APPENDIX E

Appearance and Microstructure of E110 Standard As-received Tubes after a Single-sided Oxidation at 1100 C and F/F Combination of Heating and Cooling Rates

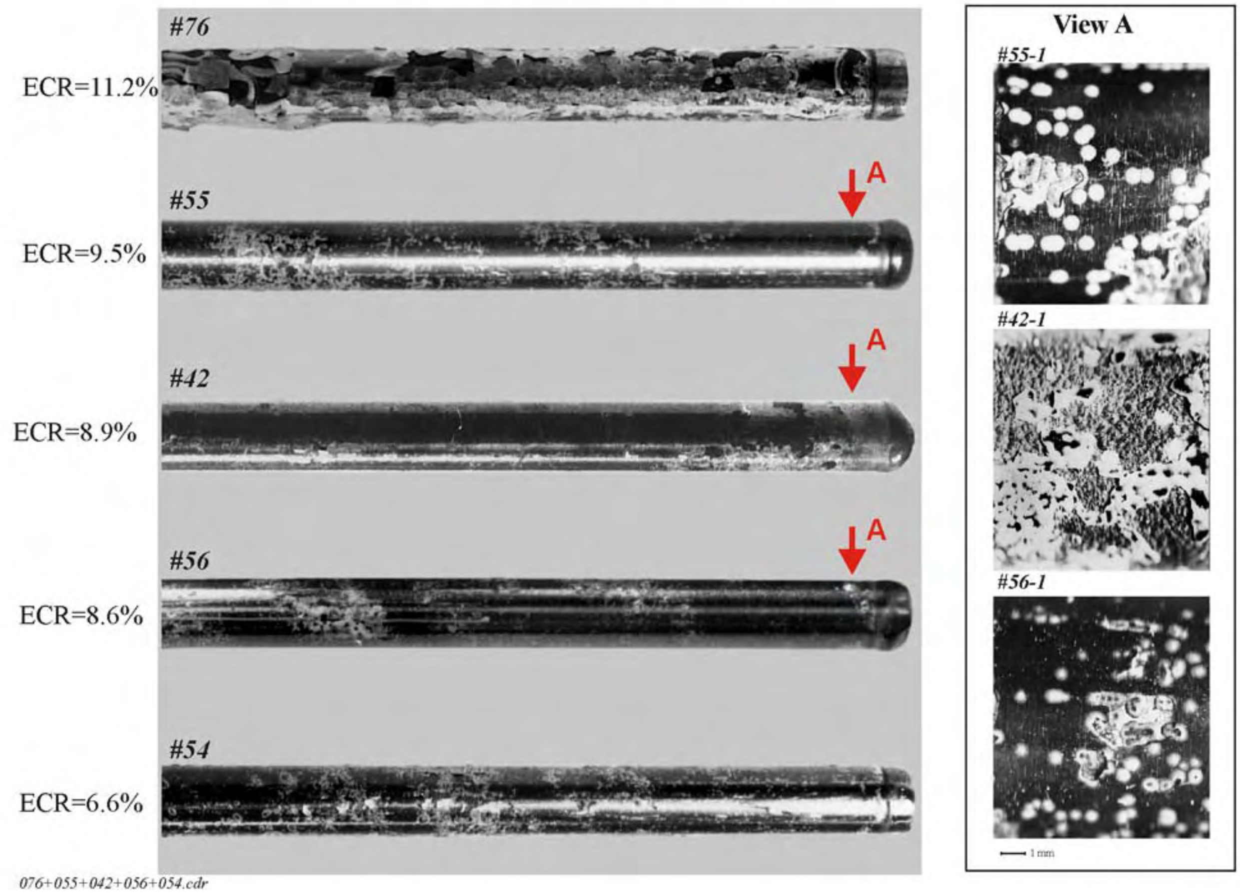


Fig. E.1. Appearance of E110 standard as-received tubes as a function of the ECR after single-sided oxidation at 1100 C and F/F combination of heating and cooling rates

#54-5 ECR=6.6 %	**#42-5** ECR=8.9 %
Etched	Etched

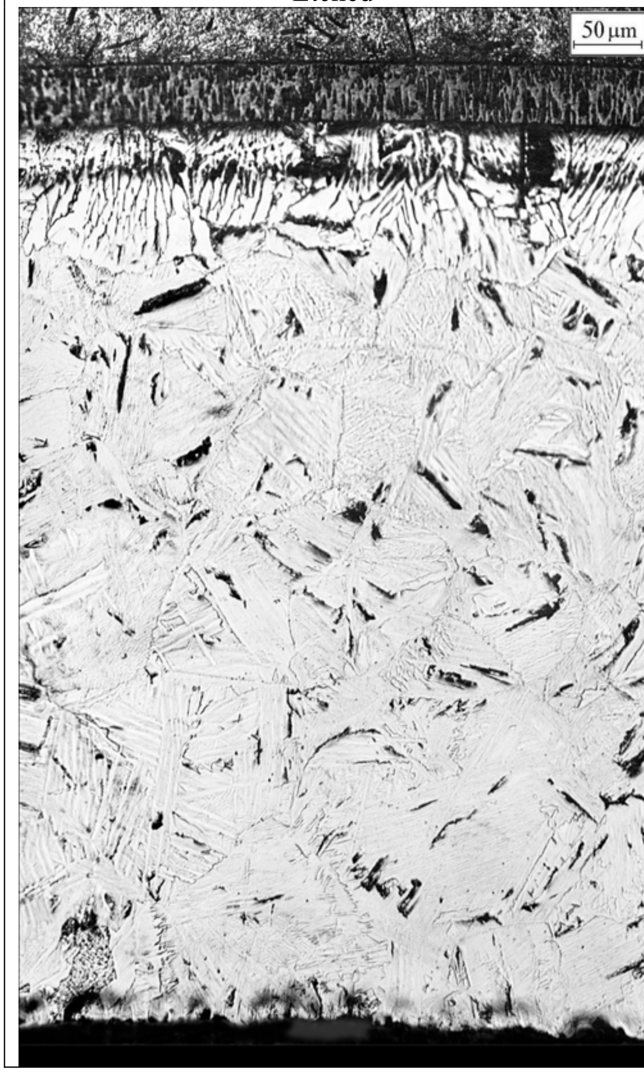


Fig. E.2. Microstructure of E110 standard as-received tubes after a single-sided oxidation at 1100 C and F/F combination of heating and cooling rates

APPENDIX F

Appearances and Microstructures of E635 Standard As-received Tubes after a Double-sided Oxidation at 1000, 1100 C and F/F Combination of Heating and Cooling Rates

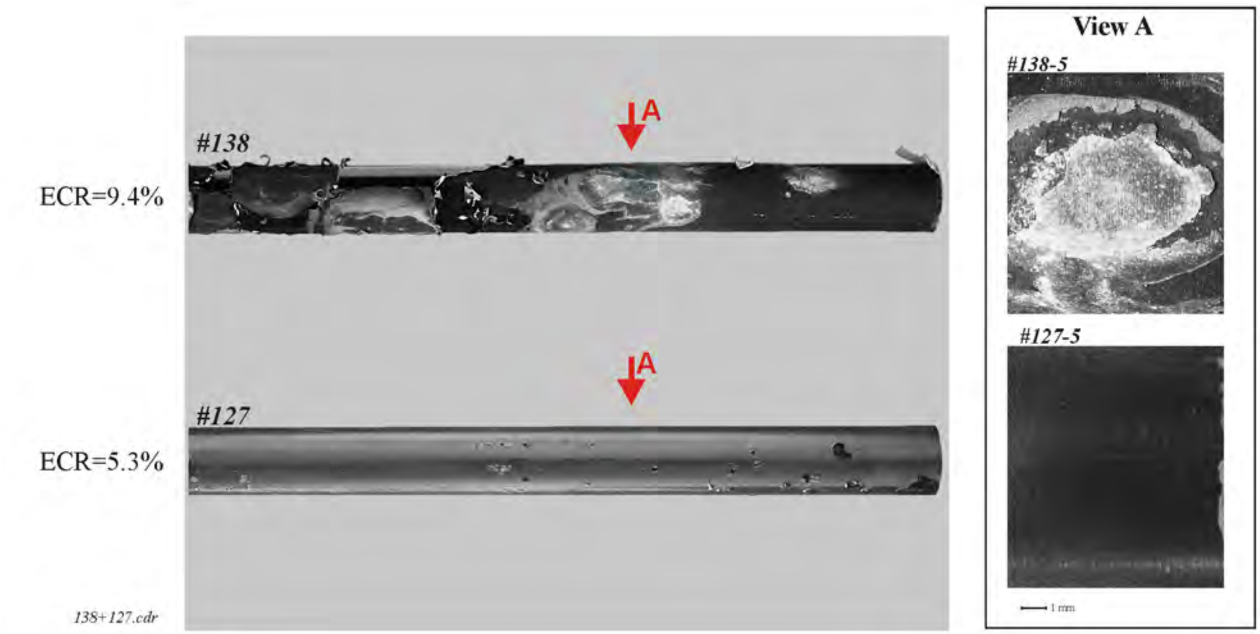


Fig. F-1. Appearance of E635 standard as-received tubes as a function of the ECR after a double-sided oxidation at 1000 C and F/F combination of heating and cooling rates

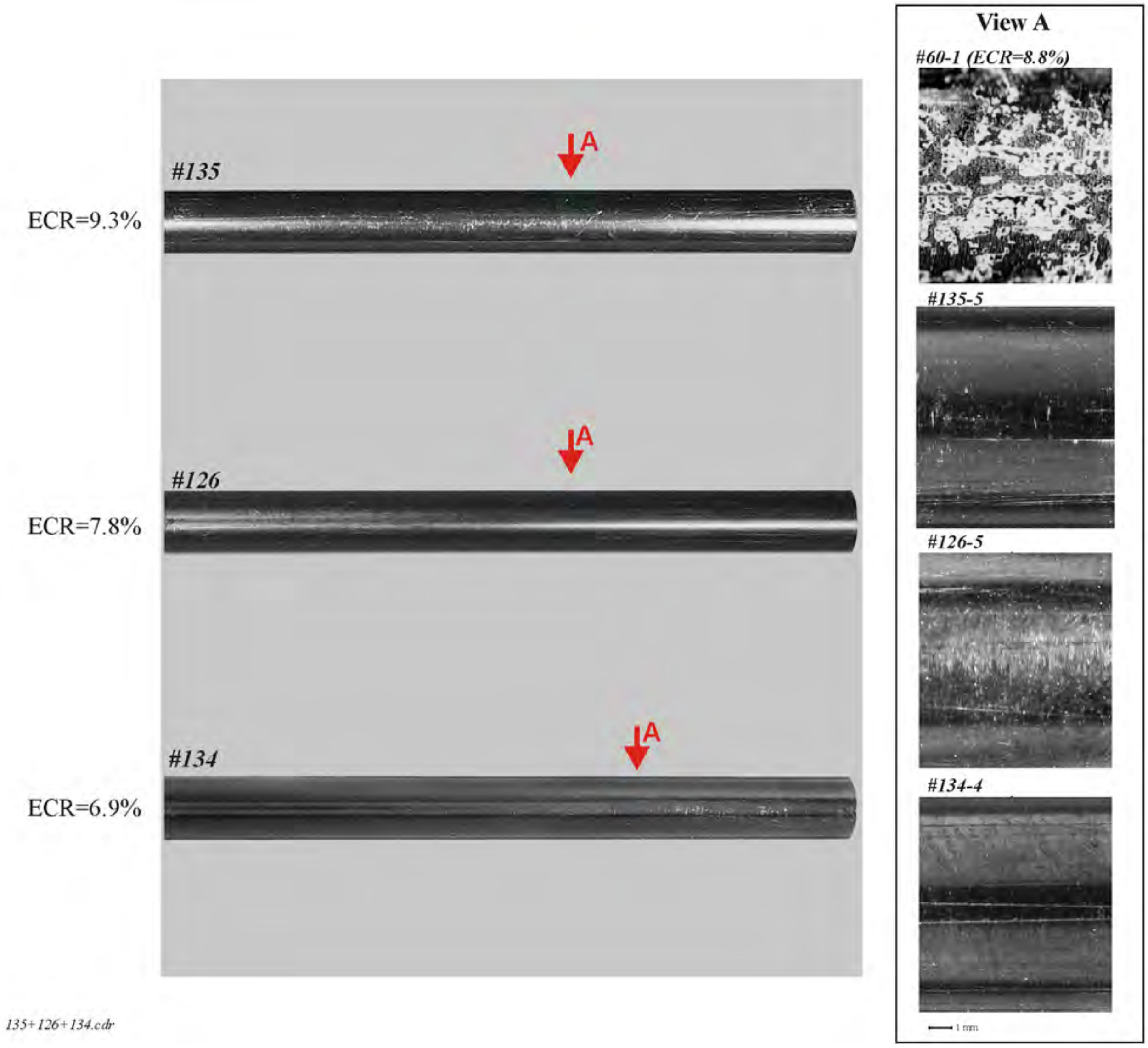


Fig. F-2. Appearance of E635 standard as-received tubes as a function of the ECR after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

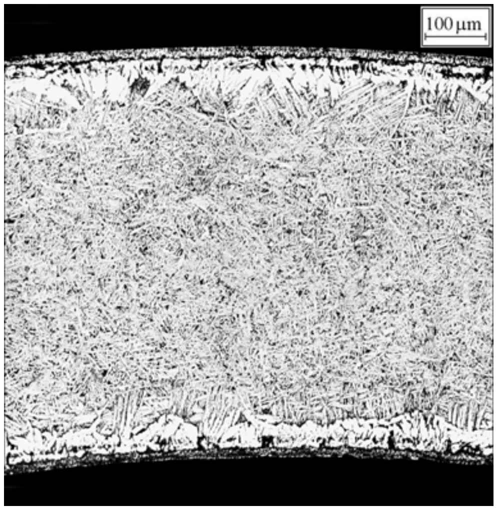
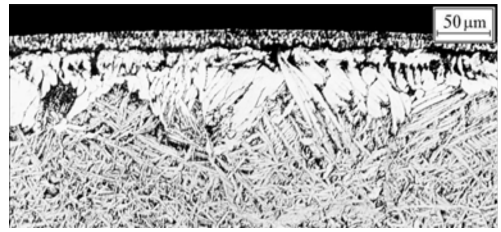
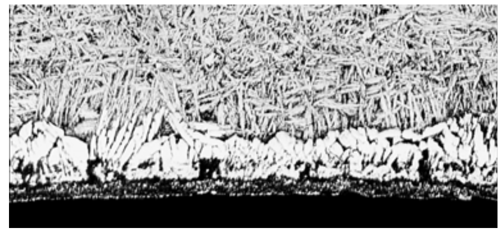
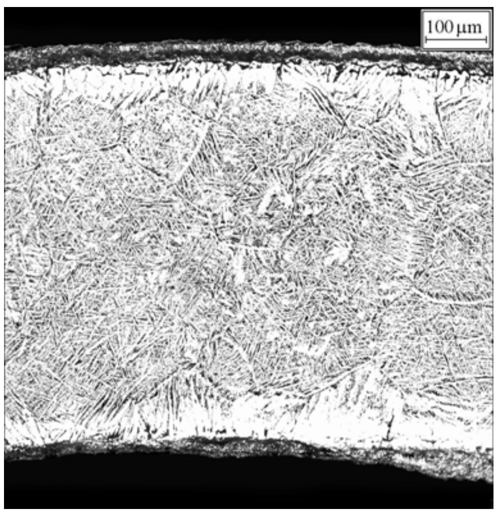
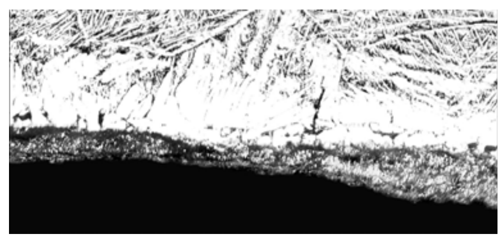
#127-5 ECR=5.3%	*Etched* 	*Etched*  
#138-5 ECR=9.4%	*Etched* 	*Etched*  

Fig. F-3. Microstructure of E635 standard as-received tubes after a double-sided oxidation at 1000 C and F/F combination of heating and cooling rates

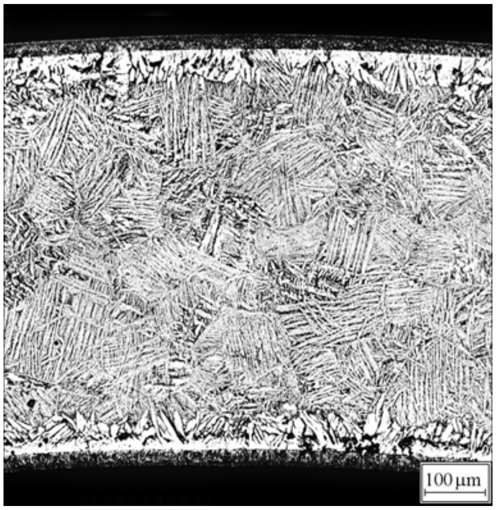
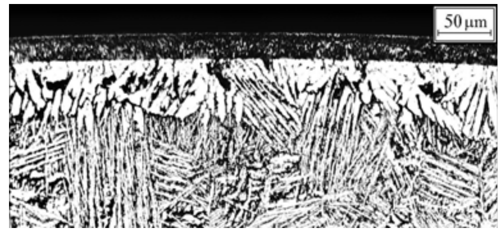
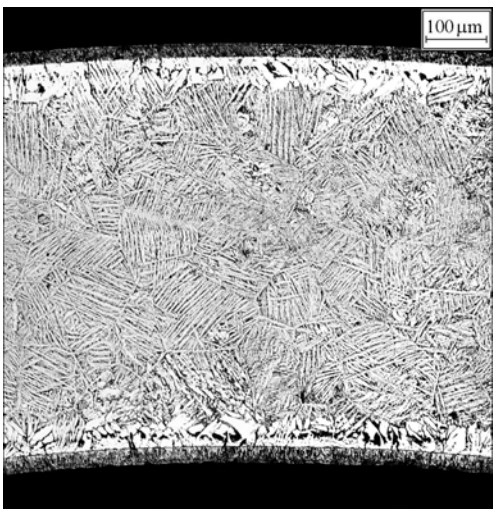
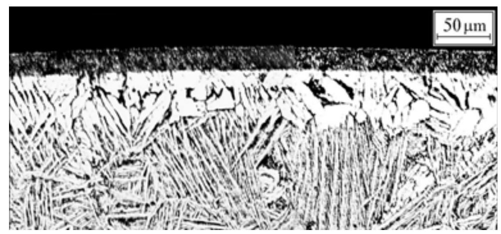
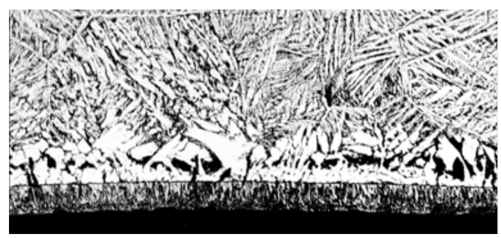
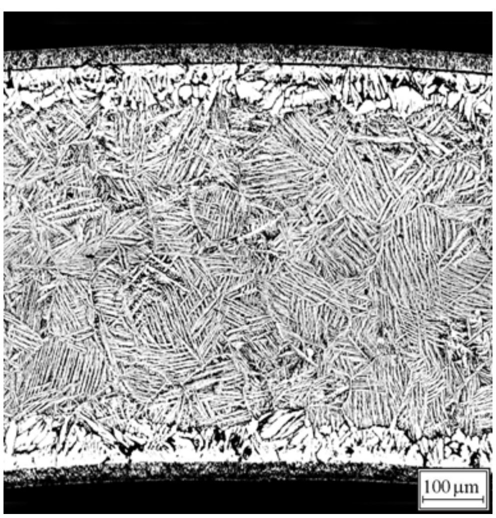
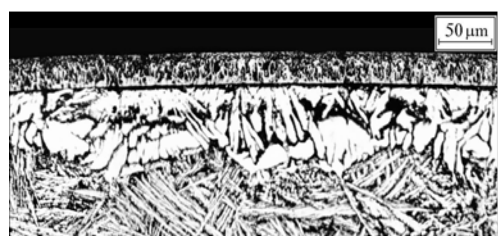
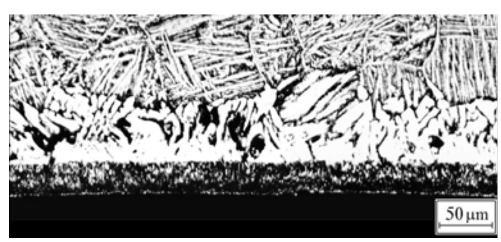
#134-4 ECR=6.9%	*Etched* 	*Etched*  
#126-5 ECR=7.8%	*Etched* 	*Etched*  
#135-5 ECR=9.3%	*Etched* 	*Etched*  

Fig. F-4. Microstructure of E635 standard as-received tubes after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

APPENDIX G

Appearances and Microstructures of Zry-4 As-received Claddings after a Double-sided Oxidation at 1100 C and S/S, F/F Combinations of Heating and Cooling Rates

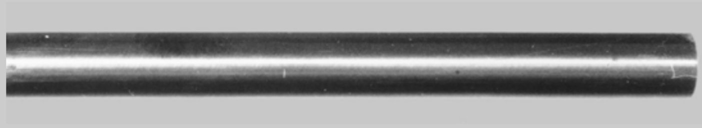
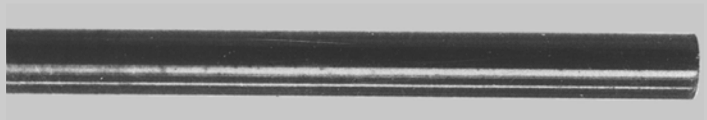
ECR=11.5 % F/F	**#64** 
ECR=11.3 % S/S	**#43** 

Fig. G-1. Appearance of Zry-4 as-received claddings after a double-sided oxidation at 1100 C and S/S, F/F combinations of heating and cooling rates

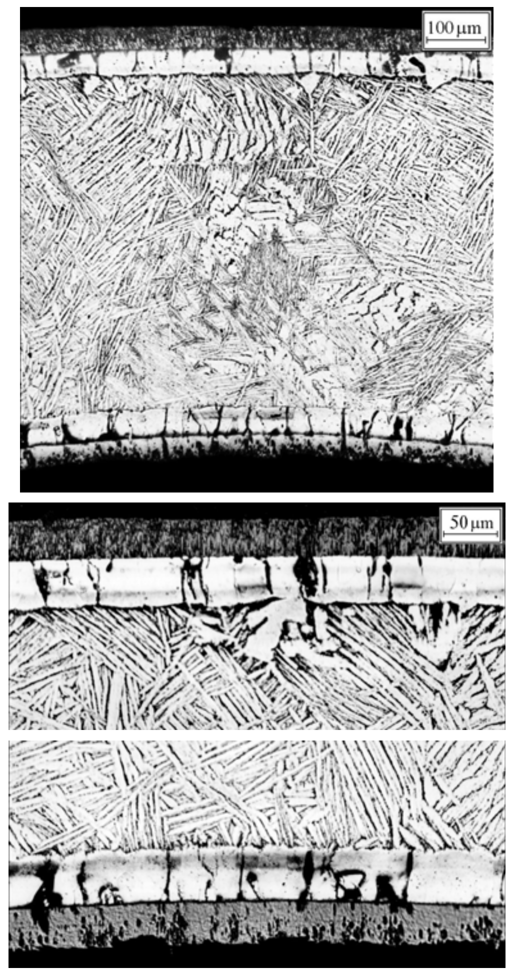
Etched	
#43-5 ECR=11.3 % (S/S)	#64-5 ECR=11.5 % (F/F)
	

Fig. G-2. Microstructure of Zry-4 as-received claddings after a double-sided oxidation at 1100 C and S/S, F/F combinations of heating and cooling rates

APPENDIX H

Appearance and Microstructure of E110, E635 As-received Tubes Manufactured on the Basis of the Sponge Zr, $E110_{low\ Hf}$ As-received Tubes after a Double-sided Oxidation at 900, 1000, 1100, 1200 C and F/F Combination of Heating and Cooling Rates

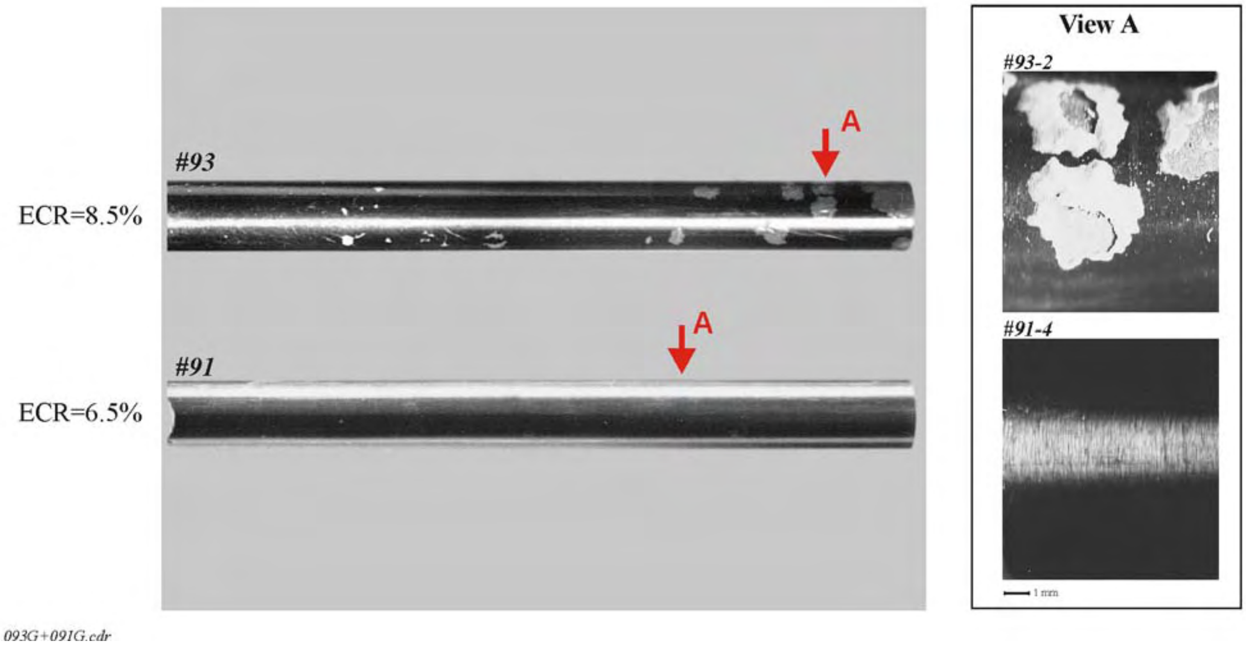


Fig. H-1. Appearance of $E110_{G(fr)}$ as-received tubes as a function of the ECR after a double-sided oxidation at 1000 C and F/F combination of heating and cooling rates

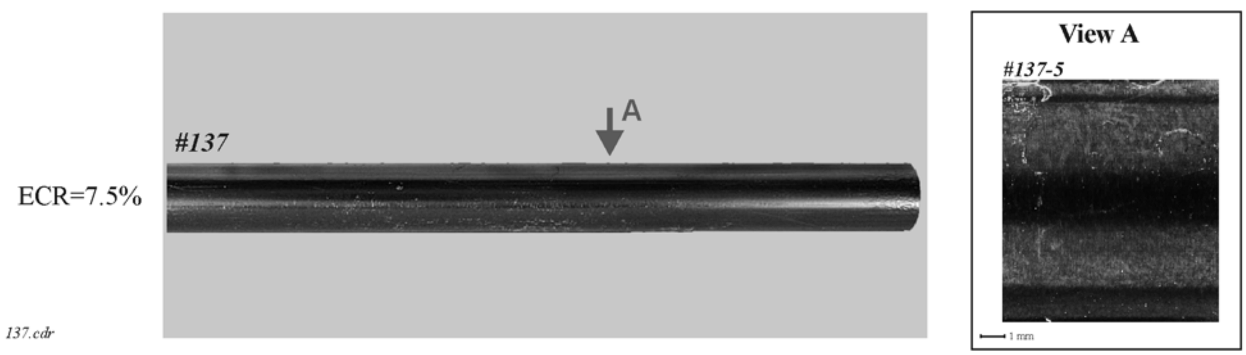


Fig. H-2. Appearance of $E110_{G(3ru)}$ as-received tubes as a function of the ECR after a double-sided oxidation at 900 C and F/F combination of heating and cooling rates

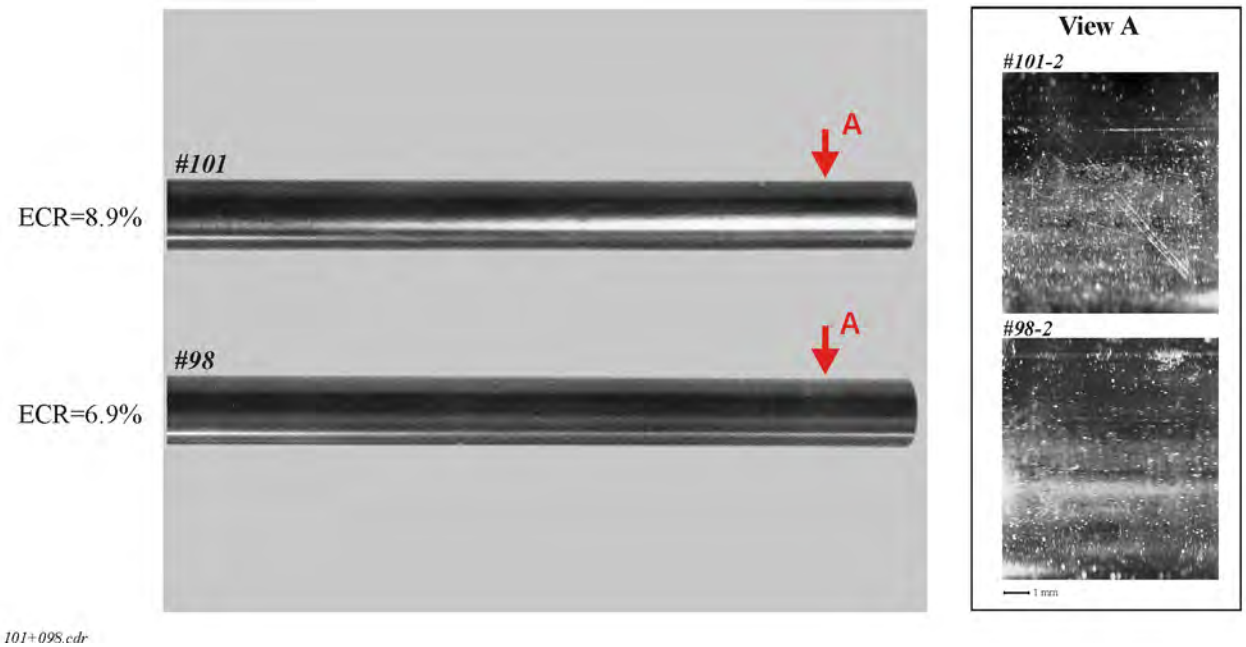


Fig. H-3. Appearance of $E110_{G(3ru)}$ as-received tubes as a function of the ECR after a double-sided oxidation at 1000 C and F/F combination of heating and cooling rates

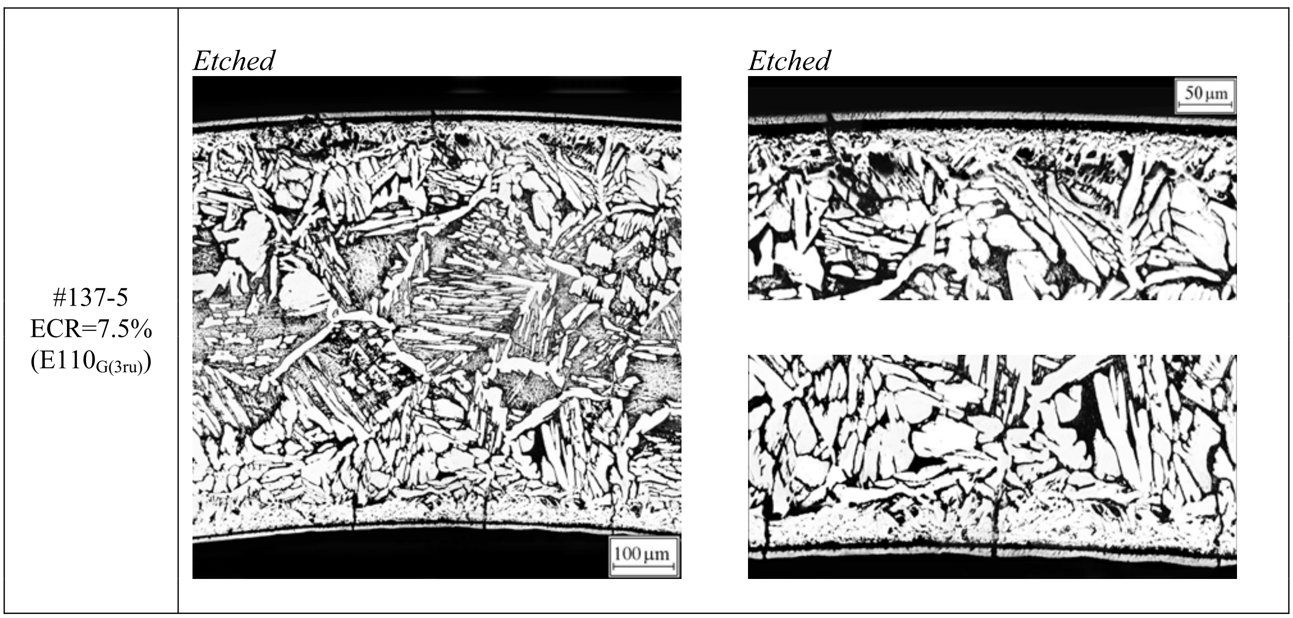


Fig. H-4. Microstructure of $E110_{G(3ru)}$ as-received tubes after a double-sided oxidation at 900°C and ECR=7.5 % (F/F combination of heating and cooling rates)

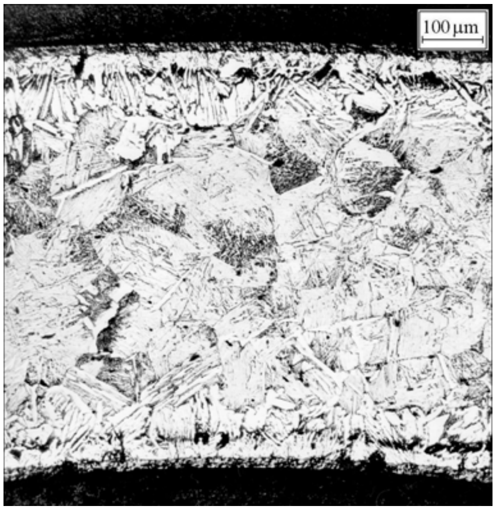
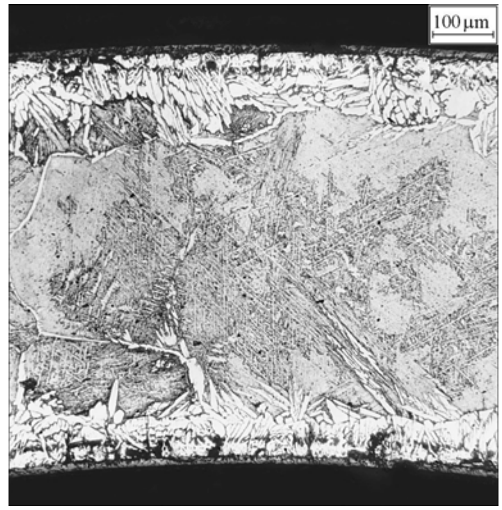
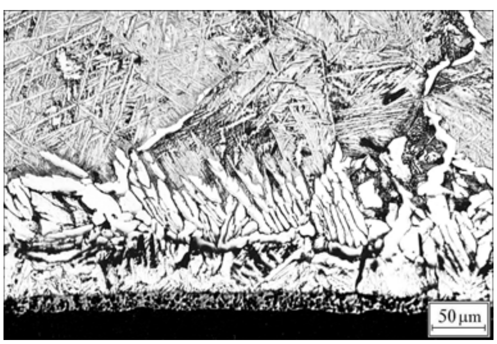
#98-4 ECR=6.9 %	$E110_{G(3ru)}$	#91-4 ECR=6.5 %	$E110_{G(fr)}$
Etched  		*Etched*  	
Etched   		*Etched*   	

Fig. H-5. Microstructure of $E110_{G(3ru)}$ and $E110_{G(fr)}$ as-received tubes after a double-sided oxidation at 1000°C and ECR=6.5–6.9 % (F/F combination of heating and cooling rates)

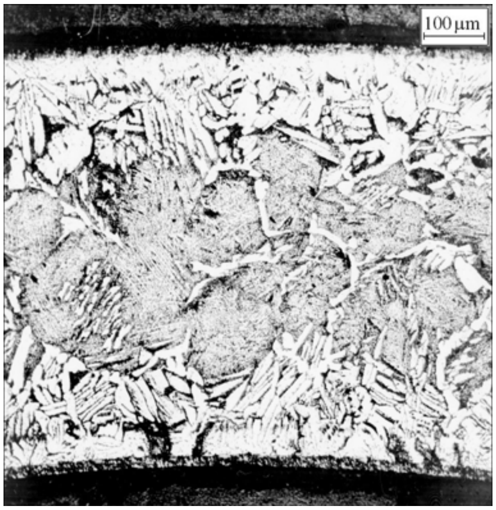
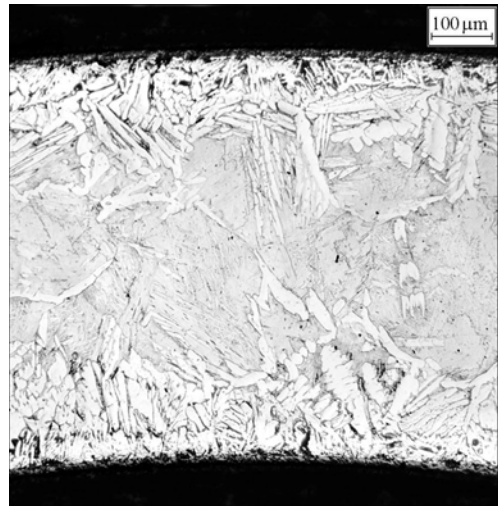
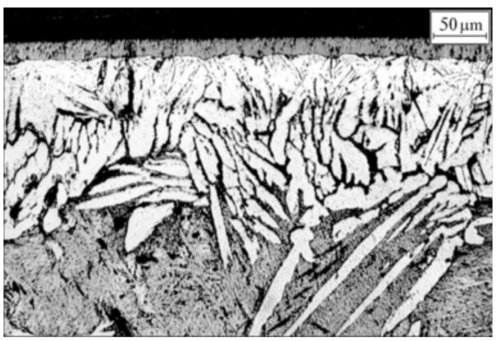
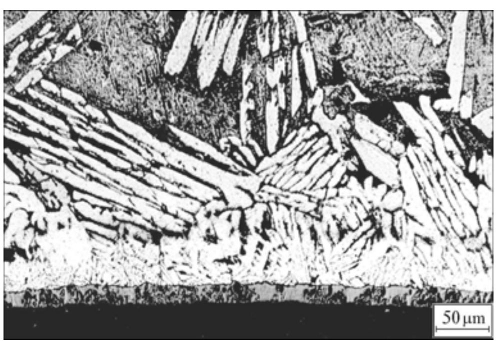
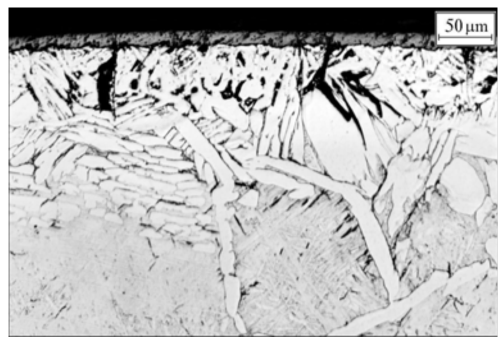
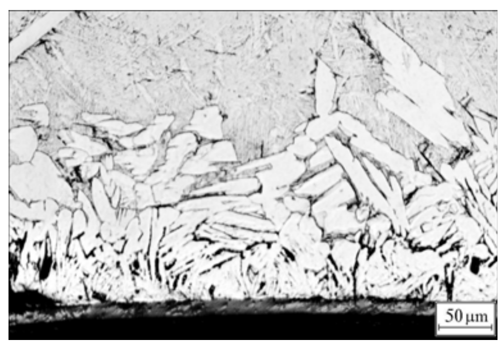
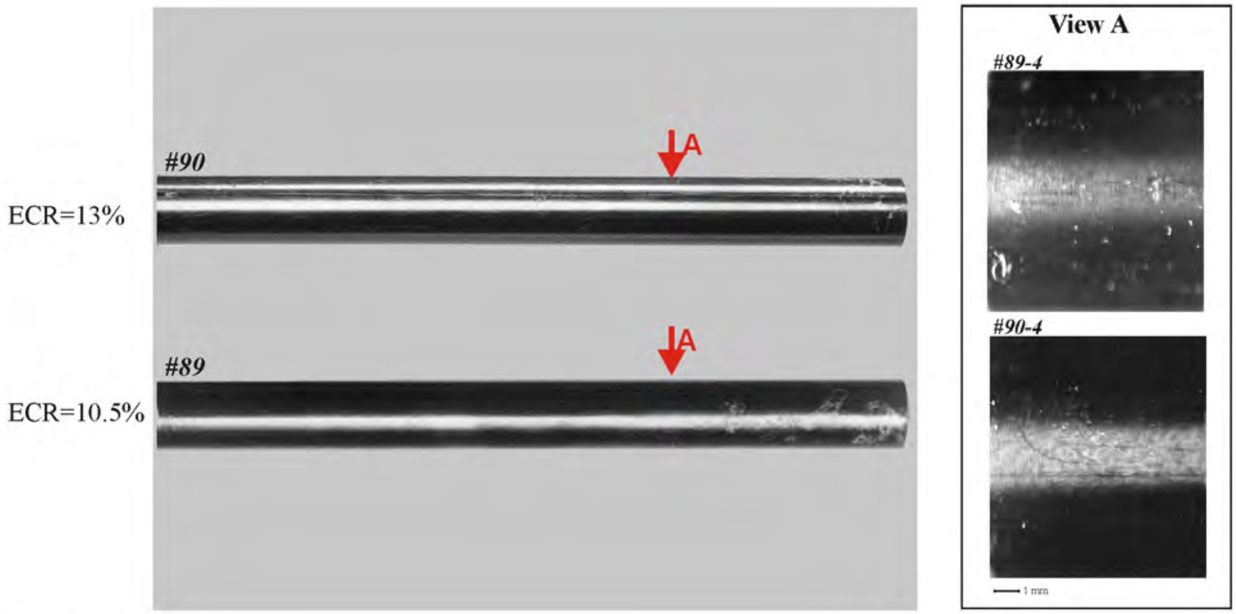
#101-4 ECR=8.9 %	E110$_{G(3ru)}$	#93-4 ECR=8.5 %	E110$_{G(fr)}$
Etched 		*Etched* 	
Etched  		*Etched*  	

Fig. H-6. Microstructure of E110$_{G(3ru)}$ and E110$_{G(fr)}$ as-received tubes after a double-sided oxidation at 1000°C and ECR=8.5–8.9 % (F/F combination of heating and cooling rates)



090+089.cdr

Fig. H-7. Appearance of E110$_{G(fr)}$ as-received tubes as a function of the ECR after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

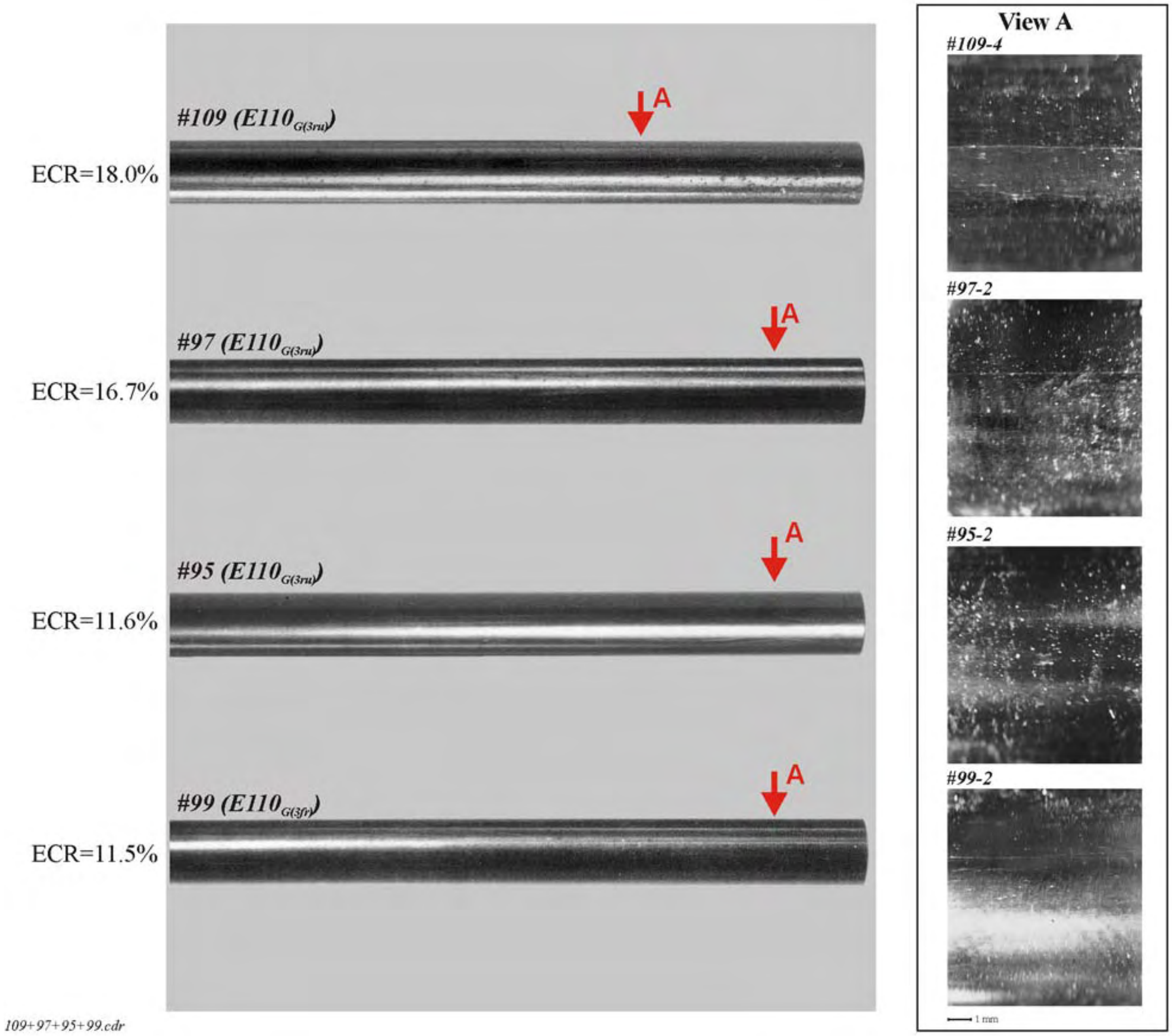


Fig. H-8. Appearance of $E110_{G(3ru)}$ and $E110_{G(3fr)}$ standard as-received tubes as a function of the ECR after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

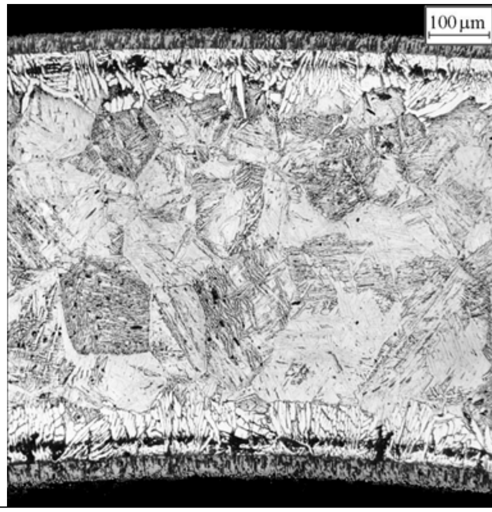
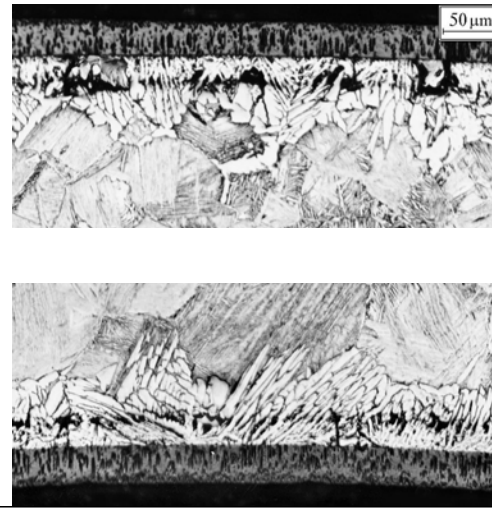
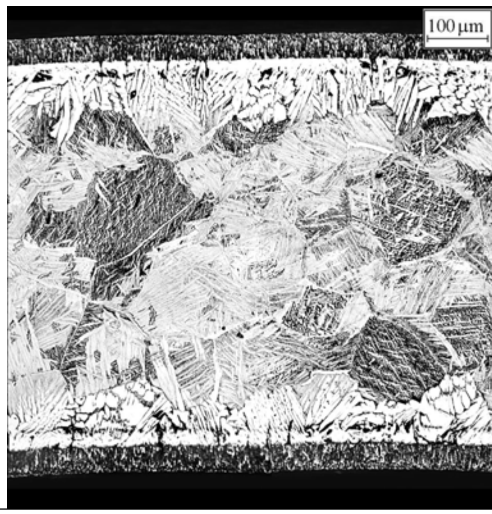
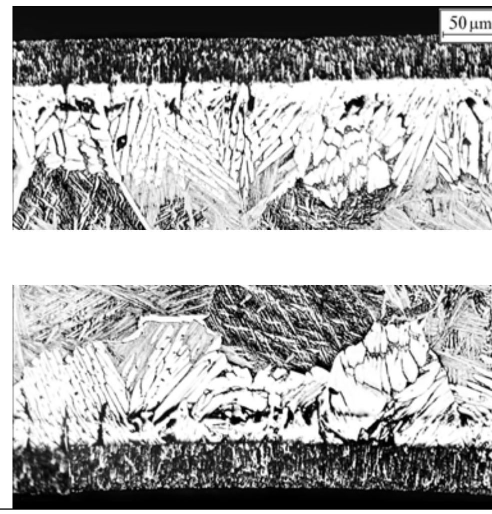
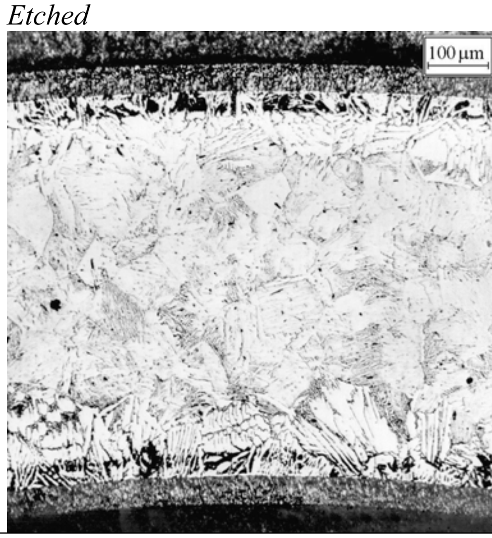
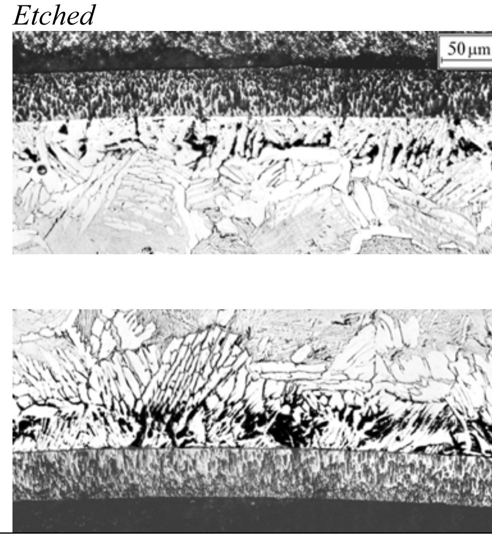
#89-4 ECR=10.5% (E110$_{G(fr)}$)	*Etched* 	*Etched* 
#99-4 ECR=11.5% (E110$_{G(3fr)}$)	*Etched* 	*Etched* 
#90-4 ECR=13.0% (E110$_{G(fr)}$)	*Etched* 	*Etched* 

Fig. H-9. Microstructure of E110$_{G(fr)}$, E110$_{G(3fr)}$ as-received tubes after a double-sided oxidation at 1100°C and F/F combination of heating and cooling rates

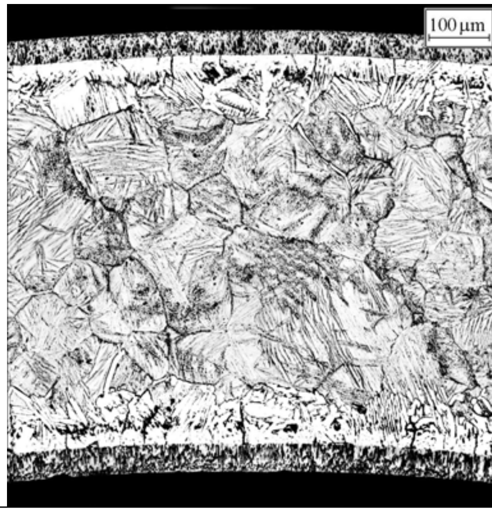
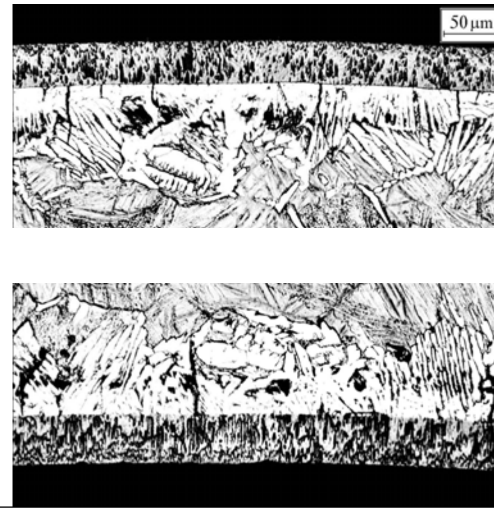
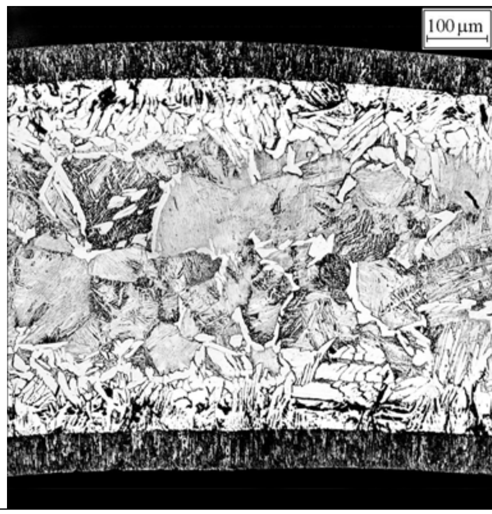
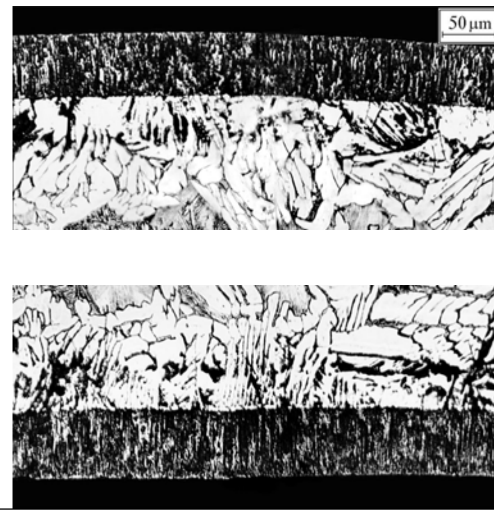
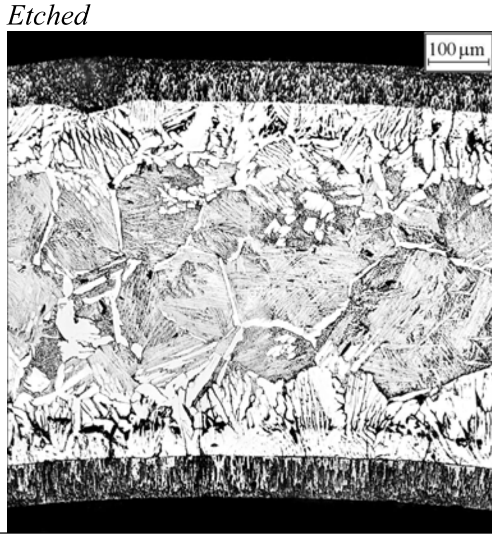
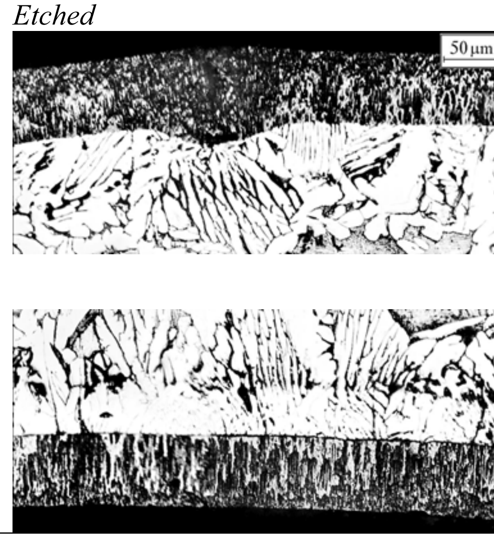
#95-7 ECR=11.6%	*Etched*  	*Etched* 
#97-10 ECR=16.7%	*Etched*  	*Etched* 
#109-5 ECR=18.0%	*Etched*  	*Etched* 

Fig. H-10. Microstructure of $E110_{G(3ru)}$ as-received tubes after a double-sided oxidation at 1100°C and F/F combination of heating and cooling rates

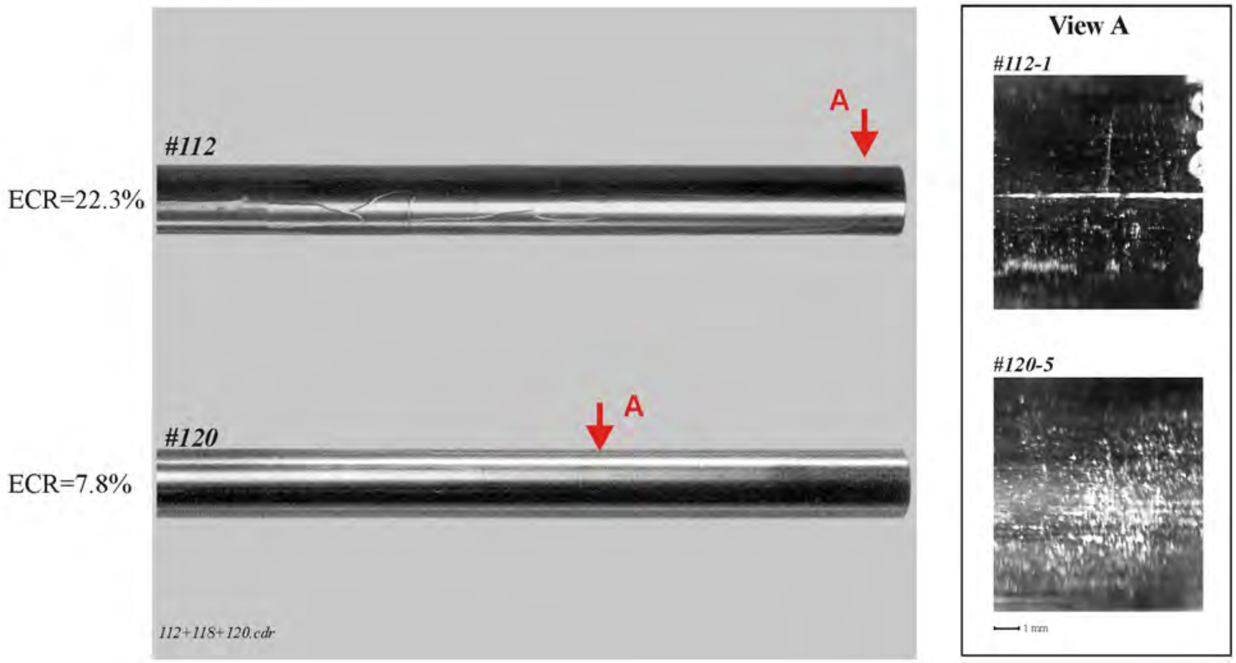
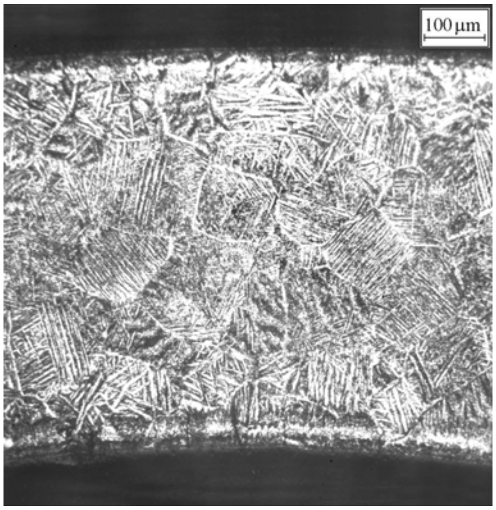
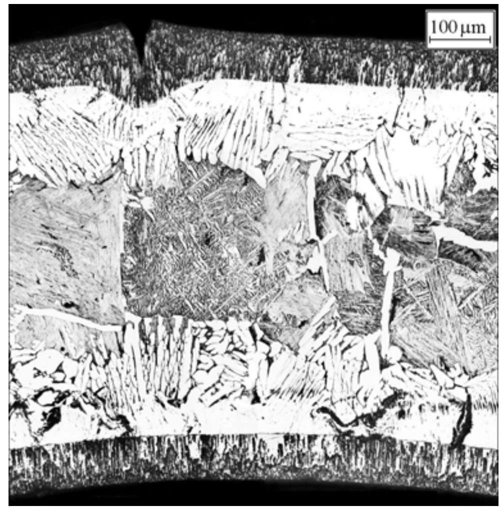
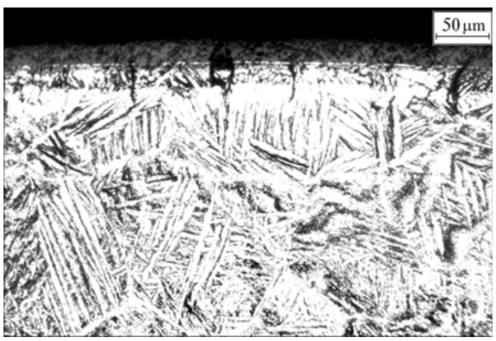
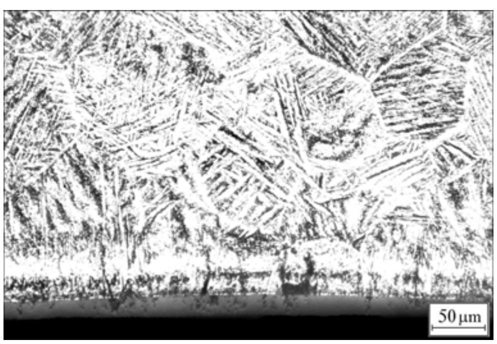
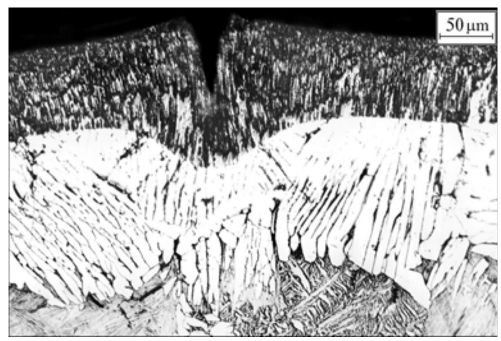


Fig. H-11. Appearance of $E110_{G(3ru)}$ as-received tubes as a function of the ECR after a double-sided oxidation at 1200 C and F/F combination of heating and cooling rates

<table>
<tr><td>#120-5
ECR=7.8 %</td><td></td><td>#112-2
ECR=23.5 %</td><td></td></tr>
<tr><td colspan="2">Etched

</td><td colspan="2">Etched

</td></tr>
<tr><td colspan="2">Etched



</td><td colspan="2">Etched


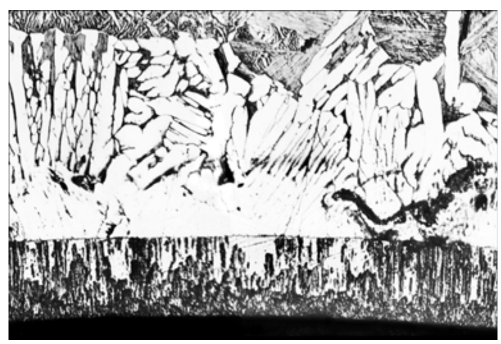
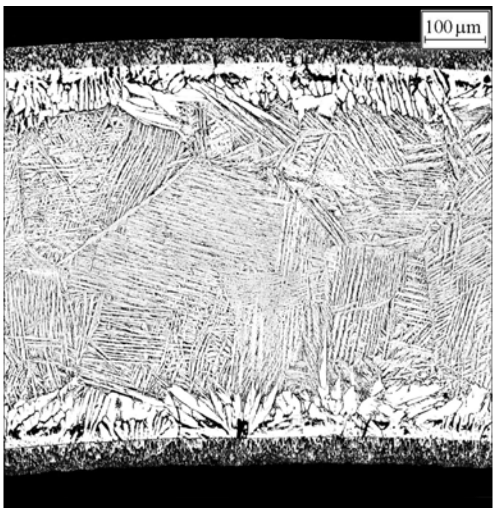
</td></tr>
</table>

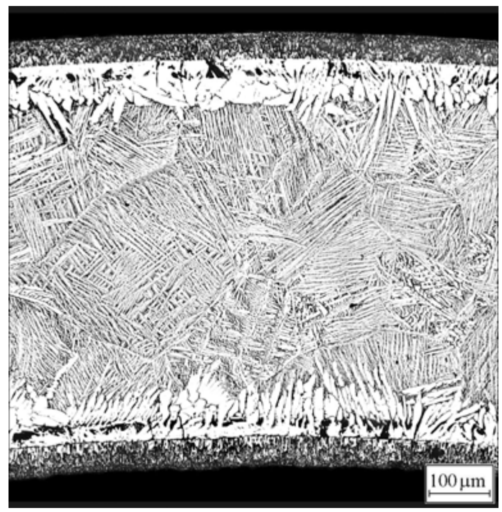
Fig. H-12. Microstructure of $E110_{G(3ru)}$ as-received tubes after a double-sided oxidation at 1200°C and F/F combination of heating and cooling rates

#108-4	ECR=11.0 %	#100-4	ECR=12.5 %

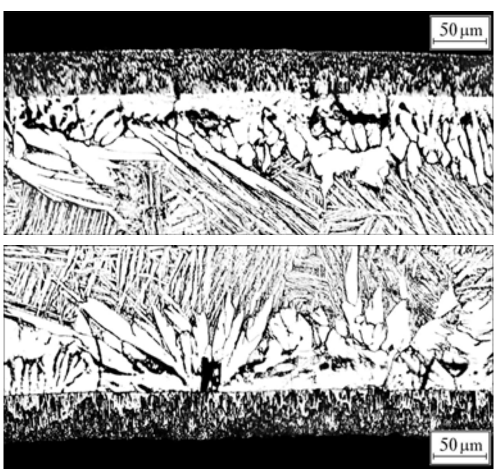
Etched



Etched



Etched



Etched

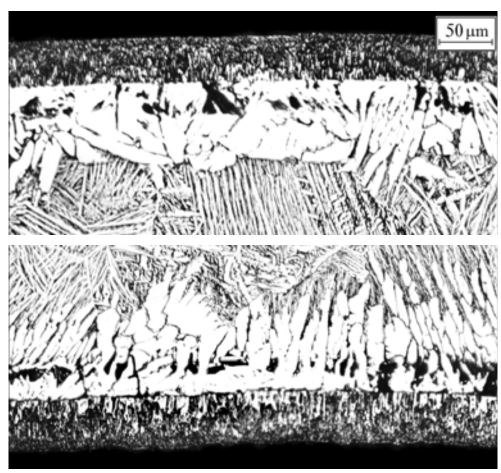


Fig. H-13. Appearance and microstructure of E635$_{G(fr)}$ as-received tubes after a double-sided oxidation at 1100°C and F/F combination of heating and cooling rates

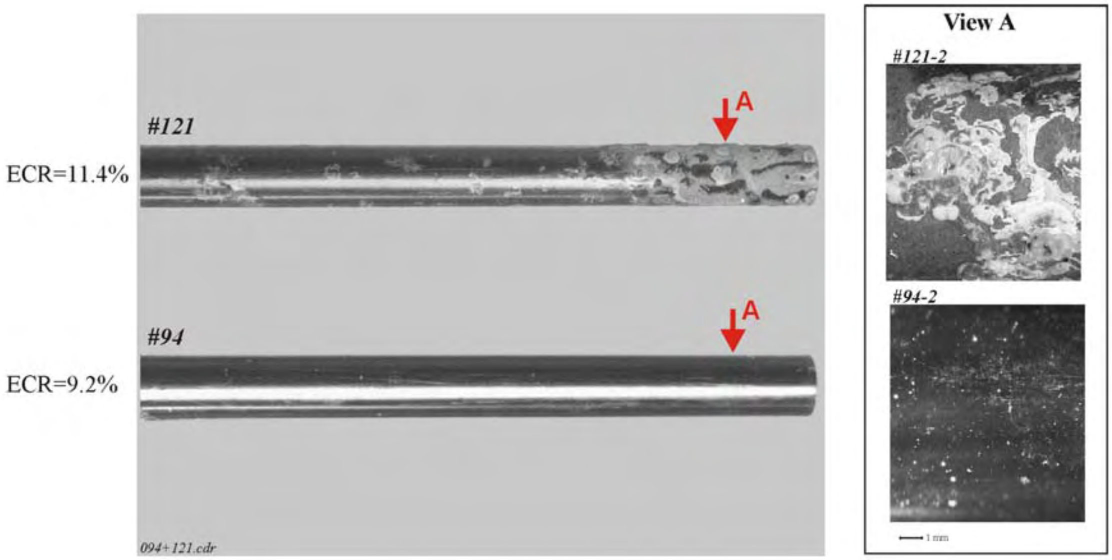


Fig. H-14. Appearance of E110$_{low\ Hf}$ as-received tubes after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

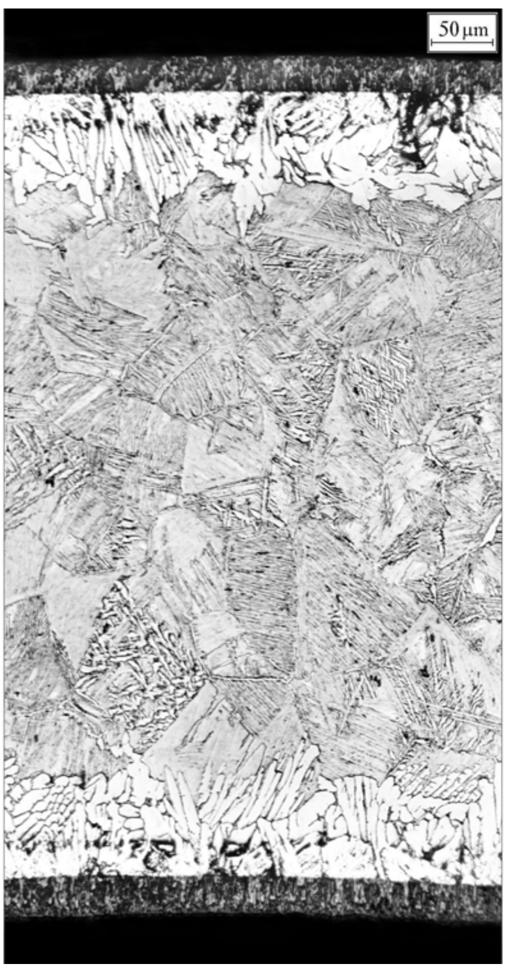
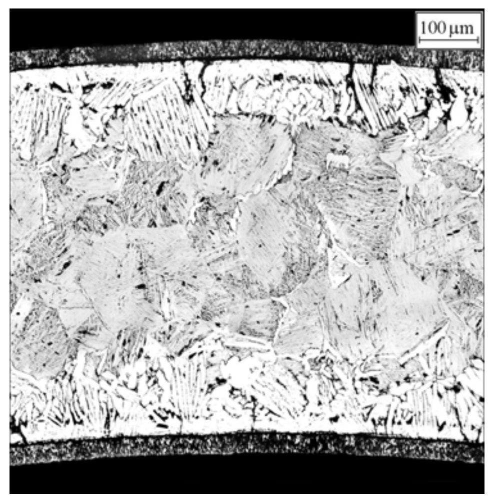
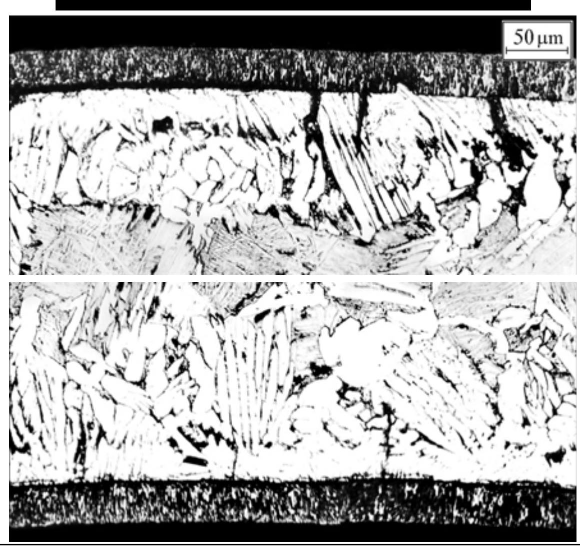
#94-4 ECR=9.2 %	**#121-4** ECR=11.4 %
Etched	Etched
	

Fig. H-15. Microstructure of E110$_{low\ Hf}$ as-received tubes after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

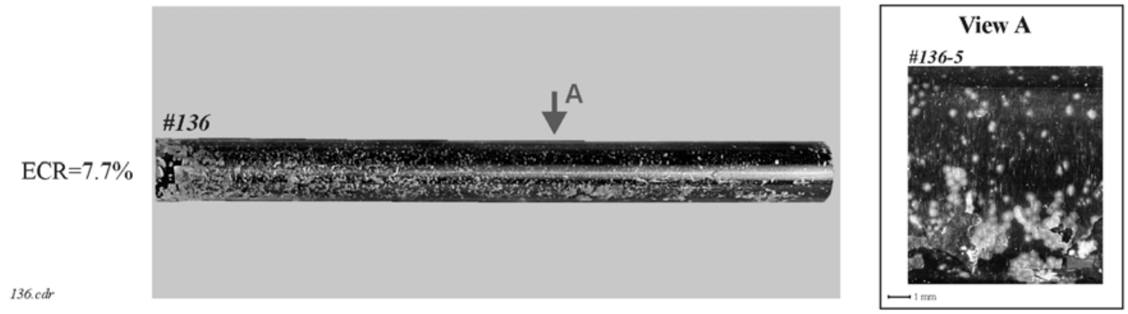


Fig. H-16. Appearance of E110$_m$ as-received machined/etched tubes after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

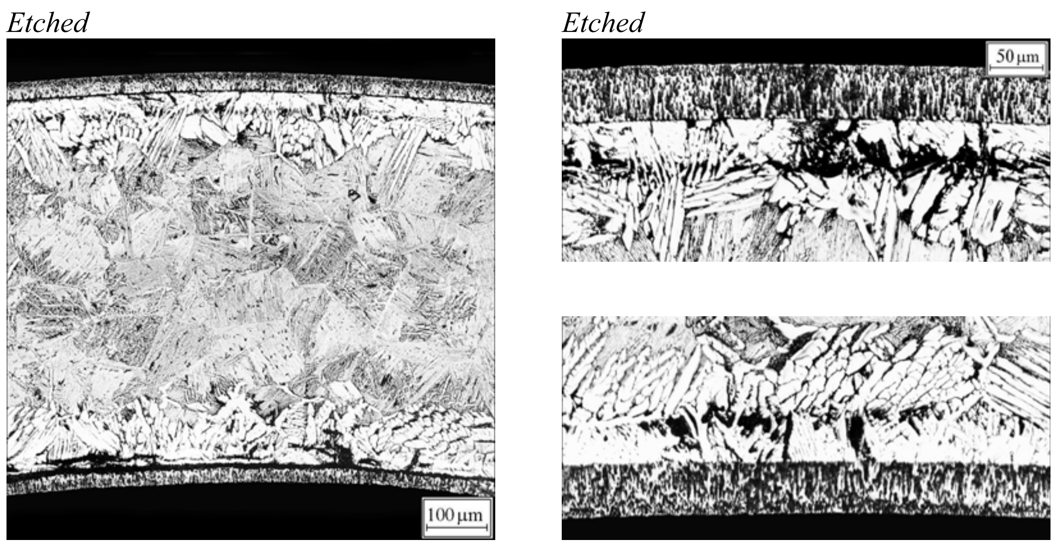
#136-5 ECR=7.7% (E110$_m$)	

Fig. H-17. Microstructure of E110$_m$ as-received machined/etched tubes after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

APPENDIX I

Appearance and Microstructure of E110 Commercial Irradiated Cladding after a Double-sided Oxidation at 1000, 1100, 1200 C and S/S, S/F, F/F Combinations of Heating and Cooling Rates

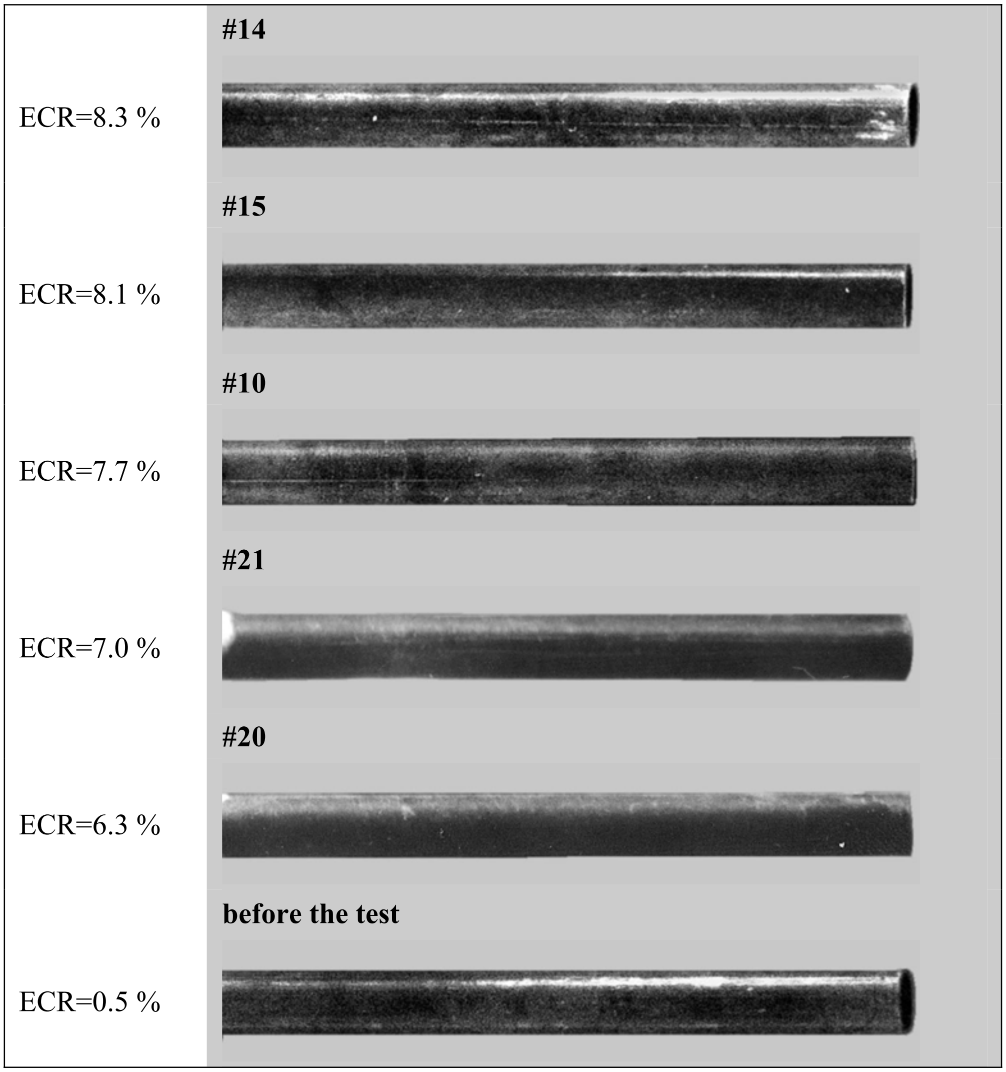


Fig. I-1. Appearance of E110 commercial irradiated claddings before and after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

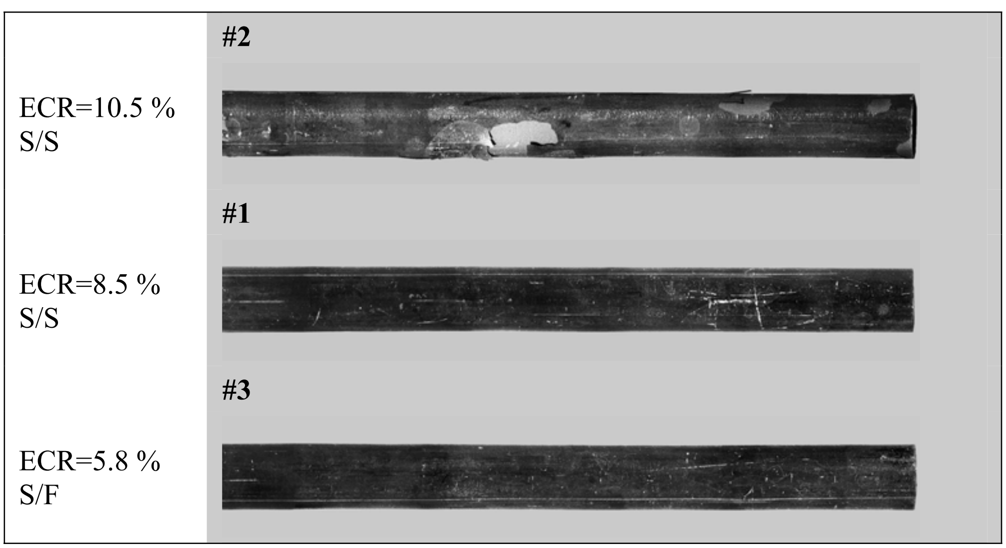


Fig. I-2. Appearance of E110 commercial irradiated claddings after a double-sided oxidation at 1100 C and S/S, S/F combinations of heating and cooling rates

Fig. I-3. Appearance of E110 commercial irradiated claddings after a double-sided oxidation at 1000 C, 1200 C and F/F combination of heating and cooling rates

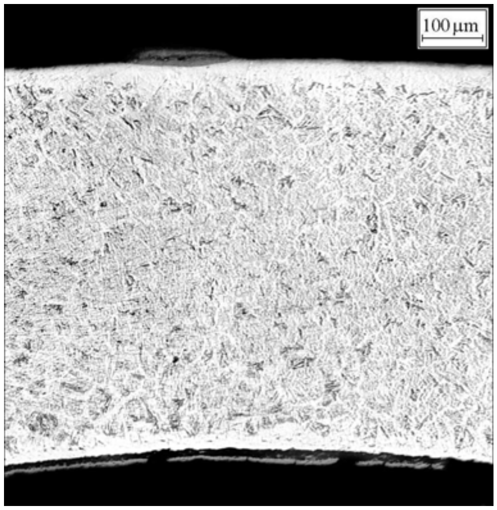
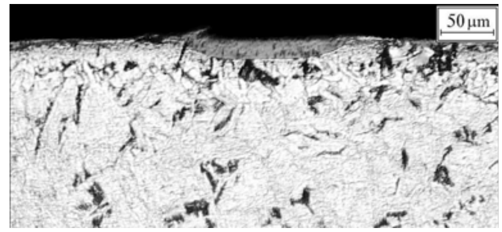
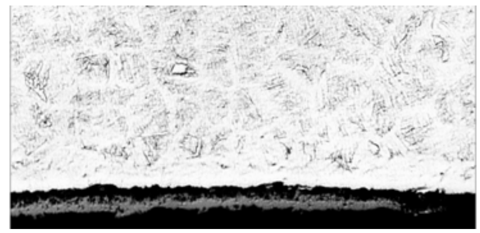
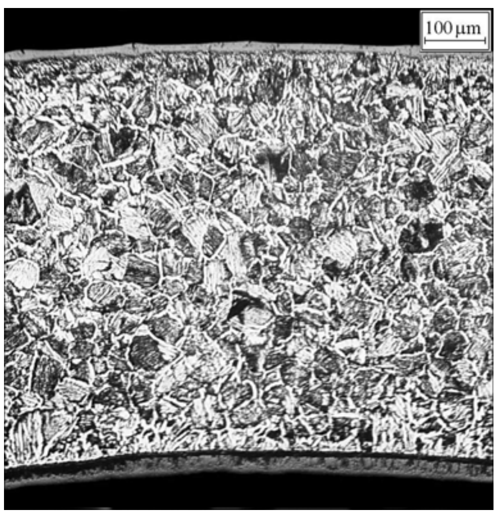
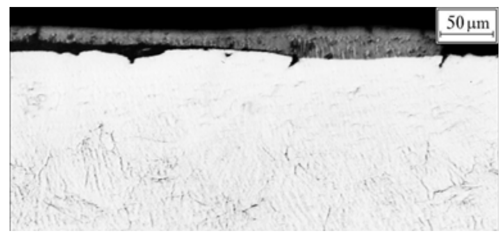
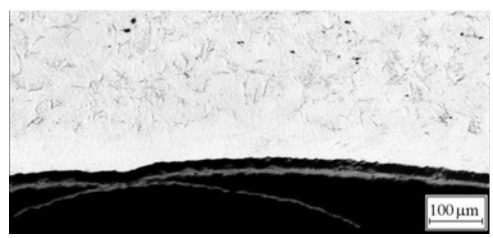
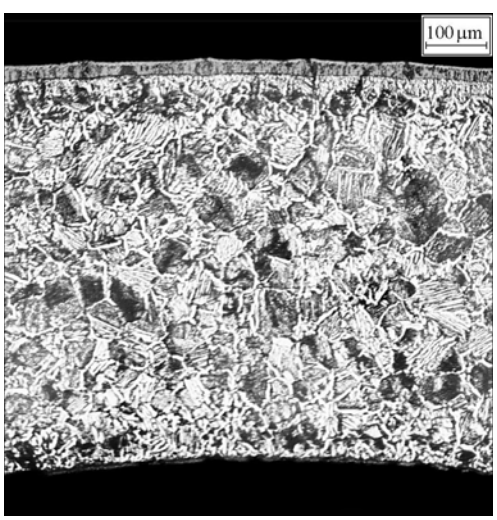
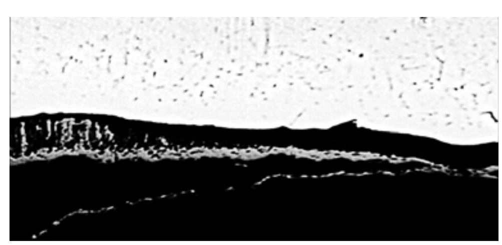
#3-4 ECR=5.8% S/F	*Etched* 	*Etched*  *Polished* 
#1-4 ECR=8.5% S/S	*Etched* 	*Polished*  
#2-4 ECR=10.5% S/S	*Etched* 	*Polished*  

Fig. I-4. Microstructure of E110 commercial irradiated cladding after a double-sided oxidation at 1100 C and S/F, S/S combinations of heating and cooling rates

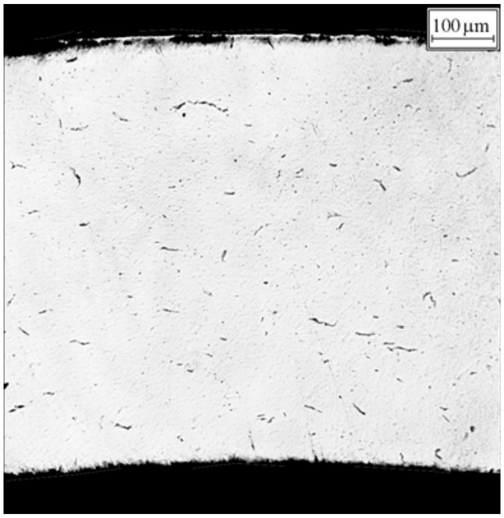
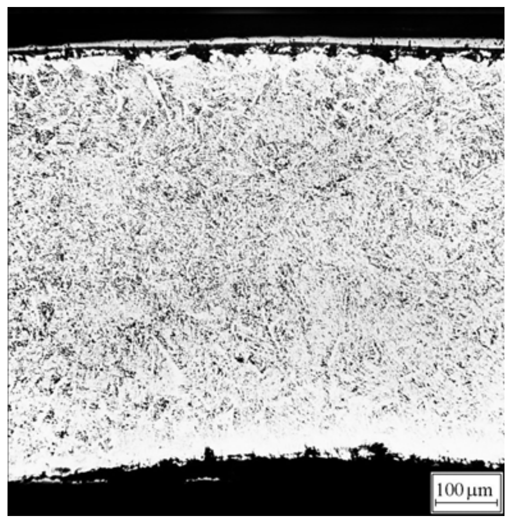
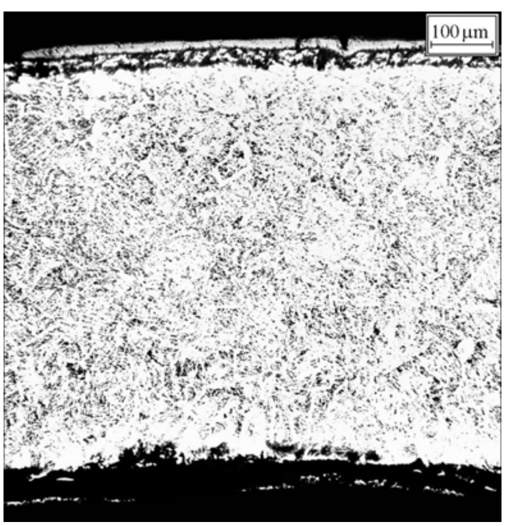
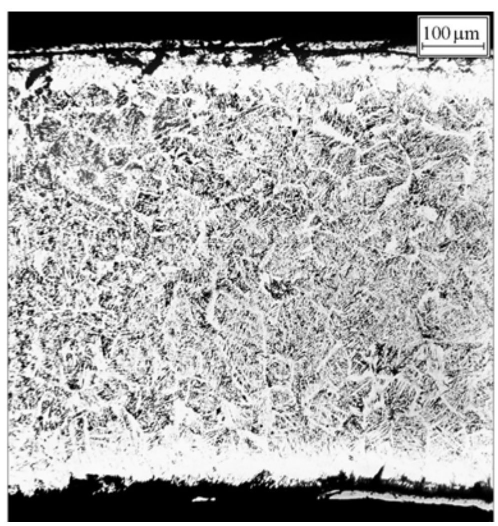
Etched	
before the oxidation tests  	#20-4 ECR=6.3 % 
#21-4 ECR=7.0 %  	#10-4 ECR=7.7 % 
#15-4 ECR=8.1 %  	#14-4 ECR=8.3 % 

Fig. I-5. Microstructure of E110 commercial irradiated claddings before and after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

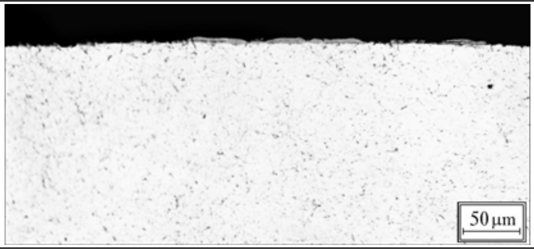
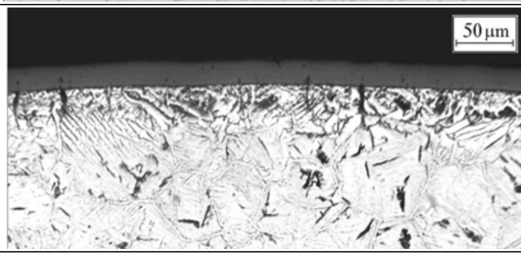
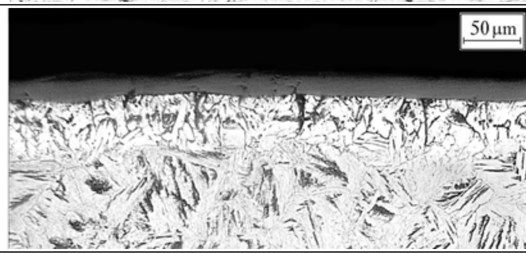
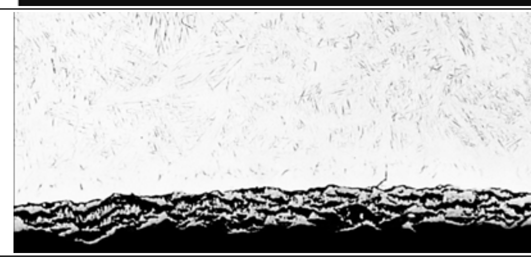
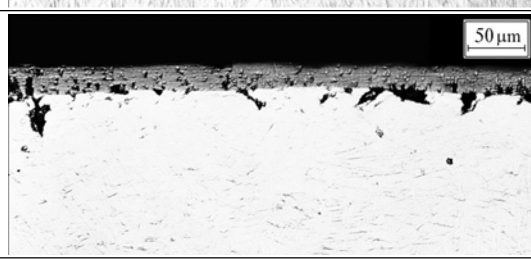
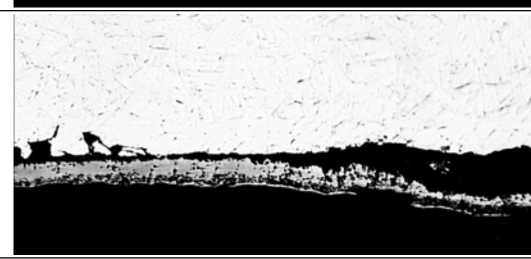
Sample	External surface	Internal surface
Before oxidation tests (Polished)		
#20-4 ECR=6.3 % (Etched)		
#21-4 ECR=7.0 % (Etched)		
#10-4 ECR=7.7 % (Polished)		
#15-4 ECR=8.1 % (Polished)		
#14-4 ECR=8.3 % (Polished)		

Fig. I-6. Microstructure of ZrO_2 and α-Zr(O) layers in E110 commercial irradiated cladding before and after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

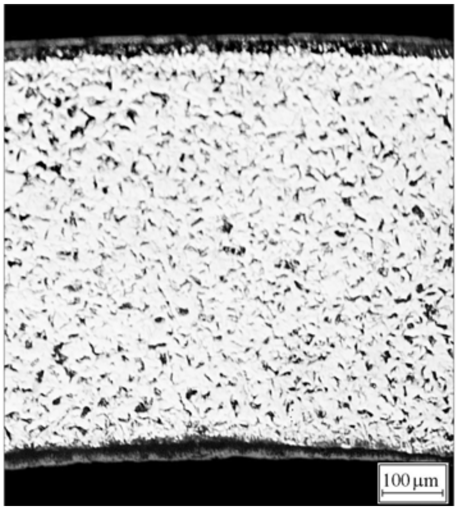
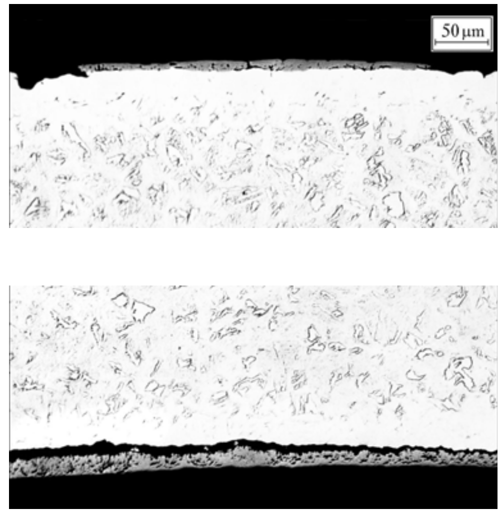
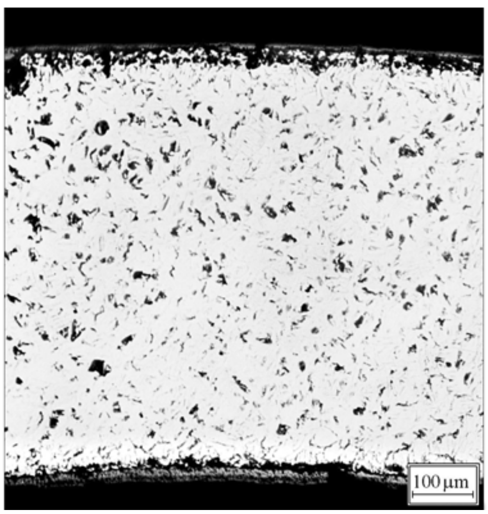
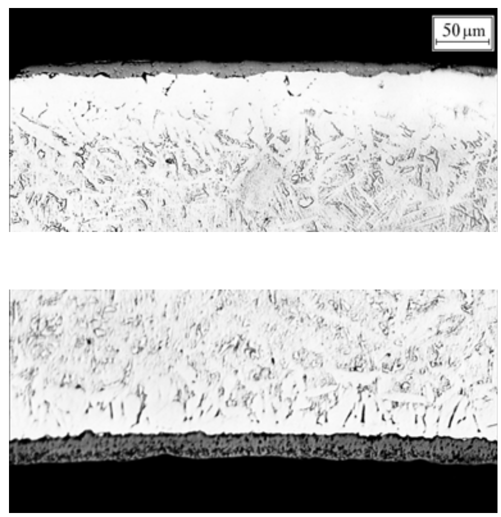
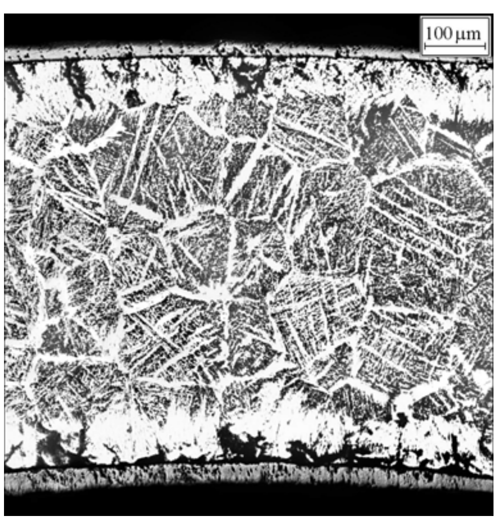
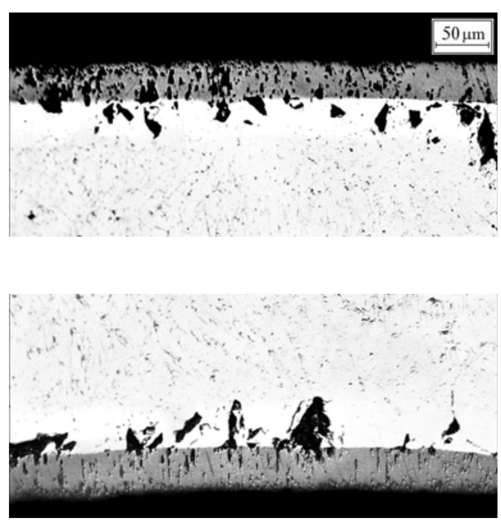
#16-4 ECR=4.7% T=1000 C	*Etched* 	*Polished* 
#17-4 ECR=6.5% T=1000 C	*Etched* 	*Polished* 
#18-4 ECR=16.0% T=1200 C	*Etched* 	*Polished* 

Fig. I-7. Microstructure of E110 commercial irradiated cladding after a double-sided oxidation at 1000°C, 1200 C and F/F combination of heating and cooling rates

NRC FORM 335 (9-2004) NRCMD 3.7 — U.S. NUCLEAR REGULATORY COMMISSION **BIBLIOGRAPHIC DATA SHEET** *(See instructions on the reverse)*	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.) NUREG/IA-0211
2. TITLE AND SUBTITLE EXPERIMENTAL STUDY OF EMBRITTLEMENT OF ZR-1% NB VVER CLADDING UNDER LOCA RELEVANT CONDITIONS	3. DATE REPORT PUBLISHED MONTH: March — YEAR: 2005 4. FIN OR GRANT NUMBER Y6789
5. AUTHOR(S) L. Yegorova, K. Lioutov, N. Jouravkova, A. Konobeev V. Smirnov, V. Chesanov, A. Goryachev	6. TYPE OF REPORT IRSN 2005-194 NSI RRC KI 3188 7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Nuclear Safety Institute of Russian Research Centre "Kurchatov Institute" Moscow, Russian Federation
State Research Centre "Research Institute of Atomic Reactors" Dimitrovgrad, Russian Federation

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

During 2001-2004, research was performed to develop test data on the embrittlement of niobium-bearing (Zr-1%Nb) cladding of the VVER type under loss-of-coolant accident (LOCA) conditions. Procedures were developed and validated to determine the zero ductility threshold. Pre-test and post-test examinations included weight gain and hydrogen content measurements, preparation of metallographic samples, and examination of samples using optical microscopy, scanning electron microscopy and transmission electron microscopy. Sensitivity of the zero ductility threshold to heating and cooling rates was determined. Oxidation kinetics and ductility threshold were measured for the standard E110 alloy, six variants with different impurities, Zircaloy, and irradiated E110. Oxidation temperatures were varied from 800-1200 C, and mechanical (ring compression) testing temperatures were varied from 20-300 C. It was concluded that (a) the current type of E110 cladding has an optimal microstructure, (b) oxidation and ductility of the oxidized cladding are very sensitive to microchemical composition and surface finish, (c) the use of sponge zirconium for fabrication of cladding tubes provides a significant reduction of the oxidation rate and an increase in the zero ductility threshold, and (d) additional improvement in oxidation and ductility can be achieved by polishing the cladding surface.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*		13. AVAILABILITY STATEMENT
Alloy	Niobium	unlimited
Cladding	Oxidation	14. SECURITY CLASSIFICATION
E110	Ring Compression	*(This Page)* unclassified
Hydrogen Content	Russian	*(This Report)* unclassified
Kurchatov Institute	Zirconium	15. NUMBER OF PAGES
Loss-of-Coolant Accident	Zircaloy	16. PRICE
Material Properties		