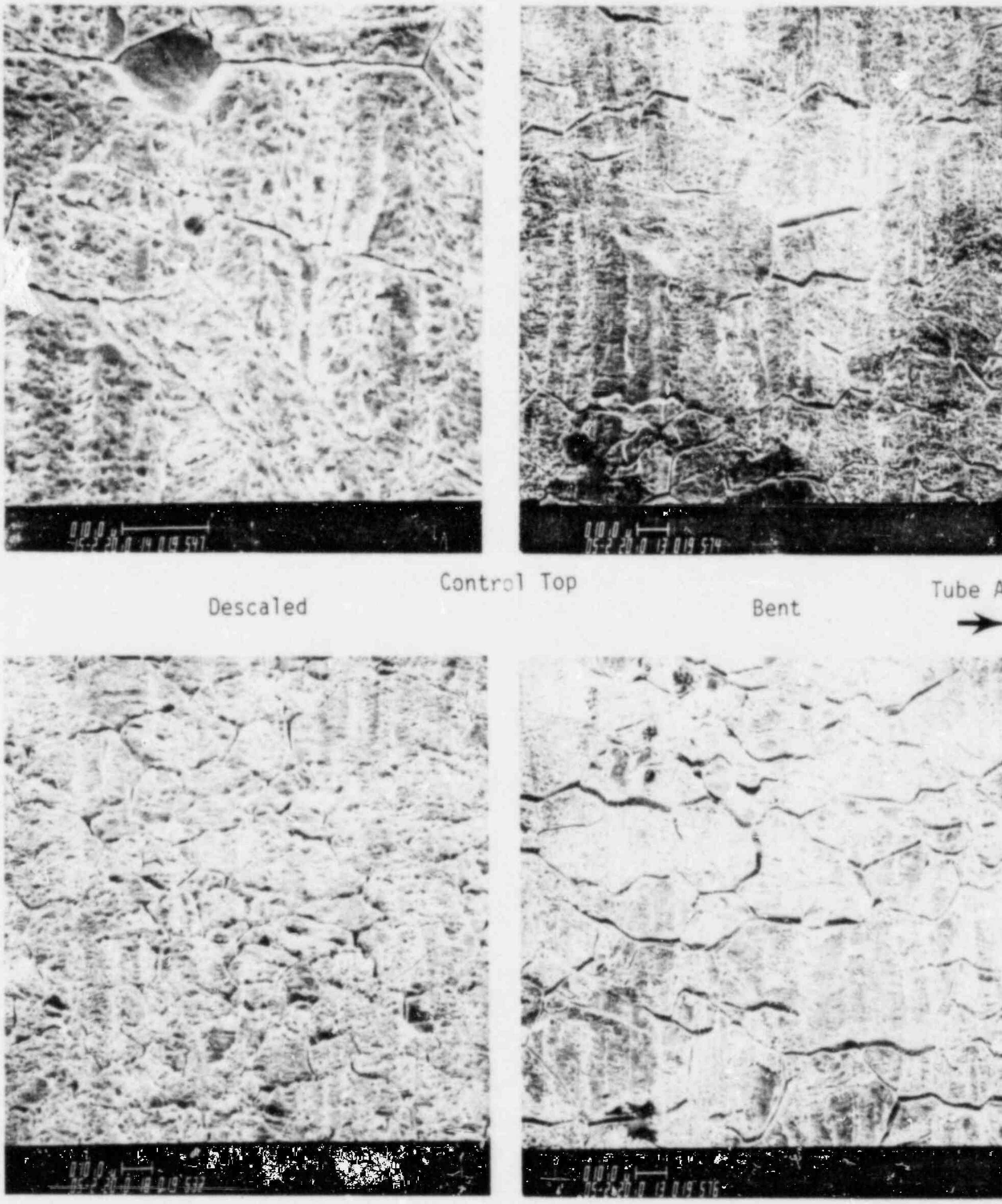
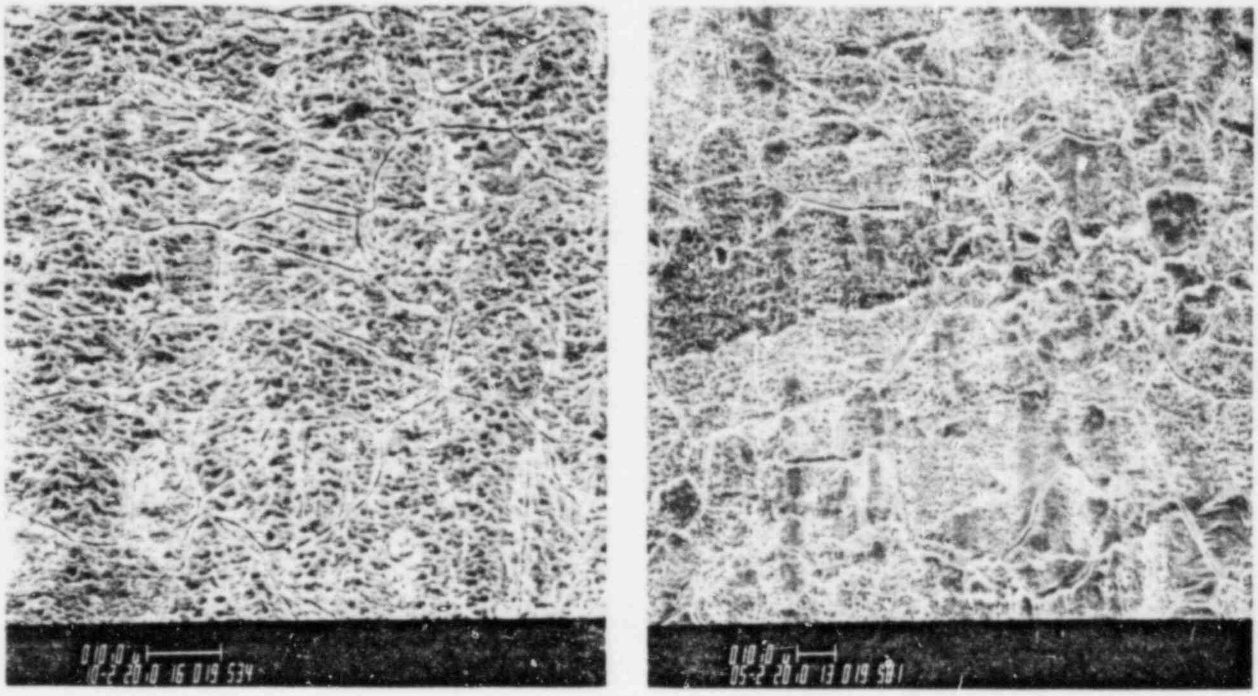


Figure C-1. SEM Photomicrographs of Tube Sample B73-8-3RET Control Specimens

Figure C-2. SEM Photomicrographs of Tube Sample B73-8-3REB Control Specimens

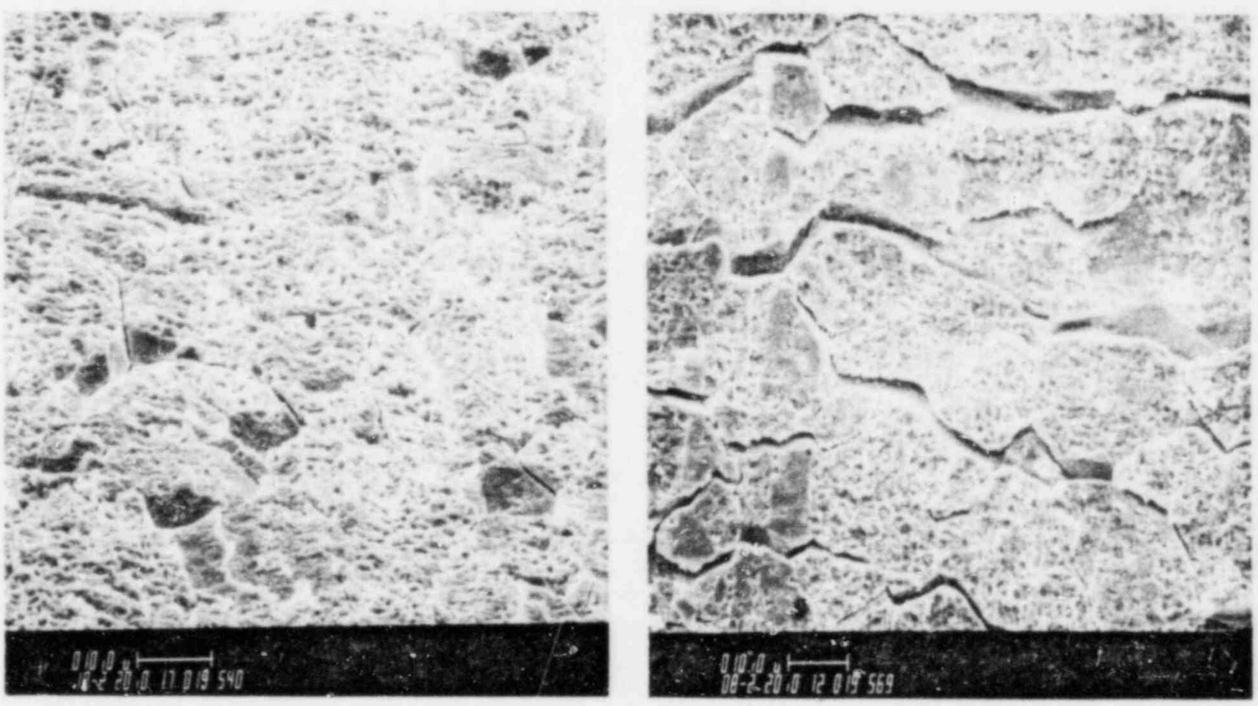


Control Top

Descaled

Bent

Tube Axis →



Control Bottom

Figure C-3. SEM Photomicrographs of Tube Sample B112-19-2RE Control Specimens

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