APPENDIX A

Description of Test Apparatus and Test Procedures

A-1. Description of oxidation test apparatus

The scheme of oxidation apparatus is presented in Fig. 3.2 (see section 3). The oxidation facility consists of the following basic elements:

- electric furnace;
- device for the movement of E110 sample in the several given positions (cold position, hot position, quench position);
- steam generator;
- system to supply the argon to the oxidation facility;
- measurement apparatus (measurement of temperature inside and outside of E110 sample, temperature of water in the steam generator);
- tank with the water in the low part of facility.

The electric furnace provided the radiant heating and cooling of cladding sample with the different temperature rates (see the more detail information in Appendix A-2). The steam generator provided the generation of water steam with the following parameters:

- temperature: 150 C;
- mass flow rate: 0.01–0.04 g/s (mass flow rate is a function of electric power);
- atmospheric pressure.

The system to supply the argon to the oxidation facility was used at the beginning of each test mode. This system devoted the cleaning of gas atmosphere inside the test facility from air. The temperature limit was used to change the type of coolant. The Ar flow was stopped at the temperature about of 300 C and after that the heating was continued with the water steam.

The important details of temperature measurements are described in Appendix A-4. The tank with water in the low part of facility devoted the opportunity to perform cooling of cladding sample under quench conditions.

A-2. Description of oxidation procedures

The five combinations of heating and cooling rates were used for this experimental program (see Fig. 3.3 in section 3):

1. Slow heating and slow cooling (S/S).
2. Slow heating and fast cooling (S/F).
3. Fast heating and slow cooling (F/S).
4. Fast heating and fast cooling (F/F).
5. Fast heating and quench cooling (F/Q).

The characterization of major types of test modes is described below.

<u>Slow heating (Fig. A-1):</u>

- the cladding sample was installed in the hot position (see Fig. 3.2 of section 3);
- the air atmosphere in the electric furnace was replaced on the argon atmosphere;
- the electric furnace was switched on and the cladding sample was heated to 150 C with the temperature rate 0.5 C/s;
- the argon atmosphere was replaced on the water steam atmosphere and the heating of cladding sample was continued with the rate 0.5 C/s to the hold temperature.

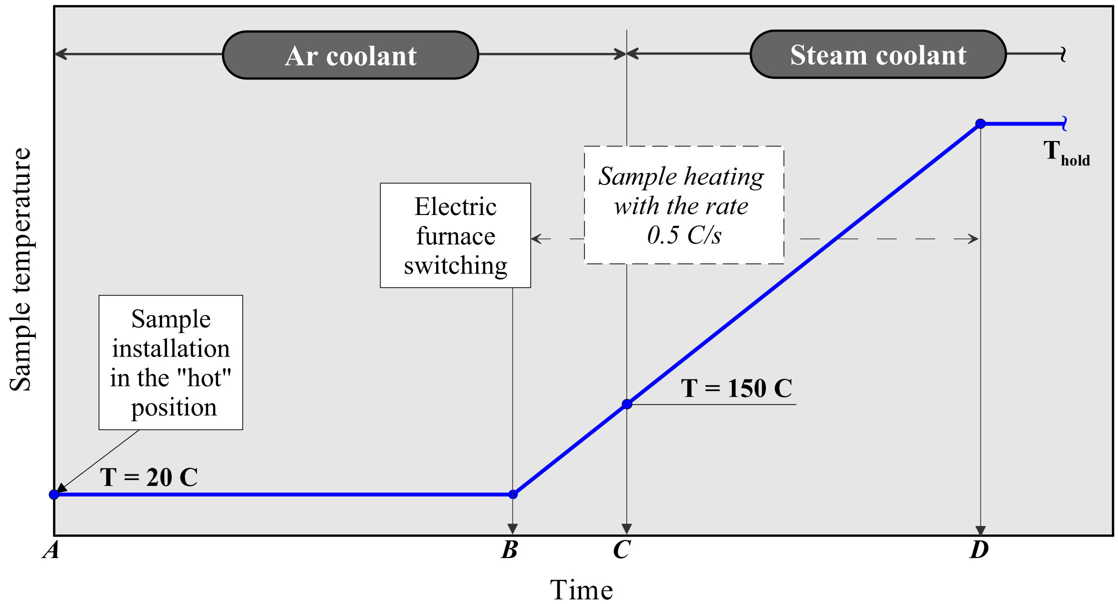

Fig. A-1. Oxidation mode with the "slow" heating: sequence diagram

Fast heating (Fig. A-2):

- the cladding sample was installed in the cold position (see Fig. 3.2 of section 3);
- the air atmosphere in the electric furnace was replaced on the argon atmosphere;
- the electric furnace was switched on and the gas medium inside the electric furnace (in the hot position) was heated to 150 C after that the argon atmosphere was replaced on the water steam and the heating of the furnace was continued during 600 seconds to the hold temperature (in accordance with the thermocouple #2 data (see Fig. 3.2 of section 3)), the temperature of cladding sample, which was located in the cold position was not above 150 C at the end of this stage;
- the cladding sample was moved in the hot position the such a way to provide the heating rate 25 C/s in the temperature range 150–800 C.

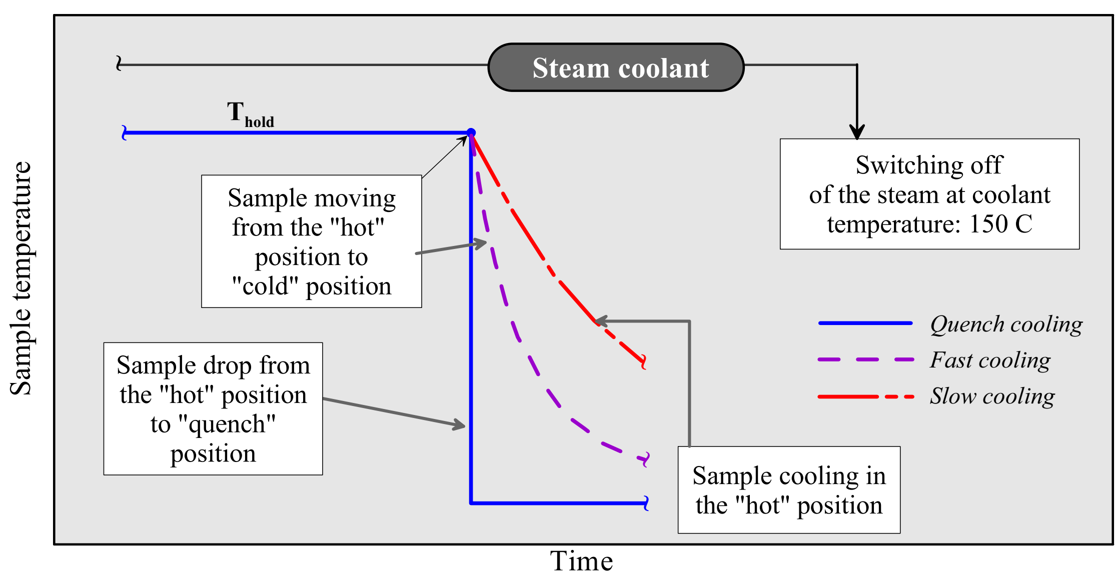

Fig. A-2. Oxidation modes with "slow", "fast", "quench" cooling: sequence diagram

Different types of cooling (Fig. A-3):

- As the slow cooling the cladding sample was cooled in the hot position with the temperature rate 0.5 C/s to 150 C, after that the steam atmosphere was replaced on the argon atmosphere and the cooling of cladding sample was continued with the same cooling rate.
- At the fast cooling the cladding sample was moved from the hot position to the cold position the such a way that the cooling rate at initial phase of this process was 25 C/s. The replacement of steam coolant to the argon coolant was made at the temperature of cladding sample 150 C.
- At the quench cooling the cladding sample was moved from the hot position to the quench position (to the cold water) with cooling rates about of 200 C/s.

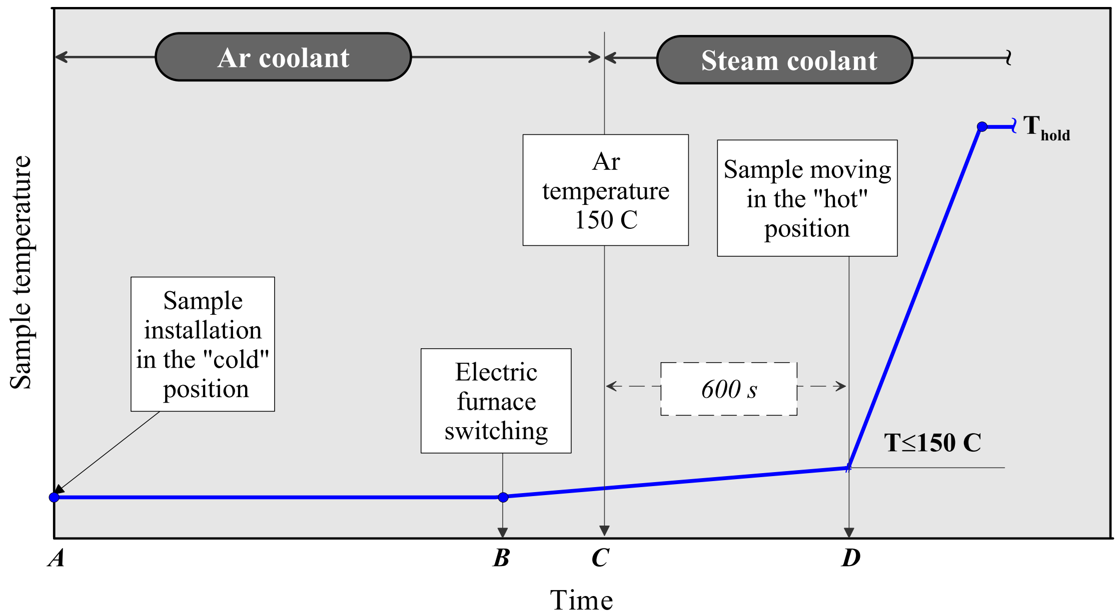

Fig. A-3. Oxidation mode with the "fast" heating: sequence diagram

A-3. The characterization of cladding samples

Table A-1. The list of tested cladding materials

Abbreviation	Alloying composition	Additional comments
E110	Zr-1%Nb	as-received E110 cladding tube manufactured from the iodide Zr, electrolytic Zr, and recycled scrap (the oxygen concentration ~0.04 % by weight)
E110A	Zr-1%Nb	as-received E110 cladding after the etching and anodizing of as-received E110 cladding tube
E110K	Zr-1%Nb	as-received E110 cladding tube manufactured from the iodide Zr, electrolytic Zr, and recycled scrap with the high content of oxygen concentration (0.11 % by weight)
$E110_{low\ Hf}$	Zr-1%Nb	as-received E110 cladding tube manufactured from the iodide Zr, electrolytic Zr, and recycled scrap with the low content of Hf (90 ppm). The standard content of Hf is about of 350 ppm
E635	Zr-1%Nb-1.2%Sn-0.35%Fe	as-received E635 cladding tube manufactured from the iodide Zr, electrolytic Zr, and recycled scrap
Zry-4	Zr-1.4%Sn	the cladding tube manufactured by Framatom ANP GmbH on January 1989

Abbreviation	Alloying composition	Additional comments
$E110_{irr}$	Zr-1%Nb	the irradiated E110 cladding refabricated from the commercial VVER-1000 fuel elements irradiated to 50–53 MWd/kg U
$E110_{G(fr)}$	Zr-1%Nb	as-received E110 cladding tube manufactured from French sponge Zr by the Russian process
$E110_{G(3fr)}$	Zr-1%Nb	as-received E110 cladding tube manufactured from 70% French sponge Zr, 30% iodide Zr and recycled scrap by the Russian process
$E110_{G(3ru)}$	Zr-1%Nb	as-received E110 cladding tube manufactured from 70% Russian sponge Zr, 30% iodide Zr and recycled scrap
$E635_{G(fr)}$	Zr-1%Nb-1.2%Sn-0.35%Fe	as-received E635 cladding tube manufactured from French sponge Zr by the Russian process

Table A-2. The geometry of unirradiated cladding materials

Parameter (mm)	Cladding material									
	E110	E110A	E110K	$E110_{low\ Hf}$	E635	Zry-4	$E110_{G(fr)}$	$E110_{G(3fr)}$	$E110_{G(3ru)}$	$E635_{G(fr)}$
Outer diameter	9.145 – 9.148	9.130	9.170	9.100	9.142	10.750	9.140	9.141	9.130	9.140
Inner diameter	7.73	7.73	7.72	7.73	7.78	9.35	7.74	7.74	7.73	7.74
Cladding thickness	0.708 – 0.709	0.700	0.725	0.685	0.681	0.700	0.700	0.700	0.700	0.700

Table A-3. Initial characteristics of irradiated cladding material

Characteristic	Unit	Value
The type of fuel assembly	–	VVER-1000 (the first unit of Zaporozhie Nuclear Power Plant)
Fuel assembly number	–	E0325
Fuel elements number	–	#156, #273
Axial coordinates of fuel element section used for the refabrication of irradiated cladding	mm	• Fuel element #156: 1640–2890 • Fuel element #273: 1800–2240
Fuel burnup as a function of axial coordinate	–	see Fig. A-4
Outer diameter of fuel element cladding as a function of axial coordinate	–	see Fig. A-5
Average fuel burnup in the section of fuel element	MWd/kg U	• Fuel element #156: 52.0 • Fuel element #273: 49.5
Average outer cladding diameter in the section of fuel element	mm	• Fuel element #156: 9.03 • Fuel element #273: 9.04
Average cladding thickness in the section of fuel element	mm	• Fuel element #156: 0.68 • Fuel element #273: 0.69
Microstructure of irradiated cladding	–	see Fig. A-6

Characteristic	Unit	Value
Average ZrO_2 thickness on the outer surface of irradiated cladding	µm	• Fuel elements ##156, 273: 5
Average ZrO_2 thickness on the inner surface of irradiated cladding	µm	• Fuel elements ##156, 273: 0
Hydrogen content in the irradiated cladding	% by weight	• Fuel elements ##156, 273: 0.0047

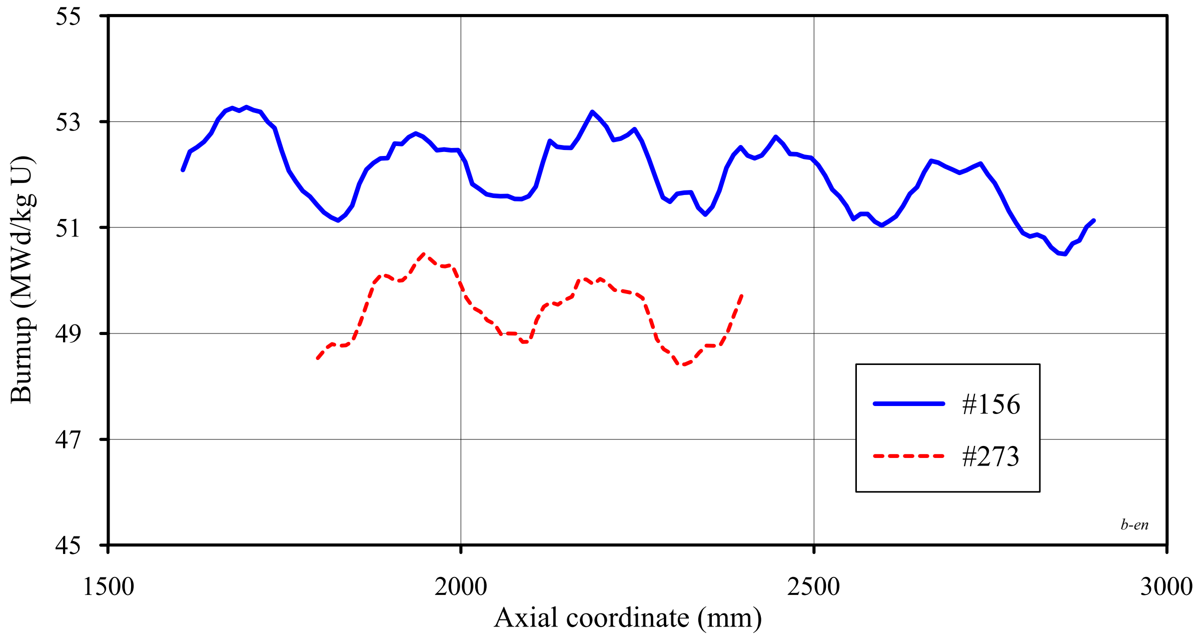

Fig. A-4. Axial burnup distribution for fuel element #156 and #273 (experimental data)

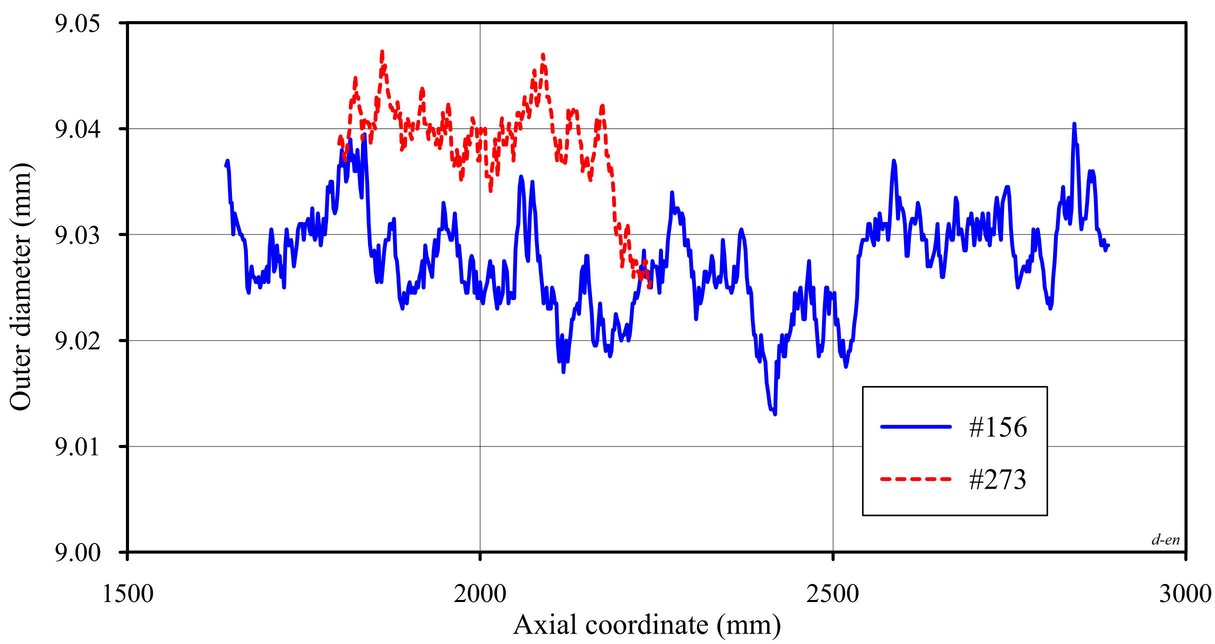

Fig. A-5. Profilometry of cladding outer diameter as a function of axial coordinate

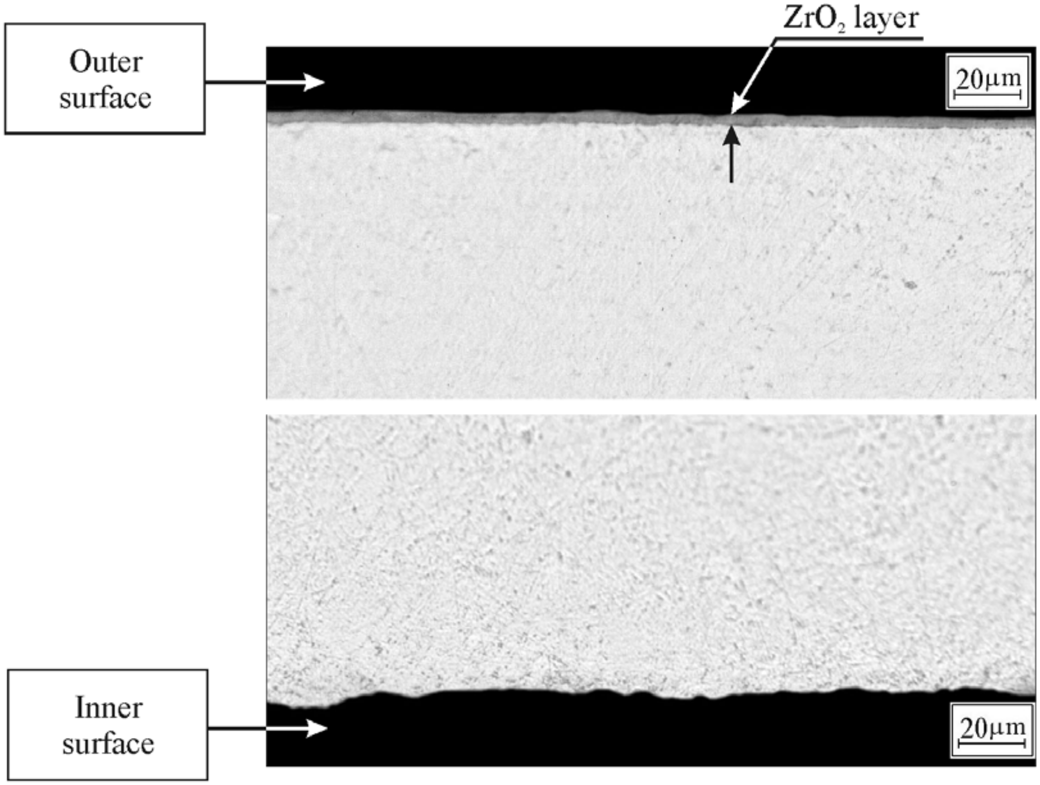

Fig. A-6. The microstructure of irradiated E110 cladding before the oxidation tests

A-4. Scoping tests performed to verify the experimental procedure of cladding temperature measurements

The following scoping tests were developed and performed to validate and verify the procedure of temperature measurements at the oxidation of cladding samples:

- scoping tests to reveal the axial temperature distribution inside the electric furnace;
- scoping tests to reveal the temperature distribution as a function of cladding sample length;
- scoping tests to obtain the comparative data characterizing two different methods of determination of cladding sample temperature:
  - the method on the basis of thermocouple, which was welded on the cladding surface;
  - the method on the basis of thermocouple, which was installed in the gas volume inside the cladding sample.

The major results of these scoping tests are presented below.

<u>The data base characterizing the axial temperature distribution inside the electric furnace</u>

The procedure of this test consisted of the following options:

- the electric furnace was heated to 1100 C (at the middle of furnace);
- the thermocouple (which was installed along the axis of electric furnace) was moved the step by step from the position #1 to the #15 (Fig. A-7);
- the processing of measured data allowed to obtain the axial temperature profile inside electric furnace;
- these data were used to determine the “cold” and “hot” positions of cladding sample (see Fig. 3.2, section 3).

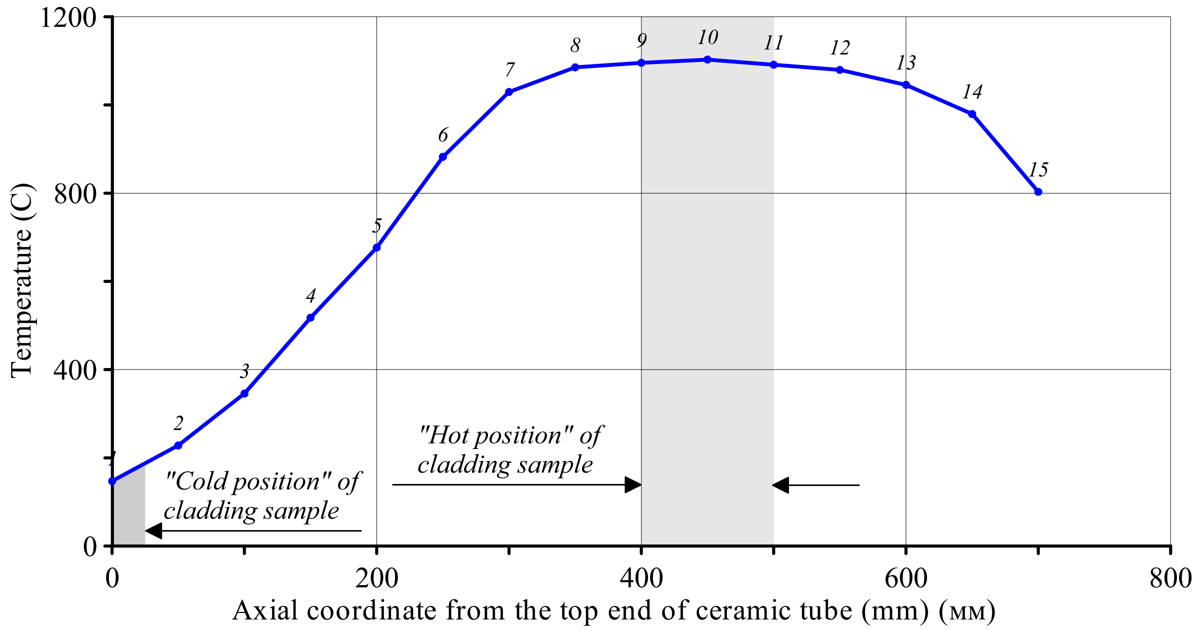

Fig. A-7. The axial temperature distribution inside the electric furnace

<u>The measurement of axial temperature distribution along the cladding sample length</u>

These measurements were performed using the following procedure:

- seven thermocouples were installed sequentially on the length of “hot” position (Fig. A-8);
- the electric furnace was heated to 1100 C (at the “hot” position);
- the processing of temperature measurements allow to reveal that the temperature nonuniformity is not more than 6 C.

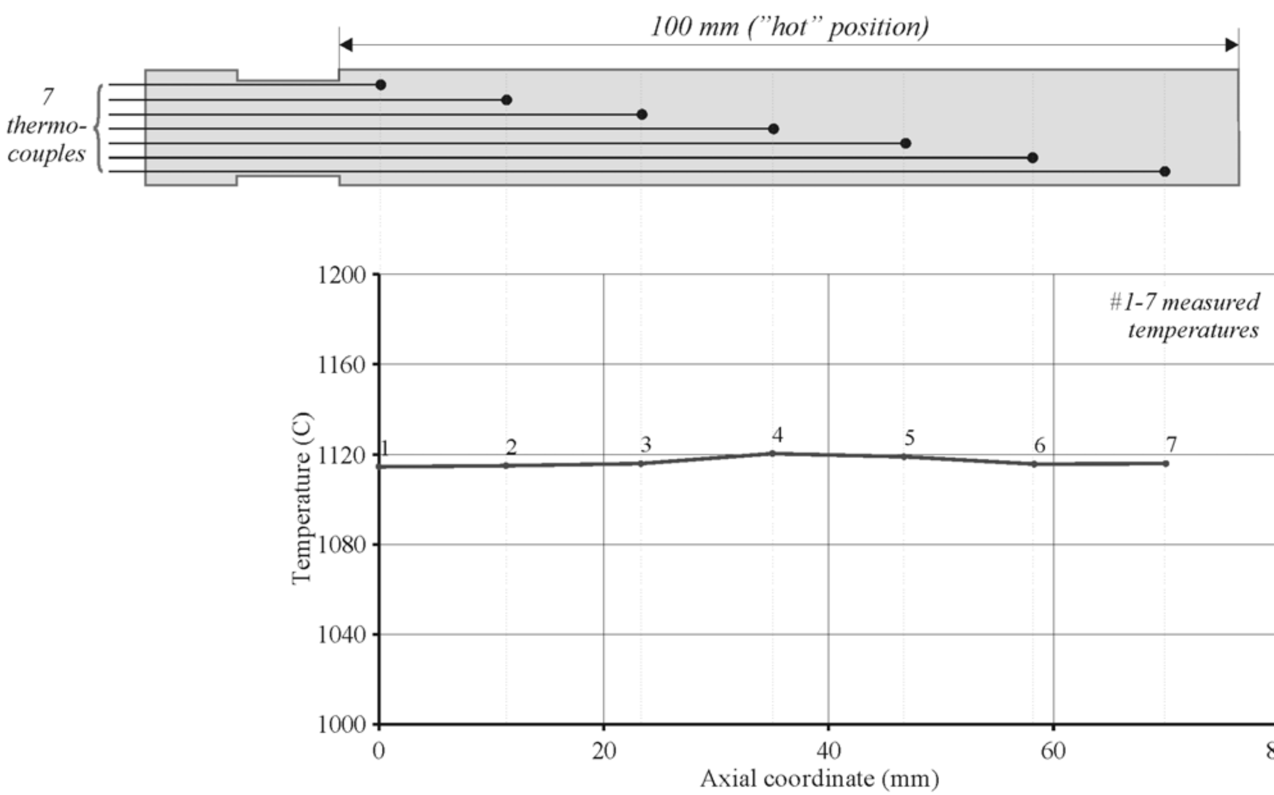

Fig. A-8. The axial temperature profile at the “hot” position

The development of comparative data to characterize two possible methods of measurement of cladding sample temperature

The following experimental procedure was used to obtain the appropriate data:

- the one thermocouple was welded on the outer surface of cladding sample;
- the second thermocouple was installed inside cladding sample along the sample axis;
- axial coordinates of both thermocouples were the same;
- the cladding sample with thermocouples was installed in the "cold" position (see Fig. 3.2., section 3);
- the electric furnace was heated to 1100 C;
- the cladding sample was removed from the "cold" position to the "hot" position, after that the cladding sample was oxidized at the hold temperature (1100 C) during approximately 400 seconds and finally the cladding sample was removed from the "hot" position to the cold position. Such a way, the oxidation of cladding sample at the F/F combinations of heating and cooling rates was performed.

The results of these comparative temperature measurements are presented in Fig. A-9.

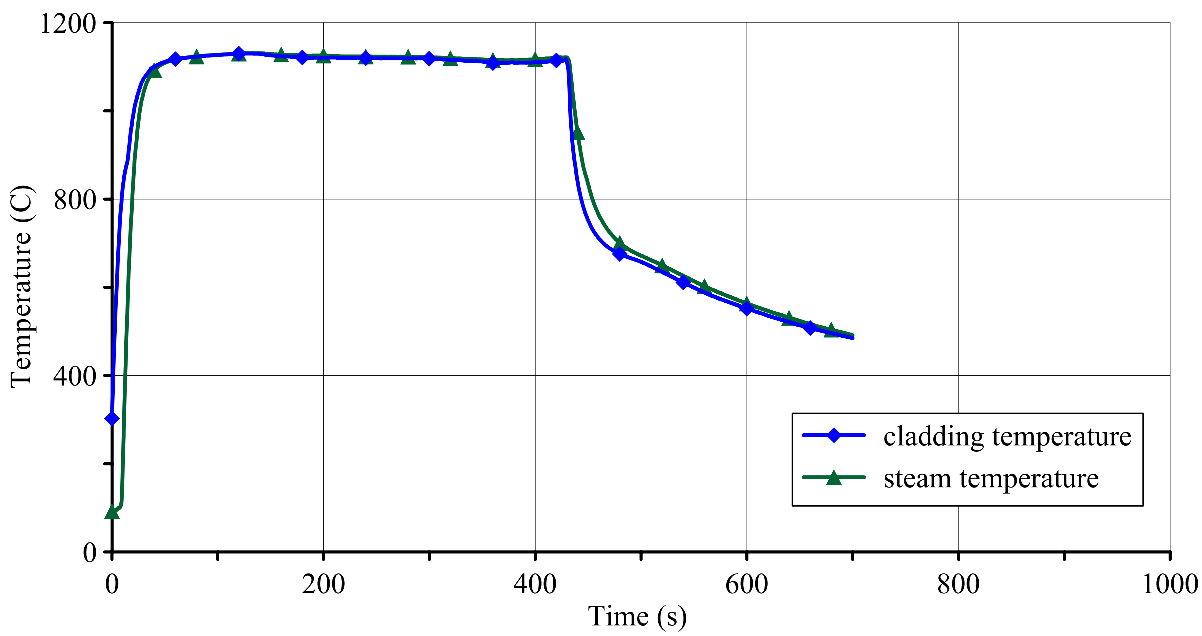

Fig. A-9. The cladding and steam temperatures under oxidation conditions with F/F combinations of heating and cooling rates

The analysis of obtained data allowed to make the following conclusions:

- the differences in the both temperature measurements at the stationary mode do not exceed the instrumental error of thermocouples;
- the thermocouple measuring the steam temperature under estimates the real cladding temperature at the heating mode, this thermocouple overestimates the cladding temperature at the beginning of cooling mode;
- the appropriate calculations shown that the systematic error of determination of effective time of oxidation (caused by above mentioned transient effects under heating and cooling conditions) is very insignificant;
- taking into account obtained comparative data it was decided to use the thermocouple placed inside the cladding sample for the temperature measurement at the oxidation tests.

A-5. The ECR measurement

By definition, the equivalent cladding reacted (ECR) is a total thickness of zirconium layer that reacts with steam assuming that all absorbed oxygen were converted to a stoichiometric zirconia layer, divided by the initial thickness of the cladding. Besides it can be shown that the ECR is the ratio between the oxygen weight, which was absorbed by the cladding during the oxidation test to the oxygen weight, which could be absorbed by the cladding at the full (100 %) oxidation.

To determine the experimental ECR, two alternative methods are used as a rule:

- the measurement of oxygen weight gain using the determination of the cladding sample weight before and after the oxidation test;
- the metallographic method which is based on the thickness measurement of the ZrO_2 and α–Zr(O) layers.

However, the following specific features of the Zr-1%Nb (E110) cladding material hamper the use of these methods:

- the spallation and falling of oxide caused by the breakaway oxidation;
- the nonuniform boundary between the α–Zr(O) layer and prior-β phase (that does not allow to measure the macroscopic value of the α–Zr(O) layer using limited numbers of metallographic samples);
- the inexact knowledge of the radial distribution of oxygen concentration in the α–Zr(O) and prior-β phase layers.

Taking into account the above stated issues a special method of the ECR measurement was developed for this work. The general idea of this method is based on the following consideration:

- the weight gain of the E110 sample obtained during the oxidation test is determined as the difference between the weight gain of this sample oxidized up to 100% zirconium/niobium oxide (this value can be calculated with a high accuracy) and the weight gain of this sample at the additional full oxidation of the E110 sample metallic part (remained after the test oxidation).

In accordance with this approach, the following additional procedures were performed for the tested ring oxidized E110 sample:

- the weight of the oxidized sample (as a rule, the weight of the ring oxidized sample fragments after the ring compression tests) was measured;
- the oxidized sample (or the sample fragments) was additionally oxidized at 1100 C in air atmosphere during 4 hours;
- the weight of the completely oxidized (100 % oxide) sample was measured.

This procedure (the extra oxidation of the E110 ring samples) is explained in detail in Table A-4.

Table A-4. The major provisions of the ECR determination procedure

Stage of procedure	Comments
1. The weight gain of the E110 cladding sample after the oxidation test (Δm_o): $\Delta m_o = \Delta M_{100} - \Delta m_c$ where ΔM_{100} – the weight gain of the cladding sample at the complete 100 % oxidation (g); Δm_c – the weight gain of the cladding sample, obtained during the extra oxidation procedure (g)	
2. The weight gain of the E110 cladding sample at the complete oxidation in air atmosphere can be determined using the following equation: $$\Delta M_{100} = M\left(0.99\frac{2\ A_O}{A_{Zr}} + 0.01\frac{5\ A_O}{2\ A_{Nb}}\right) = 0.3516\ M$$ where A_O =16 (oxygen atomic mass);	The following assumptions were used: • Zr concentration in the E110 alloy is 0.99 (by weight); • the stoichiometric ZrO_2 and Nb_2O_5 are formed at the complete oxidation of the E110 alloy in the air

Stage of procedure	Comments
A_{Zr} =91.22 (zirconium atomic mass); A_{Nb} =92.91 (niobium atomic mass); M = the weight of the unoxidized ring sample (g)	
3. Thus, the ECR (%) can be calculated using the following equation: $ECR = \frac{\Delta m_o}{\Delta M_{100}} \cdot 100\ \% = 1 - \frac{\Delta m_c}{0.3516\ M}$ Special scoping tests have been performed to estimate the calculation accuracy on determining the ΔM_{100} parameter. Results of these tests have shown that the range of relative differences between the calculated and measured ΔM_{100} is 0.01–0.12 %	It should be noted that the weight gain of the E110 cladding sample after the oxidation test (Δm_0) is not contained in the ECR equation. Therefore, the ECR measurement error is not the function of oxide weight and, consequently, the spallation and falling of the ZrO_2 oxide during the oxidation and handling (procedures after the test) are not important for the accuracy of the ECR measurement. This accuracy is determined by the accuracy of the sample weight measurements (the unoxidized sample and the sample before and after the extra oxidation) and by the accuracy of several other measurements described below
4. The unoxidized ring sample weight (M) can be determined using the following considerations: $M = m_l \cdot L$ where m_l – the weight of the unoxidized cladding sample 1 cm long (g/cm); L – the unoxidized ring sample length (cm)	Special scoping tests performed with nine cladding samples have shown that the m_l average value is 0.01218 g/cm. The mean square error of this parameter is very small (0.0001)
5. The unoxidized ring sample length (L) is determined by $L = L_o \frac{l}{l_o}$ where L_o – the measured length of the oxidized ring sample (cm); l – the measured length of the unoxidized (100 mm) sample; l_o – the measured length of the oxidized (100 mm) sample	The set of measurements allowed to reveal that the length (100 mm) of the E110 sample is extended by 0.5–1 % during the oxidation
6. The weight gain of the cladding sample obtained during the extra oxidation (Δm_c) can be expressed by $\Delta m_c = m_c - m_s$ where m_s – the sample mass before the extra oxidation (g); m_c – the sample mass after the extra oxidation (g)	
7. The sample mass before the extra oxidation (m_s) will be $m_s = m_{O+Me} + m_H$ where m_{O+Me} – the mass of the sample metallic part and that of absorbed oxygen (g); m_H – the mass of absorbed hydrogen (g)	It should be taken into account that the increase in the E110 sample mass is the result of two processes: • oxygen absorption; • hydrogen absorption
8. Thus, the ECR expression is $ECR = \left(1 - \frac{\Delta m_C}{0.3516\ M} - \frac{m_H}{0.3516\ M}\right) \cdot 100\ \%$	
9. The absorbed hydrogen mass (m_H) can be determined by $m_H = C_H \cdot 10^{-6}\ m_s$	

Stage of procedure	Comments
where C_H – the measured hydrogen concentration in the ring sample (per-unit: ppm)	
10. Taking into account that the ratio of m_s to M is close to 1, the hydrogen correction factor ($\Delta ECR_H = (m_H/0.3516)100$ %) can be presented with the reasonable accuracy by $$\Delta ECR_H = \frac{C_H \cdot 10^{-4}}{0.3516}$$	C_H (ppm) $10^{-4} = C_H$ (% by weight)
11. Finally, the equation for the ECR determination has the following form: $$ECR = 100\% \left(1 - \frac{\Delta m_C\ l_O}{0.3516\ m_l\ L_O\ l}\right) - \frac{C_H \cdot 10^{-4}}{0.3516}$$	
12. The ECR measurement error was estimated using the following experimental data characterizing the errors of individual measurements: • the absolute error of m_c measurement: 0.0002 g • the absolute error of l measurement: 0.01 cm • the absolute error of l_o measurement: 0.01 cm • the relative error of m_l measurement: 1.6 % • the maximum relative error of Δm_C determination: – 2.3 % at the 5 % ECR – 1.2 % at the 10 % ECR • The relative error of L_O measurement (using five azimutally distributed measurements): 0.8 %	
• The relative error of l/l_O determination: 1 % The relative error of ECR measurement is • 3.1 % at the ECR=5 • 2.4 % at the ECR=10 %	
13. The expression to determine the specific weight gain $\Delta m_{O(SP)}$ was formulated on the basis of the ECR data: $$\Delta m_{O(SP)} = \frac{0.3516\ m_l\ l\, 10^3}{\pi (d_O + d_i)\, l_O\ 100\%} ECR$$ at the double-sided oxidation $$\Delta m_{O(SP)} = \frac{0.3516\ m_l\ l\, 10^3}{\pi\ d_O\ l_O\ 100\%} ECR$$ at the single-sided oxidation where $\Delta m_{O(SP)}$ – the specific weight gain (mg/cm^2); d_O – the outer cladding diameter (cm); d_i – the inner cladding diameter (cm)	The following equation was used to determine the specific weight gain: $$\Delta m_{O(SP)} = \frac{\Delta m_O}{S}$$ where: S – the sample surface area
14. Several modifications were developed to determine the ECR in the irradiated claddings: • the weight of the irradiated cladding 1 cm long before the oxidation (m_l) was determined • the initial ECR of irradiated claddings (the ECR developed during the irradiation) was determined (ECR_i = 0.5 %)	a) Several scoping tests were performed with the irradiated cladding samples to measure the parameter m_l in accordance with the approach presented in the item 4. b) The following expression was used to determine the ECR_i:

Stage of procedure	Comments
	$$ECR_i = \frac{\delta_{ZrO_2}}{1.56\,\delta_{cl}} 100\%$$
	where δ_{ZrO2} – ZrO₂ layer thickness on the outer and inner cladding surfaces before the oxidation (5 µm)
	δ_{cl} – the irradiated cladding thickness (685 µm)
	1.56 – Pilling-Bedworth coefficient
15. The final equation for the ECR in the irradiated cladding is	
$$ECR = 100\%\left(1 - \frac{\Delta m_C\ l_O}{0.3516\ m_l\ L_O\ l}\right) - \frac{C_H 10^{-4}}{0.3516} + 0.5\%$$	

A-6. Determination of the oxidation equivalent time

It is known that to estimate the oxidation kinetics of the cladding, the experimental data characterizing the specific weight gain dependence on the oxidation time at the given temperature are required. But the real experimental oxidation history of the tested cladding sample consists of three test modes (Fig. A-10):

1. The transient mode (the oxidation temperature transient) on the sample heating.
2. The steady state mode (the oxidation temperature is approximately constant).
3. The transient mode on the sample cooling.

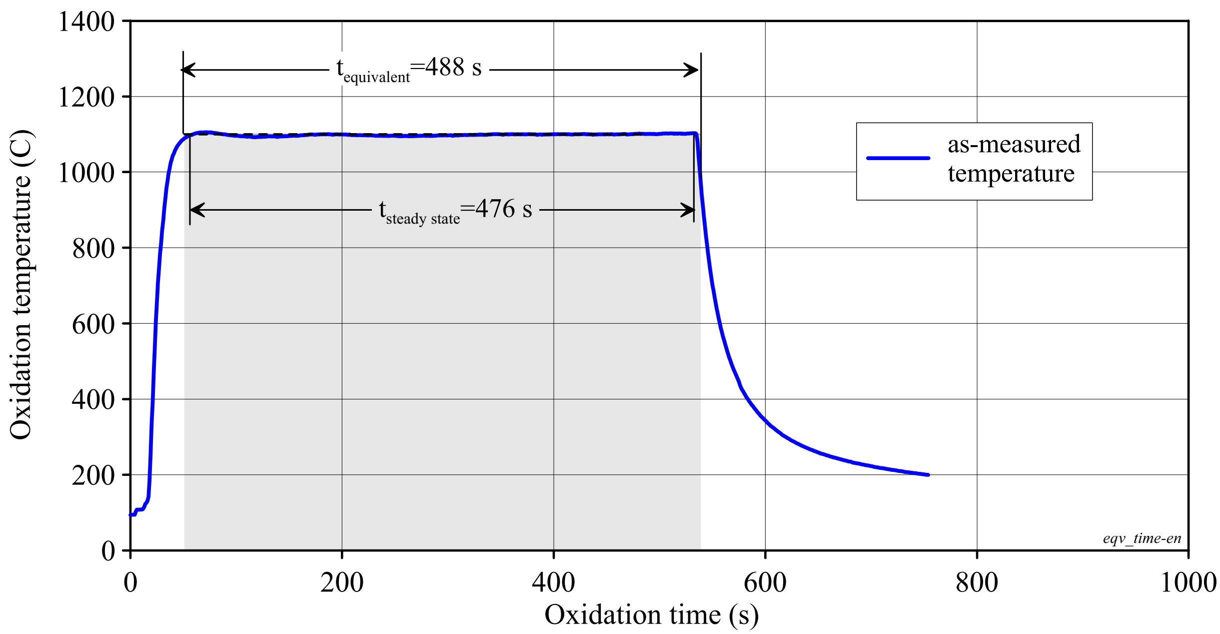

Fig. A-10. The oxidation history of the E110 as-received tube at 1100 C and F/F combination of heating and cooling rates

To transform the transient oxidation conditions into the oxidation kinetics (T=const), the equivalent time (t_{eq}) is used:

$$t_{eq} = \frac{\int_0^{t_{ox}} \exp\left(-\frac{Q}{R\,T(t)}\right) dt}{\exp\left(-\frac{Q}{R\,T_{eq}}\right)},$$

where: t_{ox} – time for the complete oxidation (s);

Q – the activation energy (cal/mole);

R – the gas constant (1.987 cal/mole K);

T(t) – the oxidation temperature as a function of time (K);

T_{eq} – the assigned steady temperature (K).

In accordance with the published data [1, 2, 3], the following value for the activation energy was used:

Q=39940 cal/mole.

The appropriate estimates have shown that the relative error of the equivalent time on using other values for the activation energy do not exceed 0.3 %.

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APPENDIX B

Tables with Results of Oxidation and Mechanical Tests: E110, E110A, E110K, E110pol, E635, $E110_{G(fr)}$, $E110_{G(3ru)}$, $E110_{G(3fr)}$, $E110_{low\ Hf}$, $E635_{G(fr)}$, Zry-4 as-Received Tubes and E110 Commercial Irradiated Claddings

Table B-1. A summary list of tested unirradiated tube samples. Characterization of test conditions and major test results

Material	Oxidation type	Heating/ Cooling comb.	Steady temp. (C)	Sample number	Equiv. Time (s)	Measured ECR (%)	Weight gain (mg/cm^2)	Residual ductility (%)	Relative displacement (%)	H cont. (ppm)
E110	double-sided	F/F	800	123	7205	3.4	2.7	59.8	65.3	80
				132	28814	10.7	8.5	8.0	15.6	466
				144	21850	8.6	6.7	16.0	23.0	150
			900	130	2407	3.9	3.1	57.2	58.2	106
				131	4804	6.7	5.4	31.8	32.1	194
				142	8120	12.3	9.6	0.0	2.7	3010
			950	140	5012	13.4	10.5	0.0	3.2	2780
				141	2490	11.2	8.8	0.0	2.9	920
			1000	44	865	7.7	6.2	8.4	13.0	
				45	798	7.6	6.1	20.7	24.4	
				119	871	5.7	4.5	19.4	26.4	173
			1100	28	529	10.5	8.4	0.6	6.9	
				30	426	8.9	7.1	0.2	5.1	1110
				41	284	8.2	6.6	0.0	4.5	1130
				46	194	6.5	5.2	57.2	57.7	75
				47	209	7.0	5.6	57.7	58.3	30
				62	445	8.0	6.4	4.9	11.9	660
				65	488	7.5	6.0	42.1	44.3	40
				68	605	10.0	7.9	3.3	10.0	
				81	496	8.1	6.5	1.5	8.5	280
				82	499	7.9	6.3	1.9	6.9	390
				83	341	10.0	8.0	0.5	5.5	
				85	307	6.0	4.8	- *	- *	
				86	336	6.9	5.5	- *	- *	
				92	555	8.5	6.8	1.4	7.2	690
				96	762	9.8	7.8	- *	- *	
				104	1814	16.1	12.8	0.0	4.8	
				105	818	11.8	9.4	- *	- *	
				110	1714	13.7	10.7	0.0	4.4	
				111	770	8.5	6.7	8.4	14.2	
			1120	25	403	9.9	7.9	0.1	4.7	1010
			1200	102	364	13.3	10.6	0.0	4.5	926
				106	308	11.5	9.1	0.0	4.4	430
		F/Q	1100	63	250	6.1	4.9	57.7	58.2	30
				66	375	7.1	5.7	47.3	49.3	90
				71	445	9.7	7.7	2.7	9.4	580
		F/S	1100	17	- **	10.0	8.0	0.0	4.2	730
				19	-	14.2	11.3	0.0	4.5	
				35	-	11.0	8.8	0.0	3.1	1150
				37	-	9.4	7.6	14.1	19.2	
				40	-	8.7	7.0	6.1	10.8	
				48	-	8.7	7.0	56.2	56.4	
				52	-	6.2	5.0	57.0	54.8	180
		S/F	1100	27	-	4.6	3.6	40.3	42.3	150
				32	-	7.1	5.7	24.4	28.0	
				34	-	7.2	5.8	2.1	8.5	
				49	-	7.6	6.1	4.1	11.2	
				51	-	7.7	6.2	0.5	5.6	

Material	Oxidation type	Heating/ Cooling comb.	Steady temp. (C)	Sample number	Equiv. Time (s)	Measured ECR (%)	Weight gain (mg/cm^2)	Residual ductility (%)	Relative displacement (%)	H cont. (ppm)
E110	double-sided	S/S	1100	29	-	5.8	4.6	45.2	39.7	320
				31	-	8.0	6.4	21.3	23.3	
				33	-	7.5	6.0	3.8	10.0	530
				36	-	11.7	9.4	0.2	3.8	1460
				38	-	7.6	6.1	4.6	9.5	360
	single-sided	F/F	1100	42	1374	8.9	13.1	24.4	32.9	540
				54	936	6.6	9.8	62.6	70.4	650
				55	1457	9.5	14.4	21.3	28.3	300
				56	1245	8.6	12.7	11.7	19.2	360
				76	1821	11.2	16.5	0.0	3.3	
E110A	double-sided	F/F	1100	117	675	9.0	7.1	0.0	5.1	554
E110K	double-sided	F/F	1100	58	488	14.0	11.4	0.0	3.1	
				67	480	9.7	7.9	0.0	3.1	1630
				88	559	7.0	5.7	0.0	2.7	
E110$_{\text{low Hf}}$	double-sided	F/F	1100	94	672	9.2	7.1	38.0	41.6	17
				121	1289	11.4	8.8	2.6	9.0	426
E110pol	double-sided	F/F	1000	119	871	4.3	3.4	59.6	60.0	44
			1100	92	555	8.0	6.4	46.3	52.0	28
E635	double-sided	F/F	1000	127	670	5.3	4.2	57.4	57.6	98
				138	1493	9.4	7.5	0.0	5.5	400
			1100	60	-	8.8	7.0	0.4	6.3	
				61	-	9.6	7.6	0.0	4.8	
				126	289	7.8	6.2	30.4	32.6	138
				134	300	6.9	5.5	12.4	18.7	107
				135	460	9.3	7.4	7.2	13.8	35
E110$_{G(3fr)}$	double-sided	F/F	1100	99	755	11.5	9.1	15.0	23.6	13
E110$_{G(3ru)}$	double-sided	F/F	900	137	14400	7.5	5.9	35.5	38.3	66
			1000	98	2519	6.9	5.4	42.4	46.0	16
				101	5028	8.9	7.0	28.3	31.1	11
			1100	95	739	11.6	9.1	15.0	22.5	4
				97	1548	16.7	13.1	11.4	17.3	17
				109	1743	18.0	14.2	3.6	9.2	101
			1200	112	932	23.5	18.5	0.0	4.9	2200
				120	168	7.8	6.1	3.2	8.0	824
E110$_{G(fr)}$	double-sided	F/F	1100	89	558	10.5	8.3	11.7	18.7	15
				90	933	13.0	10.3	17.1	22.8	48
			1000	91	2016	6.5	5.1	51.9	54.3	17
				93	5013	8.5	6.7	0.9	6.6	12
E635$_{G(fr)}$	double-sided	F/F	1100	100	749	12.5	9.8	4.3	11.0	18
				108	572	11.0	8.6	0.0	2.5	
Zry-4	double-sided	F/F	1100	64	495	11.5	9.5	14.3	22.4	34
		S/S	1100	43	-	11.3	9.3	4.8	12.7	37
E110$_{m}$	double-sided	F/F	1100	136	604	7.7	6.1	1.1	8.9	90

* - Tube sample was used for the three-point bending test

** - Equivalent time calculation procedure was not developed for slow heating and slow cooling test modes

F/F, F/Q, F/S, S/F, S/S characterize the heating/cooling combinations of the oxidation mode
(F - fast, Q - quench, S - slow)

ECR, weight gain, residual ductility, relative displacement are average values obtained due to the procedure of processing of individual measurements these parameters on several rings cutted from the tube sample (see Table B-2)

Table B-2. A summary data base on results of oxidation and mechanical tests with unirradiated cladding samples[1]

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measu-red ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
17	E110	1100	10.0	2_{15}*	10.3		20	4.1	0.0	
	double-sided	F/S		4			20	4.3	0.0	
				5						MG
				6_{25}*	9.7		20	4.3	0.0	
				8		730				H2
19	E110	1100	14.2	2_{15}	13.9		20	3.9	0.0	
	double-sided	F/S		4			20	5.6	0.0	
				6_{20}*			20	3.7	0.0	
				7						MG, HV
				8_{25}*	14.4		20	4.8	0.0	
25	E110	1120	9.9	2						MG, HV
	double-sided	F/F		3						MG
				4	9.4		20	4.5	0.0	
				5			20	4.4	0.0	
				6	10.0		20	6.0	0.2	
				7	10.2		20	3.9	0.0	
				8			20	4.7	0.2	
				9		1010				H2
				10			135,200,300			MTt
27	E110	1100	4.6	1		199				H2
	double-sided	S/F		2			20	48.1	45.6	
				3			135	63.0	54.1	
				4	4.5		20	47.4	46.9	
				5						MG
				6	4.6		20	21.7	16.5	
				8		90				H2
				9						MG
				10			20	52.1	52.0	
				11		162				H2
28	E110	1100	10.5	5	10.5		20	6.5	0.4	
	double-sided	F/F		6			135	15.0	6.2	
				7			20	7.2	0.8	
29	E110	1100	5.8	2	5.4		20	38.3	38.1	
	double-sided	S/S		3						MG
				4		319				H2
				5	5.5		20	37.6	37.5	
				6			135	63.5	60.4	
				7			135	64.5	60.5	
				8	6.4		20	35.3	34.9	
				9			20	47.4	47.2	
30	E110	1100	8.9	2	9.2		20	4.0	0.0	
	double-sided	F/F		3		1113				H2
				4			135	9.4	1.8	
				5						MG
				6			135	9.0	1.7	
				7	9.2					
				8	8.3		20	6.7	0.5	
				9	8.4					
				10	9.3		20	4.5	0.0	

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measu-red ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
31	E110	1100	8.0	2	9.3		20	5.8	0.4	
	double-sided	S/S		6						MG
				8	7.6		20	34.2	33.9	
				9	7.2		20	30.0	29.7	
32	E110	1100	7.1	2	6.6		20	7.6	0.6	
	double-sided	S/F		5			20	18.7	11.7	
				6						MG
				8	7.6		20	43.7	43.6	
				9	7.2		20	41.8	41.6	
33	E110	1100	7.5	2	7.2		20	14.5	8.6	
	double-sided	S/S		4			135	63.2	60.7	
				5		870				H2
				6						MG
				7		213				H2
				8	7.4		20	6.8	1.0	
				9	7.8		20	8.5	1.7	
34	E110	1100	7.2	2	7.3		20	8.7	1.7	
	double-sided	S/F		4	7.2			12.7	4.1	
				5						MG
				8	7.1		20	9.8	2.5	
				9	7.3		20	6.9	0.1	
35	E110	1100	11.0	2	10.9		20	3.7	0.0	
	double-sided	F/S		3			135	4.7	0.0	
				4		1150				H2
				5						MG
				8	11.0		20	3.1	0.0	
				10			20	2.6	0.0	
36	E110	1100	11.7	2	12.8		20	3.2	0.2	
	double-sided	S/S		4		1457				H2
				5						MG
				6	11.8		20	3.9	0.2	
				7			135	6.6	0.7	
				8			200	57.4	57.0	
				9			300	62.3	62.0	
				10	10.6		20	4.3	0.3	
37	E110	1100	9.4	1						MG
	double-sided	F/S		2	8.9		20	44.7	44.4	
				4	9.1		20	20.2	14.3	
				5			135	64.3	60.3	
				7	9.7		20	17.1	10.9	
				9	9.7		20	7.2	0.6	
				10	9.8		20	6.6	0.4	
				11						MG
38	E110	1100	7.6	2			20	7.9	1.5	
	double-sided	S/S		3			135	60.9	60.3	
				4		315				H2
				5						MG
				7	7.6		20	10.8	3.6	
				8			135	59.5	58.4	
				9		400	20			H2, Fr
				10			20	9.8	3.1	

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measured ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
40	E110 double-sided	1100 F/S	8.7	2	7.9		20	17.5	11.8	
				5						MG
				6	9.4		20	8.5	1.9	
				8			135	17.7	10.5	
				10	8.9		20	6.4	0.3	
41	E110 double-sided	1100 F/F	8.2	3			135	67.5	60.1	
				4			20	6.5	0.0	Fr,HV,SEM
				5						MG
				6	8.1		20	4.0	0.0	
				8		1130				H2
				10	8.3		20	4.9	0.0	
42	E110 single-sided	1100 F/F	8.9	1		519				H2
				2			20	14.6	3.9	
				3	8.3		20	28.8	22.2	
				4	9.1		20	61.8	55.3	
				5						MG
				6	9.2		20	26.2	21.3	
				7		555				H2
43	Zry-4 double-sided	1100 S/S	11.3	1		37				H2
				2	9.9		20	16.5	8.6	
				3						MG
				4						MG
				5						MG
				6	11.4		20	12.4	4.6	
				7						MG
				8			135	18.7	11.4	
				10	12.7		20	7.9	1.1	
				11		271				H2
44	E110 double-sided	1000 F/F	7.7	2	9.9		20	3.8	0.0	
				5						MG
				6	6.9		20	19.6	14.1	
				10	6.2		20	15.7	11.2	
45	E110 double-sided	1000 F/F	7.6	2	7.5		20	3.8	0.0	
				5						MG
				6	7.8		20	58.9	58.3	
				10	7.4		20	10.4	3.8	
46	E110 double-sided	1100 F/F	6.5	2	6.0		20	58.9	57.9	
				3		129				H2
				4		20				H2
				5						MG
				6	6.8		20	57.2	56.8	
				7	6.5		135	71.6	61.2	
				10	6.7		20	57.1	56.9	
47	E110 double-sided	1100 F/F	7.0	2	7.1		20	58.9	58.6	
				4			135	72.4	64.2	
				5						MG
				6	7.3		20	60.2	59.8	
				7		30				H2
				8			20, 135			MTt
				9	6.3					
				10	7.2		20	55.9	54.6	

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measu-red ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
48	E110 double-sided	1100 F/S	8.7	2	8.6		20	51.4	51.2	
				5						MG
				6	8.8		20	58.4	58.1	
				7	9.1		135	69.7	62.6	
				10	8.3		20	59.8	59.4	
49	E110 double-sided	1100 S/F	7.6	2	7.5		20	10.3	3.6	
				5						MG
				6	7.8		20	14.3	7.4	
				7			20, 135			MTt
				8			200, 300			MTt
				10	7.4		20	8.9	1.3	
51	E110 double-sided	1100 S/F	7.7	2			20	8.8	1.5	
				5						MG
				6	7.8		20	5.2	0.0	
				7	7.6		135	10.9	2.5	
				10			20	2.7	0.0	
52	E110 double-sided	1100 F/S	6.2	2			20	46.3	45.4	
				4		180				H2
				5						MG
				6	6.6		20	58.6	58.2	
				7	6.5		135	72.5	63.9	
				10	5.5		20	59.4	59.1	
54	E110 single-sided	1100 F/F	6.6	2	6.6		20	72.1	63.7	
				3	6.0		135	73.7	63.2	
				4		650				H2
				5						MG
				6	7.0		20	67.5	60.5	
				7	6.8		135	64.9	53.9	
				10	6.8		20	71.8	63.6	
55	E110 single-sided	1100 F/F	9.5	2	8.7		20	57.6	51.8	
				3	9.6		135	67.5	55.0	
				4		300				H2
				6	10.0		20	15.0	7.3	
				7	10.0		135	72.5	61.9	
				9	9.4		20	12.3	4.8	
56	E110 single-sided	1100 F/F	8.6	2	8.8		20	28.5	21.8	
				3	8.3		135	63.1	52.4	
				4		360				H2
				6	9.0		20	15.1	6.9	
				7	8.5		135	73.8	61.3	
				9	8.3		20	13.9	6.4	
58	E110K double-sided	1100 F/F	14.0	2	14.8		20	3.4	0.0	
				6			20	3.2	0.0	
				9	13.2		20	2.8	0.0	
60	E635 double-sided	1100 F/F	8.8	2	8.9		20	6.2	0.3	
				5						MG
				6	8.6		20	7.4	0.9	
				9	8.9		20	5.2	0.0	
61	E635 double-sided	1100 F/F	9.6	2	9.6		20	4.8	0.0	

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measu-red ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
62	E110 double-sided	1100 F/F	8.0	2	7.6		20	13.7	6.0	
				3	8.1		135	62.8	61.8	
				4		660				H2
				6	7.8		20	13.9	7.1	
				8	8.3		135	31.9	24.9	
				9	8.1		20	8.0	1.5	
63	E110 double-sided	1100 F/Q	6.1	2	5.5		20	60.6	59.7	
				3	5.8		135	75.5	65.4	
				4		30				H2
				6	6.1		20	58.9	58.3	
				8	6.7		135	74.3	62.8	
				9	6.6		20	55.2	55.0	
64	Zry-4 double-sided	1100 F/F	11.5	2	11.3		20	21.7	12.5	
				3	11.4		135	26.5	17.0	
				4		34				H2
				5						MG
				6	11.7		20	21.9	12.4	
				8	11.5		135	28.2	18.8	
				9	11.8		20	23.6	12.8	
65	E110 double-sided	1100 F/F	7.5	2	7.1		20	55.1	54.9	
				3	7.7		135	62.5	59.2	
				4		40				H2
				5						MG
				6	7.8		20	49.8	49.5	
				8	7.4		135	72.0	64.5	
				9	7.7		20	28.0	21.9	
66	E110 double-sided	1100 F/Q	7.1	2	6.9		20	41.2	35.9	
				3	7.0		135	67.7	63.0	
				4		90				H2
				5						MG
				6	7.1		20	57.2	56.8	
				8	7.4		135	71.1	62.4	
				9	7.1		20	49.4	49.2	
67	E110K double-sided	1100 F/F	9.7	2	9.8		20	3.3	0.0	
				3	9.3		135	3.8	0.0	
				4		1630				H2
				5						MG
				6	8.7		20	3.1	0.0	
				8	10.5		135	3.9	0.0	
				9	10.4		20	2.9	0.0	
68	E110 double-sided	1100 F/F	10.0	2	9.5		20	12.4	4.7	
				3	9.6		135	30.4	22.6	
				4			200	76.3	65.0	
				5						MG
				6	10.2		20	10.7	4.1	
				7			300	76.5	65.5	
				8	10.0		135	29.1	21.7	
				9	10.5		20	6.9	1.0	

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measu-red ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
71	E110	1100	9.7	2	9.1		20	17.4	8.1	
	double-sided	F/Q		3	9.9		135	55.7	53.0	
				6	9.0		20	4.1	0.0	
				7		581				H2
				8	10.1		135	52.1	49.6	
				9	10.2		20	6.7	0.0	
76	E110	1100	11.2	2	11.9		20	3.2	0.0	
	single-sided	F/F		3	11.8		135	5.6	0.7	
				6	11.1		20	3.4	0.0	
				8	10.0		135	12.2	2.1	
				9			20	3.3	0.0	
81	E110	1100	8.1	1						
	double-sided	F/F		2	7.9		20	9.4	2.3	
				3	8.3		135	25.1	19.1	
				4		140				H2
				5						MG
				6			20	7.5	0.8	
				9			20	8.5	1.4	
				10		422				H2
82	E110	1100	7.9	2			20	7.1	2.2	
	double-sided	F/F		3	7.7		135	65.0	64.2	
				4		170				H2
				5						MG
				6			20	7.3	2.2	
				8	8.0		135	66.1	65.8	
				9			20	6.2	1.4	
				10		607				H2
83	E110	1100	10.0	1	10.0		20	7.0	0.9	
	double-sided	F/F		3			20	4.0	0.0	
85	E110	1100	6.0				20			3B
	double-sided	F/F								
86	E110	1100	6.9				20			3B
	double-sided	F/F								
88	E110K	1100		3	7.0		20	2.7	0.0	
	double-sided	F/F		4			20	2.6	0.0	
89	$E110_{G(fr)}$	1100	10.5	3			135	59.8	56.5	
	double-sided	F/F		4						MG
				5			20	21.2	12.4	
				6	10.5		20	16.2	10.9	
				7		7				H2
				8		22				H2
90	$E110_{G(fr)}$	1100	13.0	3			135	60.1	59.6	
	double-sided	F/F		4						MG
				5			20	24.3	18.2	
				6	13.0		20	21.4	16.0	
				7		30				H2
				8		107				H2
				10		6				H2

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measu-red ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
91	$E110_{G(fr)}$ double-sided	1000 F/F	6.5	3			135	60.8	59.7	
				4						MG
				5	6.5		20	49.2	48.8	
				6			20	59.4	55.0	
				7		5				H2
				8		28				H2
92	E110pol double-sided	1100 F/F	8.0	2						MG
				3		28				H2
				4			20	52.0	46.3	
	E110 double-sided	1100 F/F	8.5	7			20	7.2	1.4	
				8		694				H2
				9	8.5					MG
93	$E110_{G(fr)}$ double-sided	1000 F/F	8.5	3			135	58.4	53.8	
				4						MG
				5	8.5		20	6.3	0.9	
				6			20	6.8	1.0	
				7		12				H2
94	$E110_{lowHf}$ double-sided	1100 F/F	9.2	3			135	60.2	58.5	
				4						MG
				5	9.2		20	45.2	39.3	
				6			20	37.9	37.7	
				7		17				H2
95	$E110_{G(3ru)}$ double-sided	1100 F/F	11.6	1	11.2					
				3			135	59.1	57.4	
				4						MG
				5			20	22.6	15.5	
				6	11.9		20	22.3	14.4	
				7						MG
				8		4				H2
96	E110 double-sided	1100 F/F	9.8				20			3B
97	$E110_{G(3ru)}$ double-sided	1100 F/F	16.7	1	15.8		20			
				3			135	53.8	50.4	
				4						MG
				5			20	16.9	9.6	
				6	17.0		20	25.9	20.7	
				7	17.3		20	9.2	4.0	
				8		17				SEM, H2
				10						MG
98	$E110_{G(3ru)}$ double-sided	1000 F/F	6.9	3			135	60.1	59.0	
				4						MG
				5			20	44.0	43.7	
				6	6.9		20	47.0	41.0	
				7		16				H2
99	$E110_{G(3fr)}$ double-sided	1100 F/F	11.5	3			135		57.1	
				4						MG
				5			20	23.8	16.0	
				6	11.5		20	23.4	13.9	
				7		13				H2

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measured ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
100	$E635_{G(fr)}$ double-sided	1100 F/F	12.5	3			135	60.7	59.5	
				4						MG
				5			20	12.1	4.1	
				6	12.5		20	9.9	4.5	
				7		18				H2
101	$E110_{G(3ru)}$ double-sided	1000 F/F	8.9	3			135	55.0	50.4	
				4						MG
				5			20	28.3	28.3	
				6	8.9		20	33.8	28.3	
				7		11				H2
102	E110 double-sided	1200 F/F	13.3	2	13.0		20	4.6	0.0	
				3	13.5		135			
				4						MG
				6	13.3		20	4.5	0.0	
				7		926				H2
				8			135			
				9			20	4.5	0.0	
104	E110 double-sided	1100 F/F	16.1	5						MG
				6	16.0		20	4.8	0.0	
				7	16.0					
				8	16.2		135	4.2	0.0	
105	E110 double-sided	1100 F/F	11.8				20			3B
106	E110 double-sided	1200 F/F	11.5	2			20	4.4	0.0	
				3	11.4		135	7.7	0.9	
				4						MG
				6	11.5		20	4.4	0.0	
				7		430				H2
				8			135	8.9	1.2	
				9			20	4.3	0.0	
108	$E635_{G(fr)}$ double-sided	1100 F/F	11.0	3			135	25.1	19.6	
				4						MG
				6			20	2.5	0.0	
				8			135	5.4	0.0	
109	$E110_{G(3ru)}$ double-sided	1100 F/F	18.0	2	16.6		20	10.6	5.4	
				3	17.2		135	44.7	44.3	
				5						MG
				6	18.4		20	8.0	1.9	
				8	19.0		135	29.3	29.0	
				9	19.0		20	9.0	3.6	
				10		101				H2
110	E110 double-sided	1100 F/F	13.7	2	13.5		20	3.8	0.0	
				3	13.5		135	19.2	12.4	
				5						MG
				6	14.0		20	3.9	0.0	
				8	13.8		135	8.9	2.5	
				9	13.8		20	5.6	0.0	
				10		509	20	5.6	0.0	H2

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measu-red ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
111	E110 double-sided	1100 F/F	8.5	2	7.9		20	4.4	0.0	
				3			135	59.3	58.5	
				5						MG
				6	8.3		20	19.1	12.3	
				8	8.8		135	59.5	57.8	
				9	9.0		20	19.2	13.0	
112	$E110_{G(3ru)}$ double-sided	1200 F/F	23.5	2						MG
				3	22.3		20	4.9	0.0	
				5	24.7		135	3.2	0.0	
				6		2200				H2
117	E110A double-sided	1100 F/F	9.0	3	9.3		135	11.8	4.7	
				5						MG
				6	8.1		20	5.1	0.0	
				8	9.5		135	11.3	4.2	
				10		554				H2
119	E110pol double-sided	1000 F/F	4.3	2						MG
				3	4.3		20	60.0	59.6	
				5		44				H2
	E110 double-sided	1000 F/F	5.7	8	5.7		20	26.4	19.4	
				9		173				H2
				10						MG
120	$E110_{G(3ru)}$ double-sided	1200 F/F	7.8	2	8.1		20	18.3	9.5	
				3			135	2.2	0.0	
				4		824				H2
				5						MG
				6	7.5		20	2.3	0.0	
				8			135	27.3	20.5	
				9			20	3.5	0.0	
121	$E110_{lowHf}$ double-sided	1100 F/F	11.4	2	12.1		20	4.5	0.0	
				4						MG
				6	10.8		20	12.0	5.0	
				9	11.3		20	10.4	2.7	
				10		426				H2
123	E110 double-sided	800 F/F	3.4	2	3.0		20	67.7	61.2	
				3	3.0		135	67.4	61.3	
				5						MG
				6	3.5		20	63.8	58.0	
				7		80				H2
				8	3.8		135	63.9	56.9	
				9	3.5		20	64.5	60.1	
126	E635 double-sided	1100 F/F	7.8	2	7.6		20	42.1	41.9	
				3	7.6		135	62.4	62.0	
				5						MG
				6	8.1		20	38.3	37.9	
				7		138				H2
				8	7.9		135	56.9	56.3	
				9			20	17.5	11.5	

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measured ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
127	E635 double-sided	1000 F/F	5.3	2	4.8		20	60.1	59.9	
				3	4.8		135	70.0	65.5	
				5						MG
				6	5.7		20	54.7	54.5	
				7		98				H2
				8	5.9		135	63.5	61.2	
				9			20	58.0	57.7	
130	E110 double-sided	900 F/F	3.8	2			20	57.3	56.0	
				3	3.7		135	64.0	56.8	
				5						MG
				6	3.8		20	60.4	59.3	
				7		106				H2
				8			135	64.9	60.1	
				9			20	56.8	56.2	
131	E110 double-sided	900 F/F	7.4	2			20	30.6	30.2	
				3			135	63.4	61.2	
				5						MG
				6	7.4		20	28.4	28.1	
				7		194				H2
				8			135	59.0	56.8	
				9			20	37.2	37.0	
132	E110 double-sided	800 F/F	11.0	2	9.4		20	23.6	16.4	
				3	9.7		135	70.4	64.4	
				5						MG
				6	11.7		20	12.3	5.5	
				7		466				H2
				8	12.2		135	67.7	59.0	
				9	11.9		20	10.9	2.2	
134	E635 double-sided	1100 F/F	6.9	2	6.8		20	14.5	8.7	
				4						MG
				6	7.0		20	15.5	6.6	
				7		107				H2
				9	6.7		20	26.2	21.9	
135	E635 double-sided	1100 F/F	9.3	2	8.7		20	16.3	10.9	
				3			135	53.6	52.5	
				5						MG
				6	9.4		20	13.1	5.4	
				7		35				H2
				8			135	53.5	52.1	
				9	9.8		20	12.0	5.2	
136	E110m double-sided	1100 F/F	7.7	2	6.8		20	10.9	3.3	
				3			135	61.9	58.4	
				5						MG
				6	8.0		20	7.7	0.0	
				7		90				H2
				8			135	59.0	56.8	
				9	8.3		20	8.1	0.0	

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Average ECR (%)	Ring sample number	As-measu-red ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[2] (%)	Resid. Duct.[3] (%)	Other investigations[4]
137	$E110_{G(3ru)}$ double-sided	900 F/F	7.5	2			20	63.0	61.3	
				3	6.6		135	61.2	59.8	
				5						MG
				6	7.4		20	42.6	41.9	
				7		66				H2
				8	7.9		135	60.1	59.0	
				9	8.0		20	9.3	3.3	
138	E635 double-sided	1000 F/F	9.4	2	8.8		20	6.9	0.0	
				3	8.7		135	12.0	3.2	
				5						MG
				6	9.9		20	3.7	0.0	
				7		400				H2
				8	10.5		135	20.8	13.1	
				9	9.0		20	6.0	0.0	
140	E110 double-sided	950 F/F	13.4	2	13.7		20	2.9	0.0	
				3			135	5.9	0.0	
				5						MG
				6	12.1		20	3.5	0.0	
				7		2780				H2
				8			135	6.4	0.0	
				9	14.4		20	3.2	0.0	
141	E110 double-sided	950 F/F	11.2	2	11.2		20	3.5	0.0	
				3			135	7.7	0.0	
				5						MG
				6			20	3.1	0.0	
				7		920				H2
				8			135	5.3	0.0	
				9			20	2.2	0.0	
142	E110 double-sided	900 F/F	12.3	2	10.0		20	3.3	0.0	
				3			135	4.2	0.0	
				5						MG
				6	13.3		20	2.5	0.0	
				7		3100				H2
				8			135	4.0	0.0	
				9	13.7		20	2.2	0.0	
144	E110 double-sided	800 F/F	8.6	5						MG
				6	8.4		20	21.0	15.0	
				7		150				H2
				8	8.8		20	25.0	17.0	

1) Ring tensile tests and three point bending tests are indicated in "Other investigations" column, all other mechanical tests are ring compression tests

2) Relative displacement at failure

3) Residual ductility at failure

4) Abbreviations:

- MG metallographic cross-section
- HV microhardness measurements
- MTt ring tensile mechanical tests
- 3B three point bending tests
- Fr fractography investigation
- SEM scanning electron microscope examinations

Table B-3. A summary list of tested irradiated commercial claddings. Characterization of test conditions and major test results

Material	Oxidation type	Heating/ Cooling comb.	Steady temp. (C)	Sample number	Equiv. Time (s)	Measured ECR[1] (%)	Weight gain[2] (mg/cm^2)	Residual ductility (%)	Relative displacement (%)	H cont.[3] (ppm)
E110	double-sided	F/F	1000	16	544	6.3	4.7	18.7	26.7	470
				17	664	8.6	6.5	37.0	39.6	250
			1100	10	232	7.7	5.8	0.0	8.4	1690
				14	312	8.3	6.2	0.0	8.3	1410
				15	327	8.1	6.1	0.0	6.6	-
				20	137	6.3	4.7	26.1	30.4	30
				21	223	7.0	5.2	0.0	6.3	-
			1200	18	218	16.0	12.5	0.0	3.4	-
		S/F	1100	3	-*	5.8	4.3	11.2	20.4	170
		S/S	1100	1	-*	8.5	6.4	3.2	11.3	280
				2	-*	10.5	8.0	1.9	8.9	270

* - Equivalent time calculation procedure was not developed for slow heating and slow cooling test modes

F/F, F/Q, F/S, S/F, S/S characterize the heating/cooling combinations of the oxidation mode

(F - fast, Q - quench, S - slow)

[1] A sum of the ECR before the oxidation (0.5 %) and the ECR during the oxidation

[2] A sum of the weight gain before the oxidation (0.4 mg/cm^2) and the weight gain during the oxidation

[3] A sum of the H content before the oxidation (47 ppm) and the H content during the oxidation

Table B-4. A summary data base on results of oxidation and mechanical tests (ring compression tests) with irradiated commercial cladding samples

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Ring sample number	As-measured ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[1] (%)	Resid. Duct.[2] (%)	Other investigations[3]
1	E110 double-sided	1100 S/S	1			20	11.3	3.2	
			2			135	30.5	25.1	
			3		280				H2
			4						MG
			5	8.5					
2	E110 double-sided	1100 S/S	1			20	8.9	1.9	
			2			135	17.5	10.9	
			3		270				H2
			4						MG
			5	10.5					
3	E110 double-sided	1100 S/F	1			20	20.4	11.2	
			2			135	67.6	58.6	
			3		170				H2
			4						MG
			5	5.8					
10	E110 double-sided	1100 F/F	1			20	8.4	0.0	
			2			135	14.0	2.0	
			3		1690				H2
			4						MG, HV
			5	7.7					

Tube sample number	Material, Oxid. Type	Steady temp. (C) Heat/Cool. Comb.	Ring sample number	As-measured ECR (%)	H cont. (ppm)	Temp. of mech. Tests (C)	Relative disp.[1] (%)	Resid. Duct.[2] (%)	Other investigations[3]
14	E110 double-sided	1100 F/F	1			20	8.3	0.0	
			2			135	75.8	68.7	
			3		1410				H2
			4						MG, HV
			5	8.3					
15	E110 double-sided	1100 F/F	1			20	6.6	0.0	
			2			135	72.5	63.0	
			3						
			4						MG, HV
			5	8.1					
16	E110 double-sided	1000 F/F	1			20	26.7	18.7	
			2			135	48.0	36.0	
			3		470				H2
			4						MG, HV
			5	6.3					
17	E110 double-sided	1000 F/F	1			20	39.6	37.0	
			3		250				H2
			4						MG, HV
			5	8.6					
18	E110 double-sided	1200 F/F	1			20	3.4	0.0	
			2			135	11.3	1.2	
			3						
			4						MG, HV
			5	16.0					
20	E110 double-sided	1100 F/F	1			20	30.4	26.1	
			3		30				H2
			4						MG
			5	6.3					
21	E110 double-sided	1100 F/F	1			20	6.3	0.0	
			4						MG
			5	7.0					

[1)] Relative displacement at failure

[2)] Residual ductility at failure

[3)] Abbreviations:

MG - metallographic cross-section
H2 - hydrogen content measurements
HV - microhardness measurements

Notice. The numeration of the rings begins from the bottom of the tube based on its location in the furnace. As a rule, parts of approximately 7 mm long were cut from top and bottom of oxidized tube and rejected to avoid end effects. After that the 8 mm rings were cut and numbered from bottom. The photos of tubes in the report and in the appendices (the photos represent entire uncut tubes) are shown such that the numeration increases from the right to the left.

APPENDIX C

Temperature Histories, Appearances and Microstructures of E110 Standard As-received Tubes after a Double-sided Oxidation at 1100 C and S/S, S/F, F/S Combinations of Heating and Cooling Rates

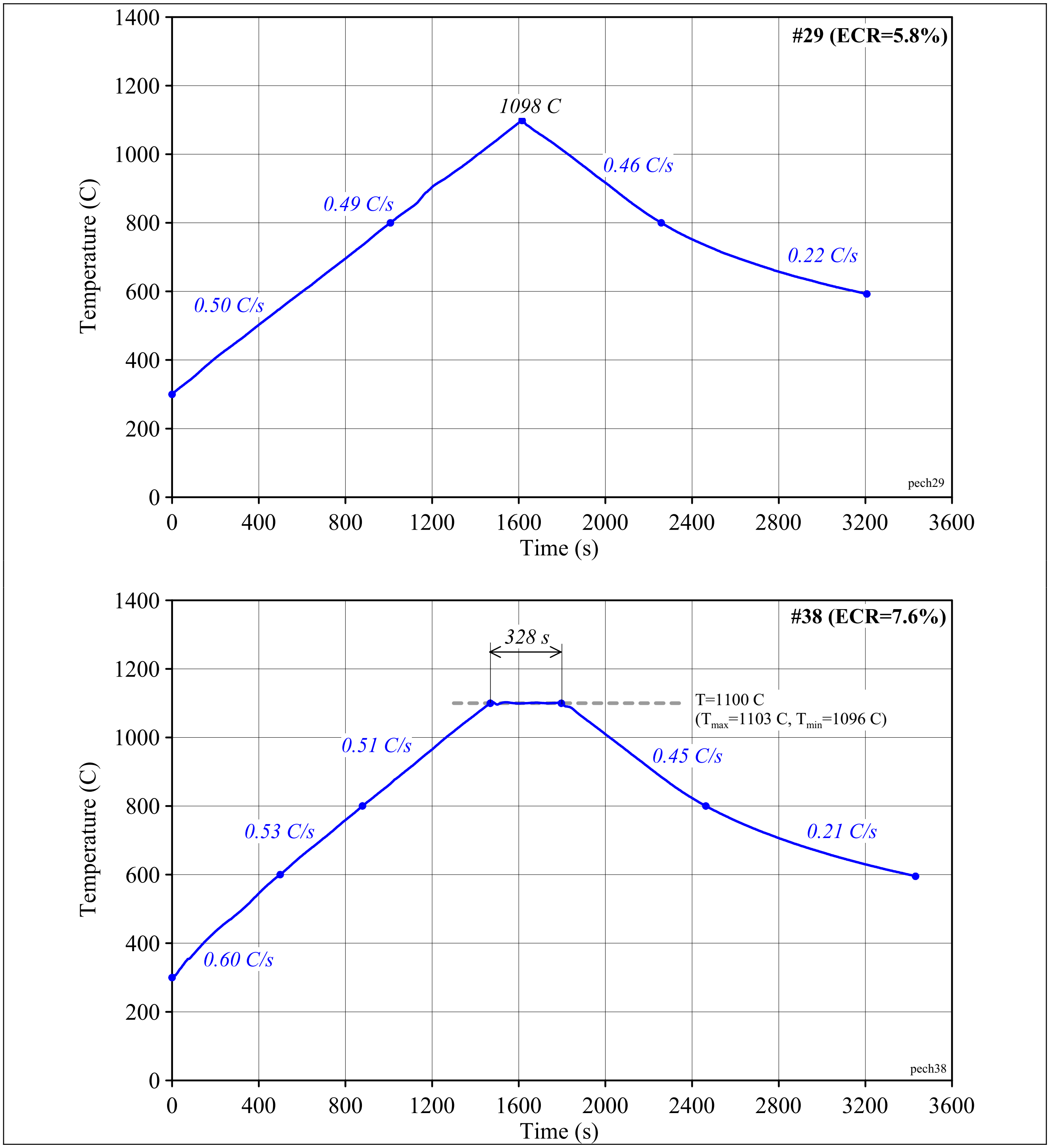


Fig. C-1. Typical temperature histories for cladding samples oxidized at S/S combination of heating and cooling rate

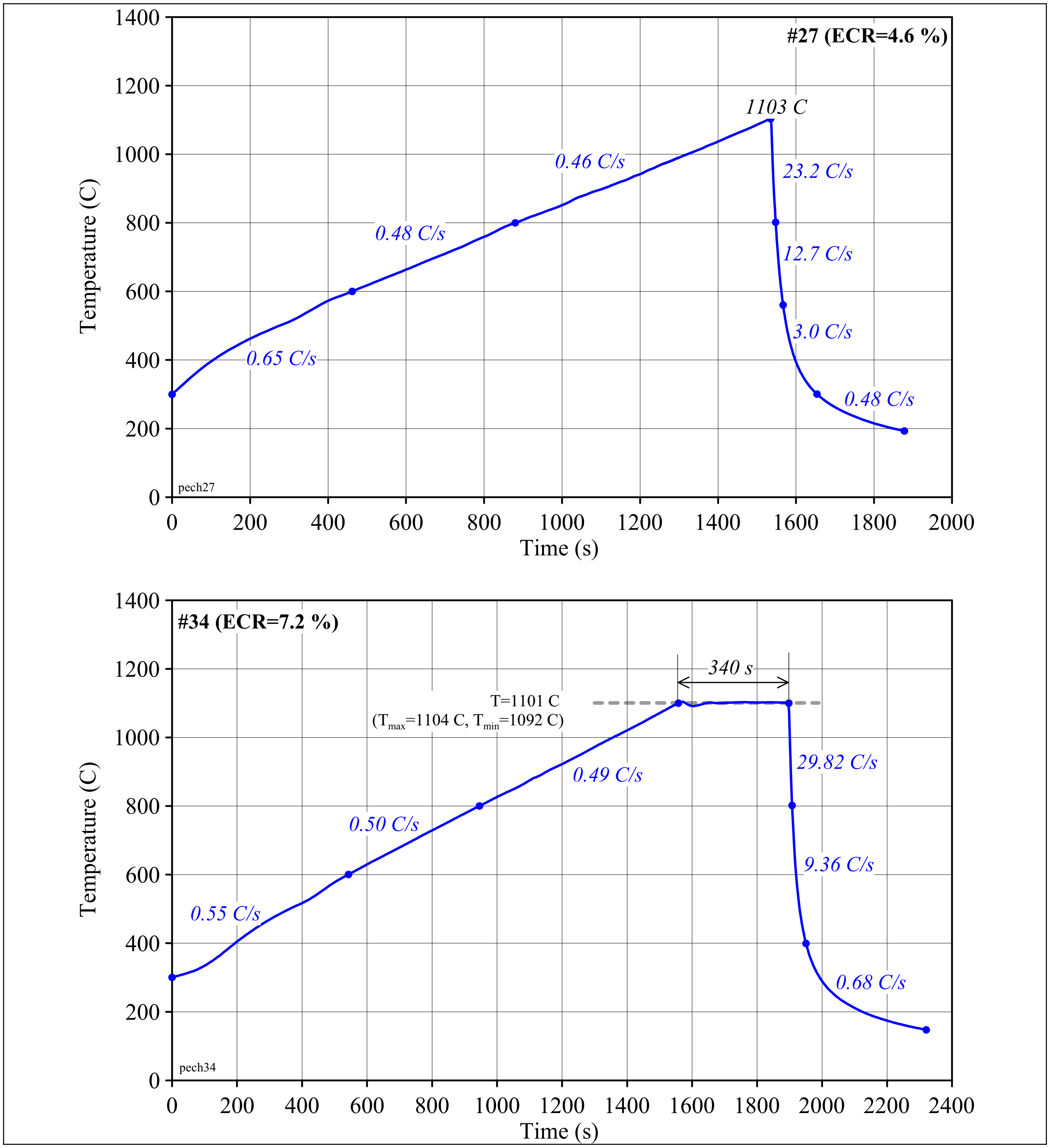


Fig. C-2. Typical temperature histories for cladding samples oxidized at S/F combination of heating and cooling rate

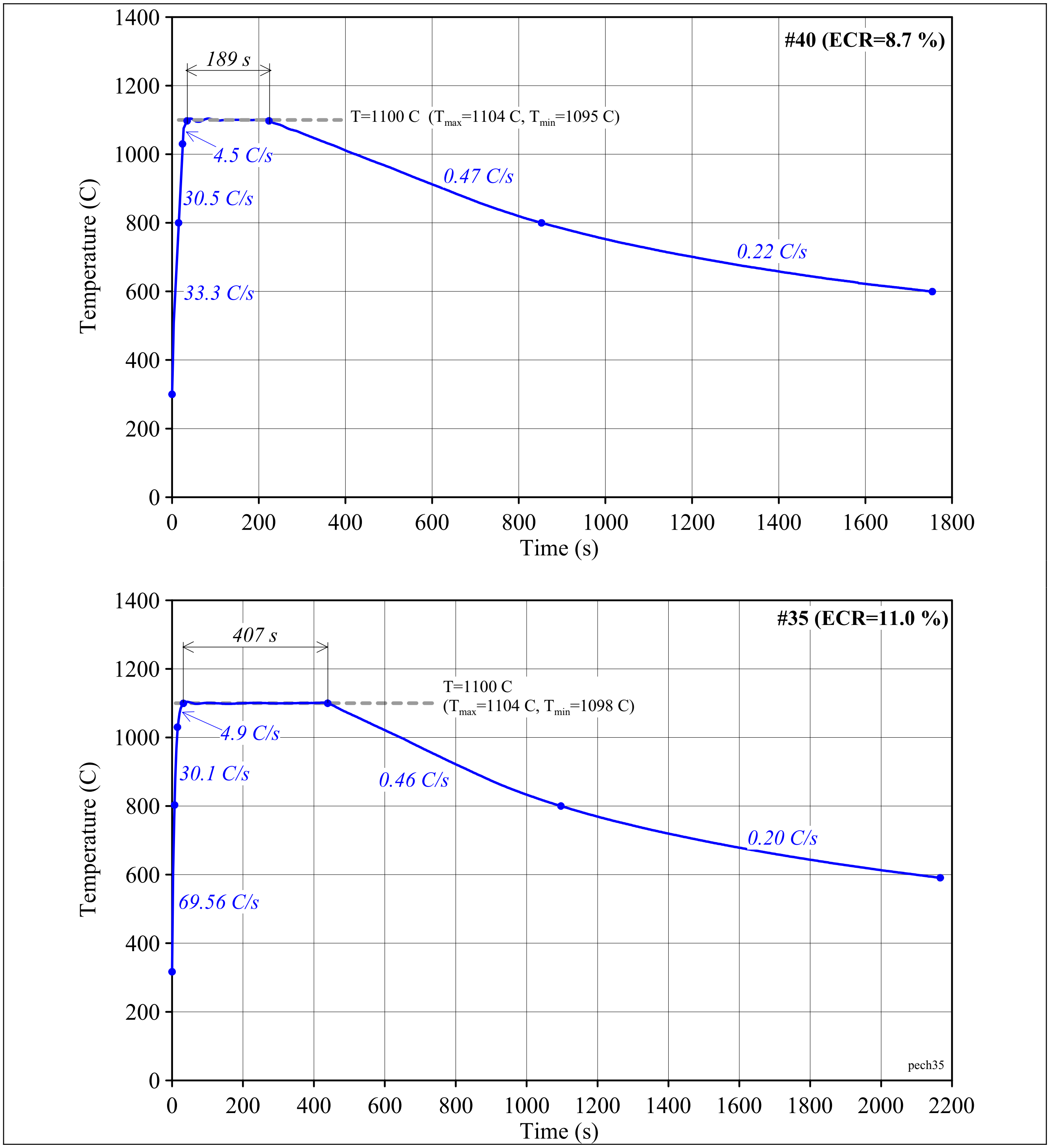


Fig. C-3. Typical temperature histories for cladding samples oxidized at F/S combination of heating and cooling rate

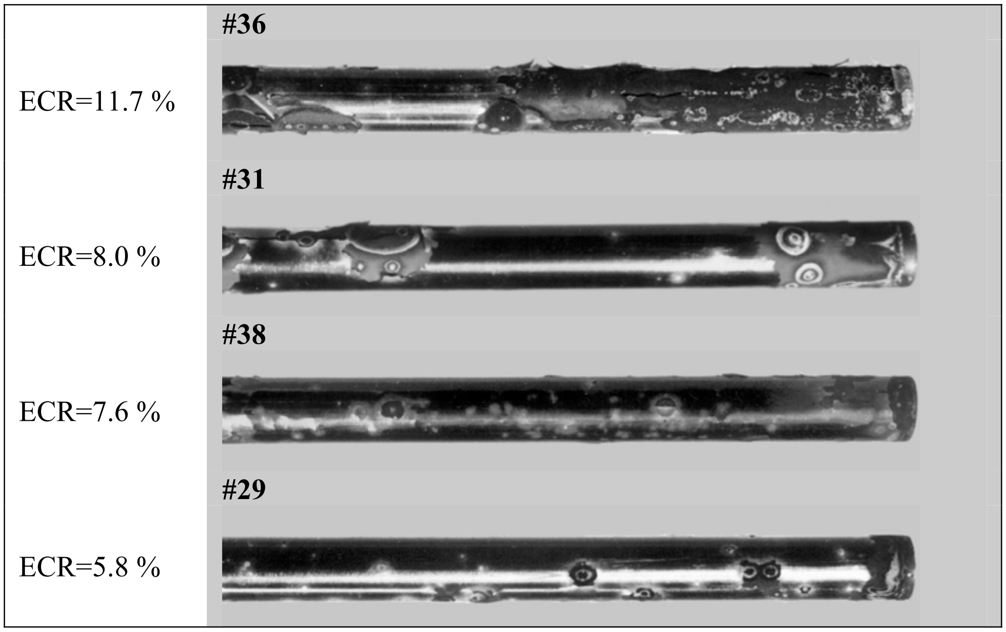


Fig. C-4. Appearance of E110 standard as-received samples as a function of the ECR after a double-sided oxidation at 1100 C and S/S combination of heating and cooling rates

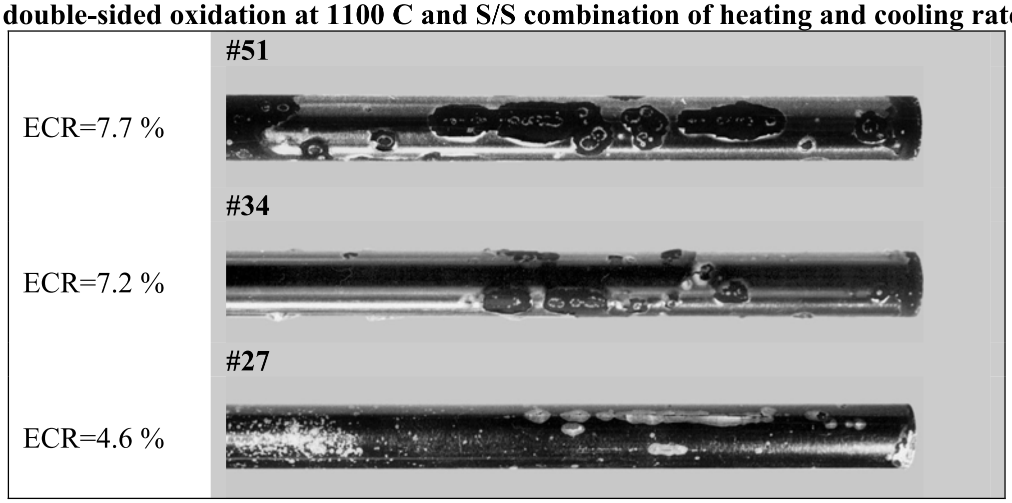


Fig. C-5. Appearance of E110 standard as-received tubes as a function of the ECR after a double-sided oxidation at 1100 C and S/F combination of heating and cooling rates

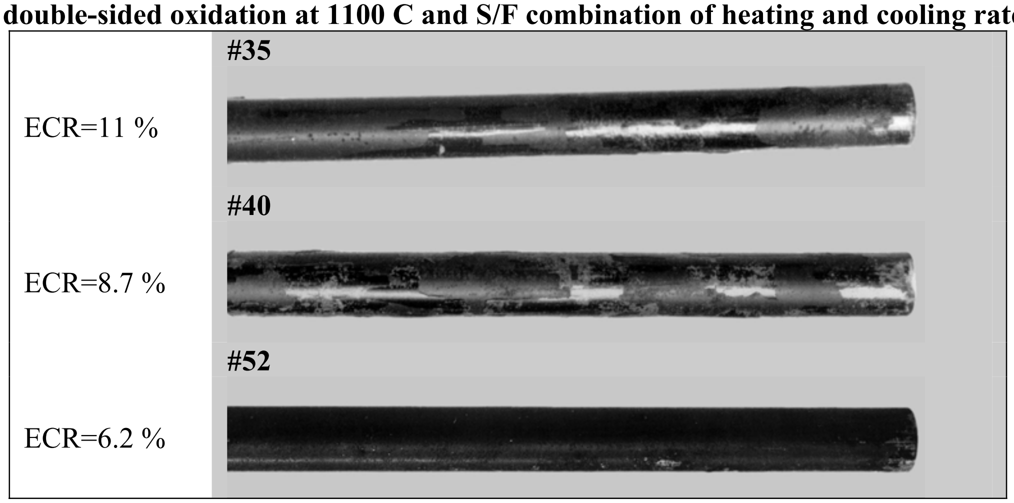


Fig. C-6. Appearance of E110 standard as-received tubes as a function of the ECR after a double-sided oxidation at 1100 C and F/S combination of heating and cooling rates

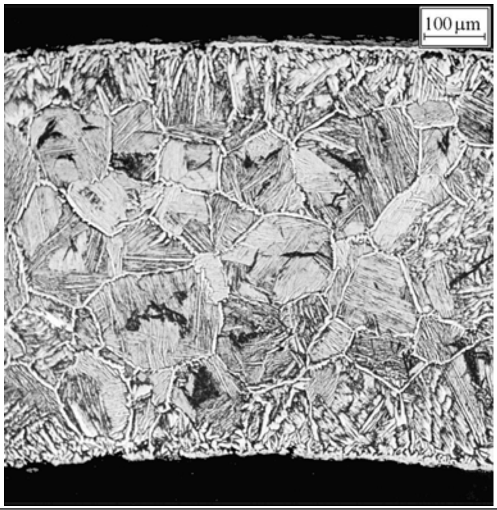
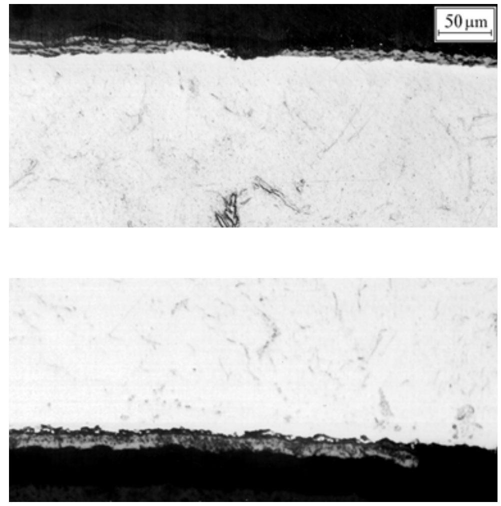
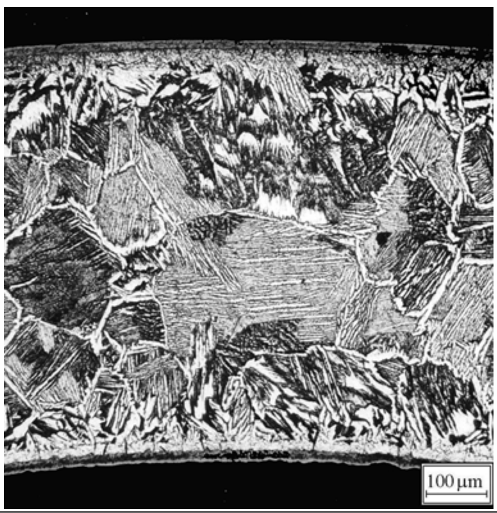
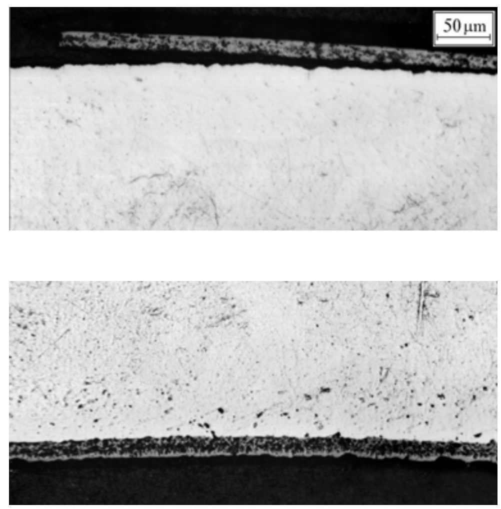
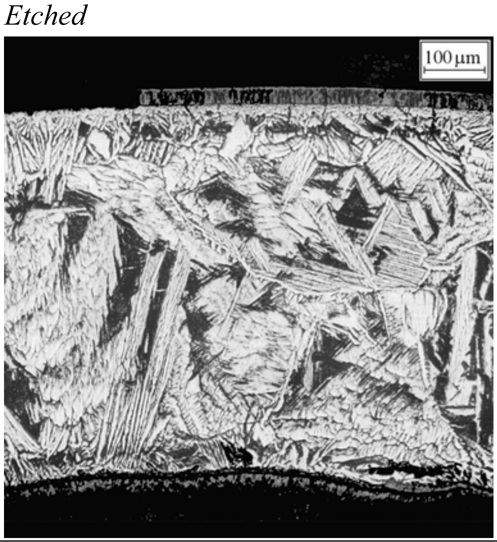
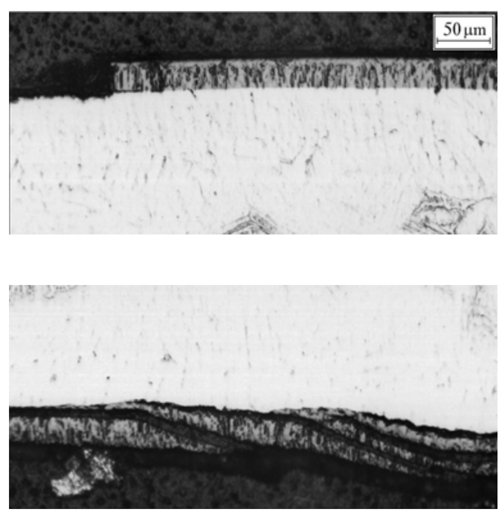
#29-3 ECR=5.8%	*Etched*  	*Polished* 
#38-5 ECR=7.6%	*Etched*  	*Polished* 
#36-5 ECR=11.7%	*Etched*  	*Polished* 

Fig. C-7. Microstructure of E110 standard as-received tubes after a double-sided oxidation at 1100°C and S/S combination of heating and cooling rates

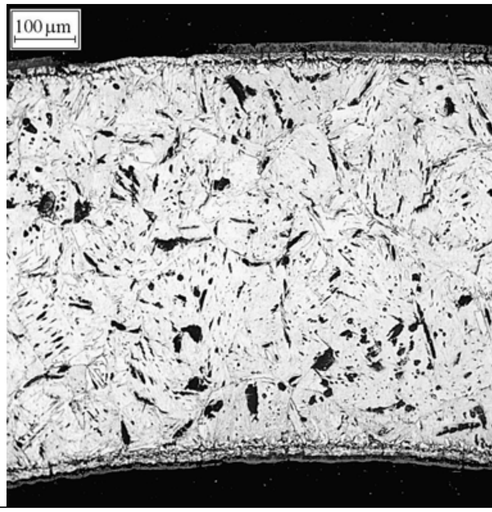
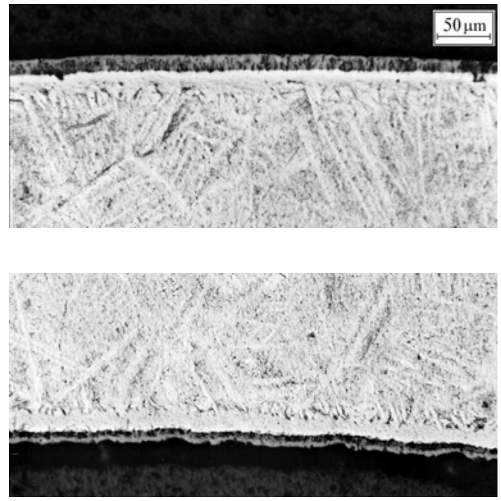
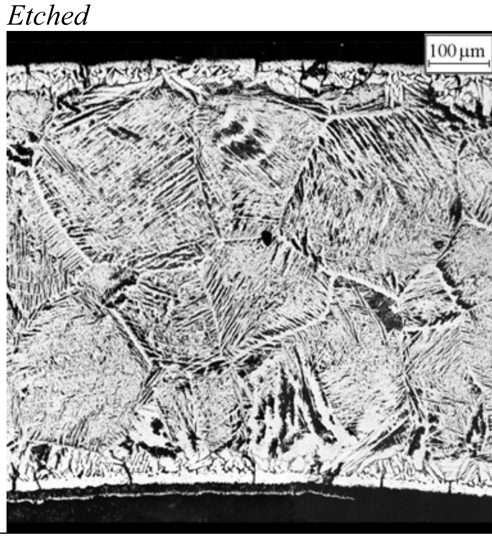
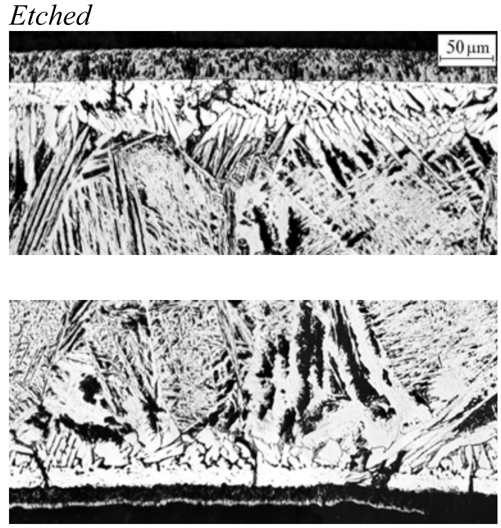
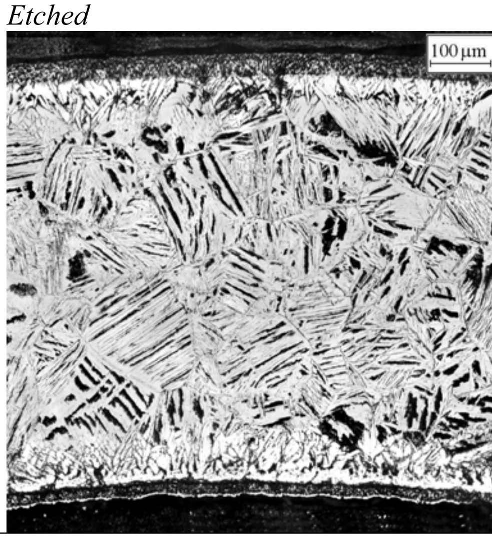
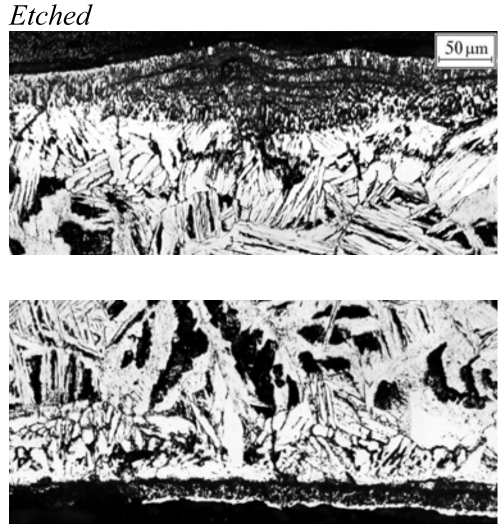
#27-5 ECR=4.6%	*Etched*  	*Polished* 
#34-5 ECR=7.2%	*Etched*  	*Etched* 
#51-5 ECR=7.7%	*Etched*  	*Etched* 

Fig. C-8. Microstructure of E110 standard as-received tubes after a double-sided oxidation at 1100°C and S/F combination of heating and cooling rates

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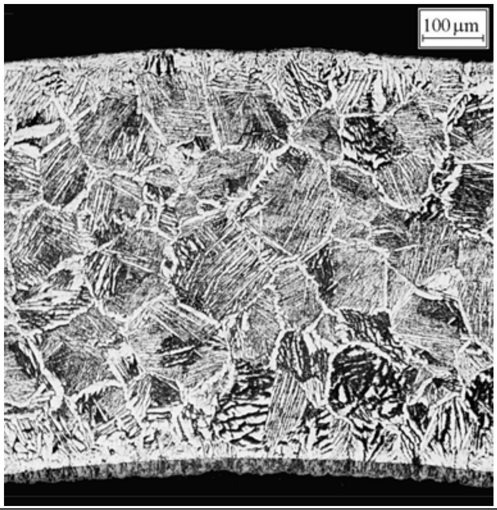</td>
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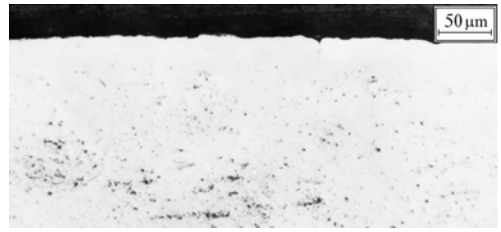
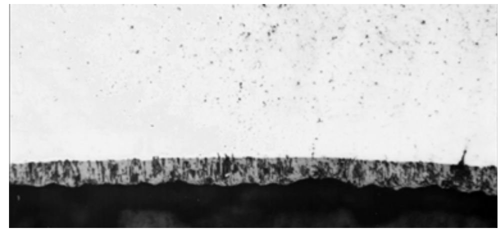</td>
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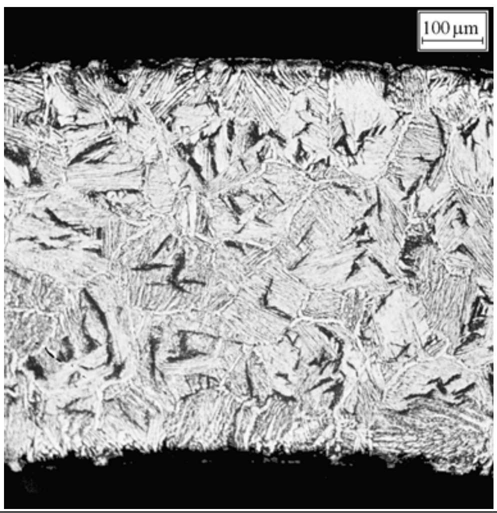
<tr>
<td>#40-5
ECR=8.7%</td>
<td>Etched
</td>
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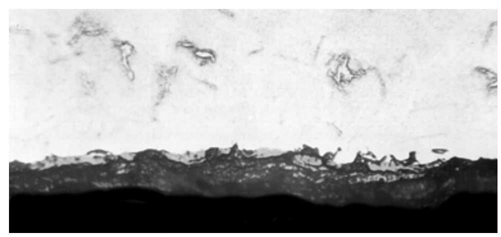</td>
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<tr>
<td>#35-5
ECR=11.0%</td>
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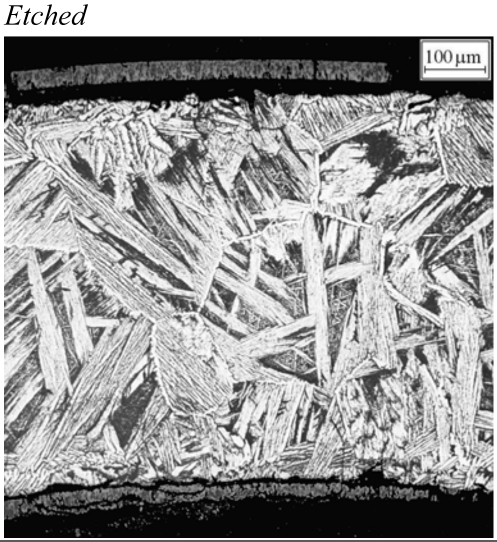</td>
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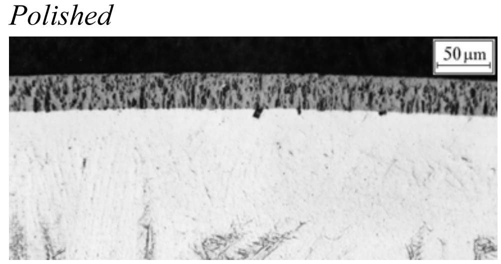
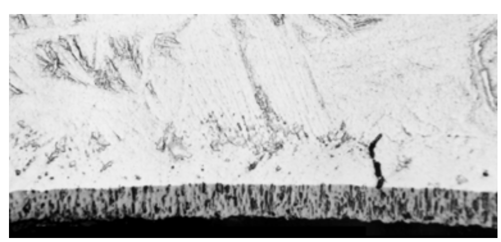</td>
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</table>

Fig. C-9. Microstructure of E110 standard as-received tubes after a double-sided oxidation at 1100°C and F/S combination of heating and cooling rates

APPENDIX D

Temperature Histories, Appearances and Microstructures of E110 Standard As-received Tubes after a Double-sided Oxidation at 800, 900, 950, 1000, 1100, 1200 C and F/F (F/Q) Combinations of Heating and Cooling Rates

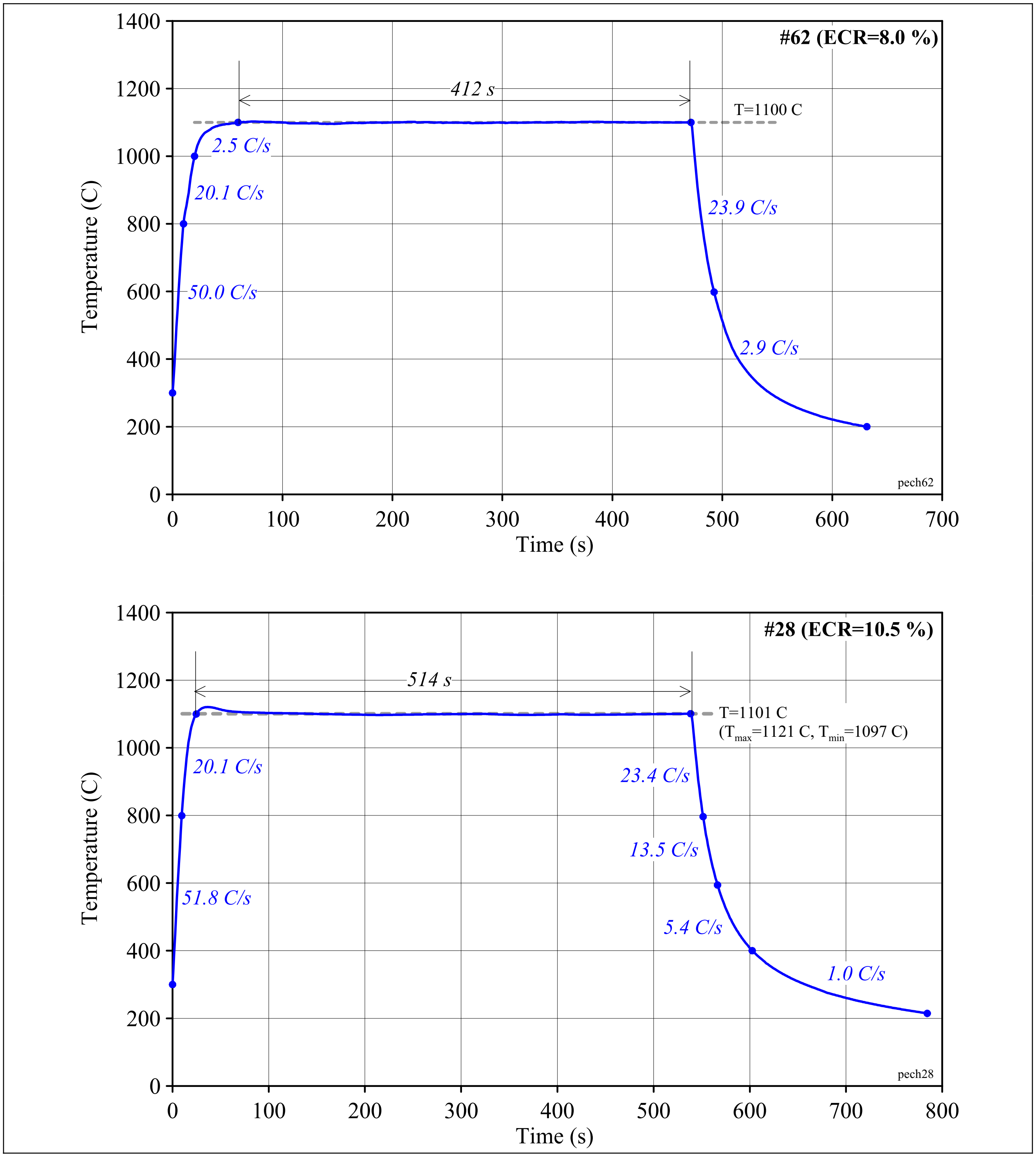

Fig. D-1. Typical temperature histories for cladding samples oxidized at F/F combination of heating and cooling rate

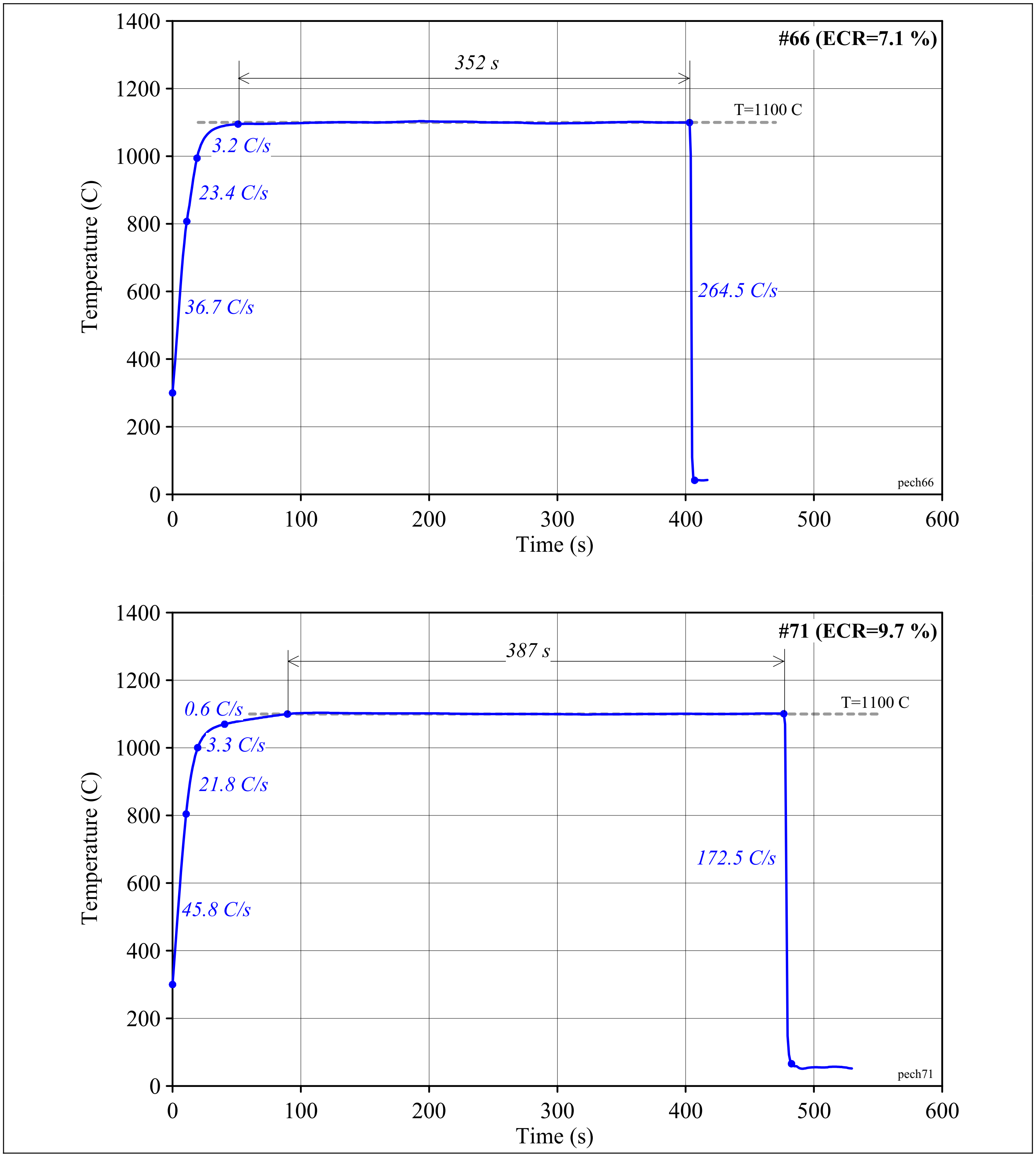

Fig. D-2. Typical temperature histories for cladding samples oxidized at F/Q combination of heating and cooling rate

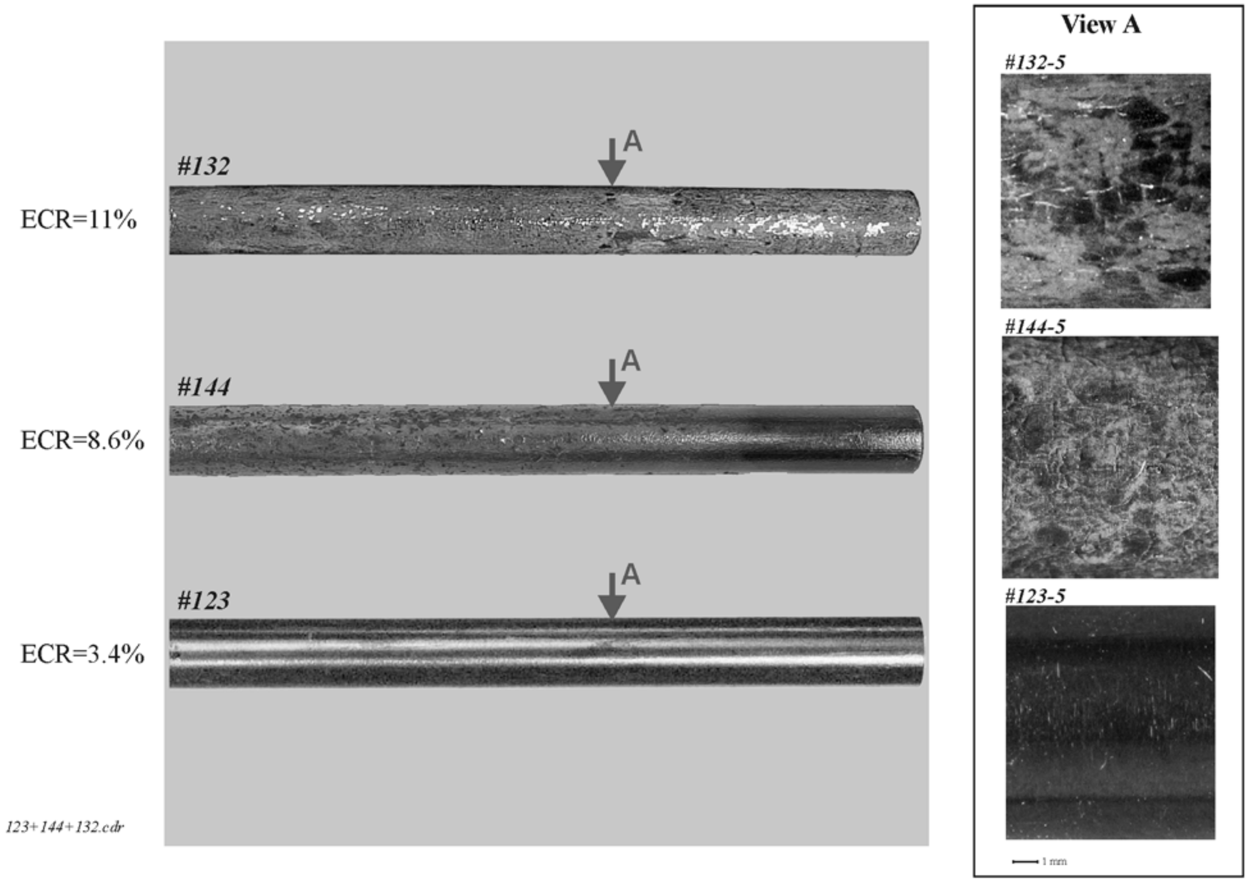

Fig. D-3. Appearance of E110 standard as-received tubes as a function of the ECR after a double-sided oxidation at 800 C and F/F combination of heating and cooling rates

<table>
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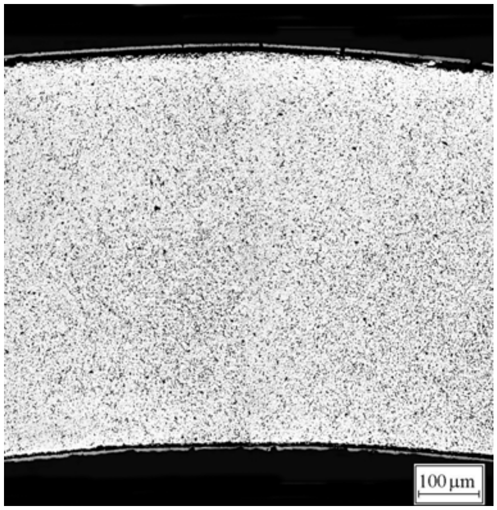
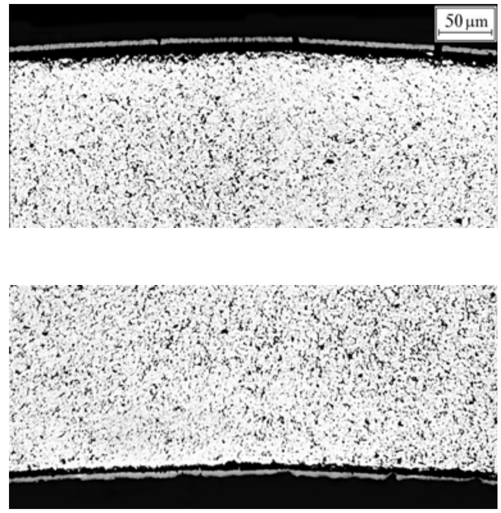
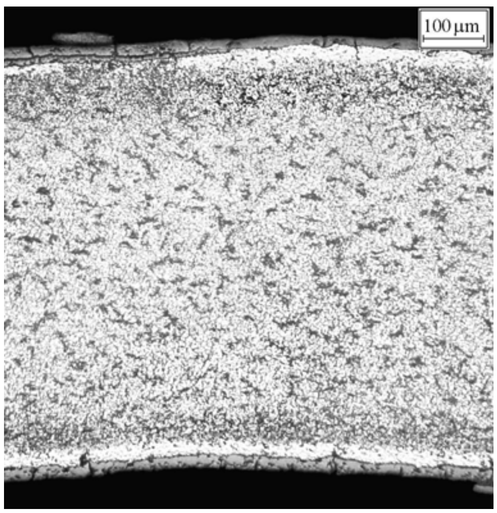
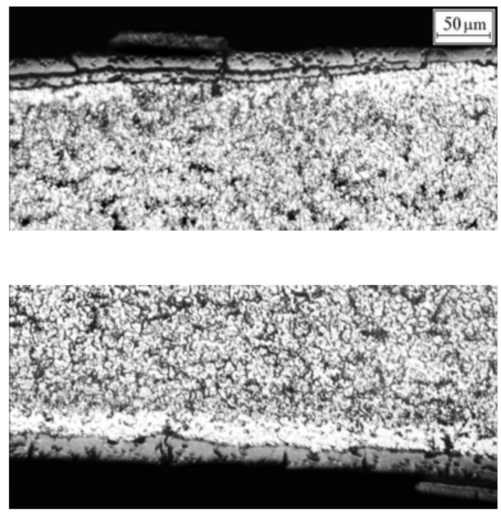
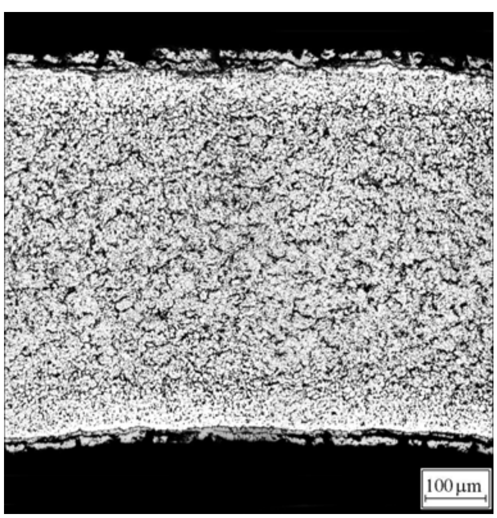
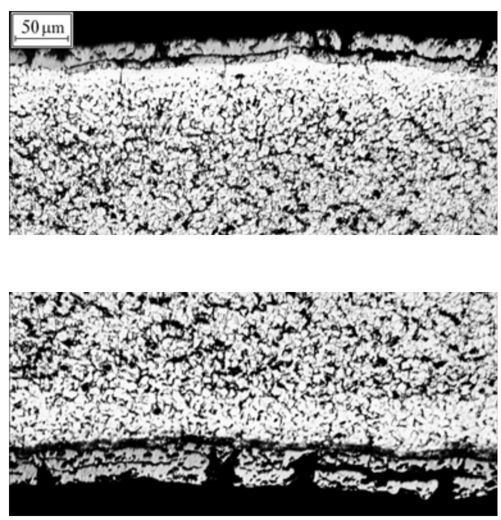
ECR=3.4%</td><td>Etched
</td><td>Etched
</td></tr>
<tr><td>#144-5
ECR=8.6%</td><td>Etched
</td><td>Etched
</td></tr>
<tr><td>#132-5
ECR=11%</td><td>Etched
</td><td>Etched
</td></tr>
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Fig. D-4. Microstructure of E110 standard as-received tubes after a double-sided oxidation at 800°C and F/F combination of heating and cooling rates

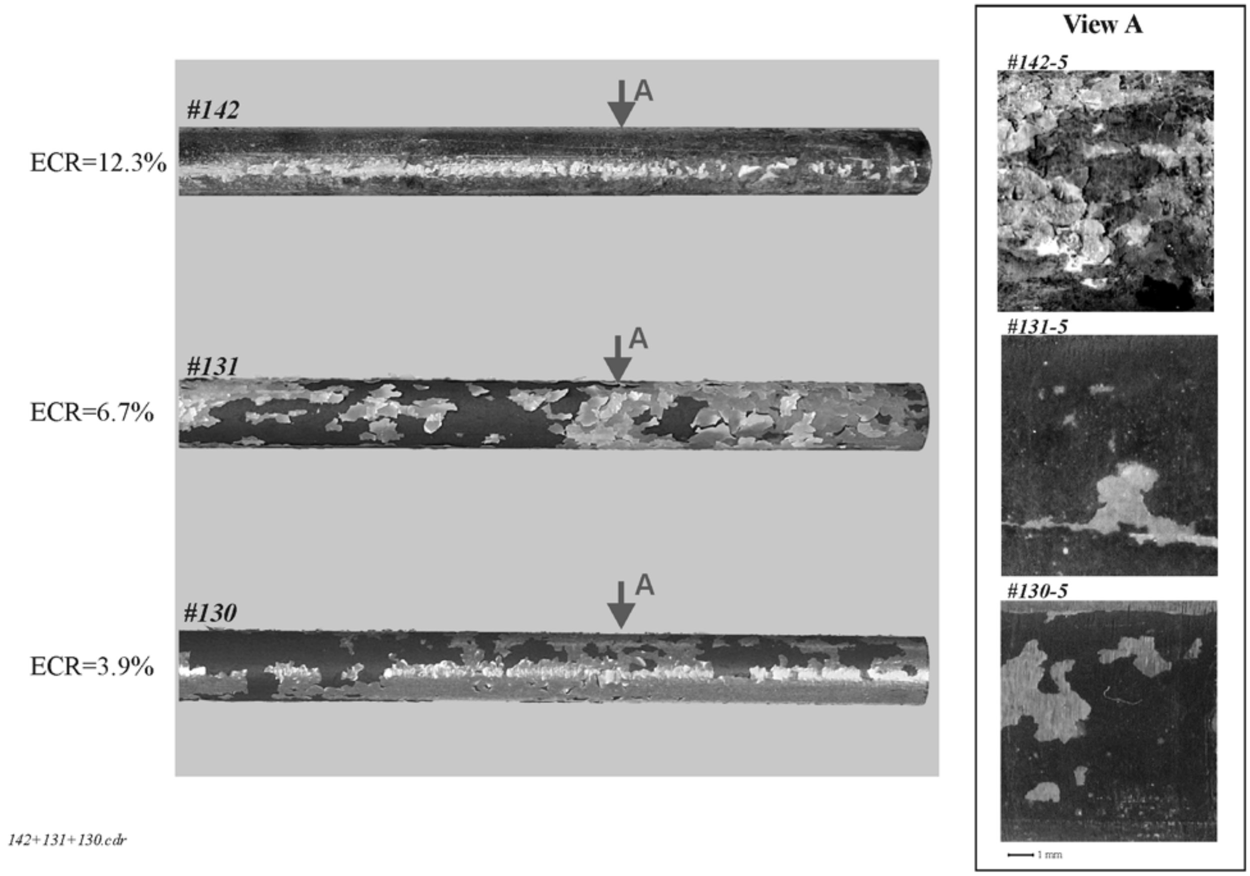


Fig. D-5. Appearance of E110 standard as-received tubes as a function of the ECR after a double-sided oxidation at 900 C and F/F combination of heating and cooling rates

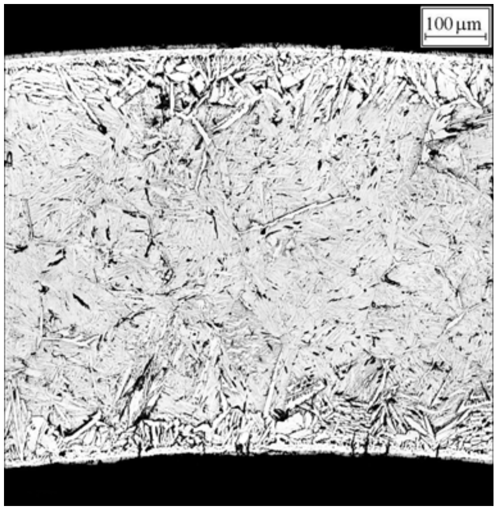
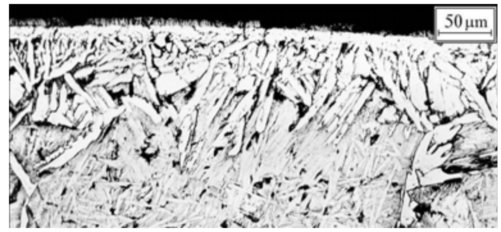
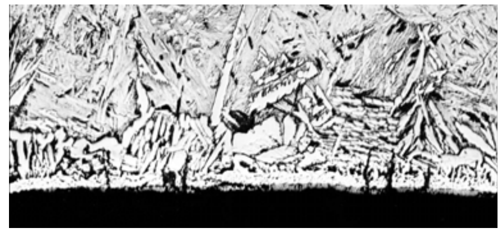
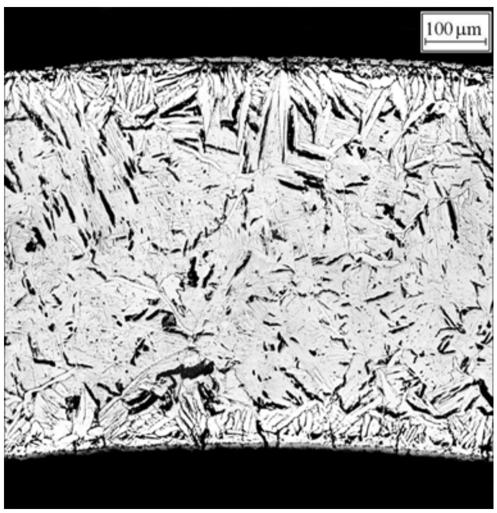
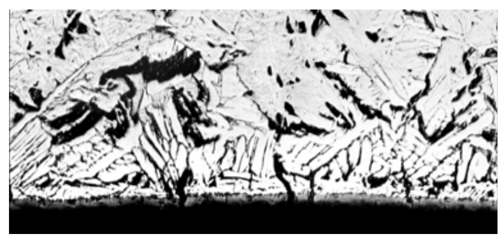
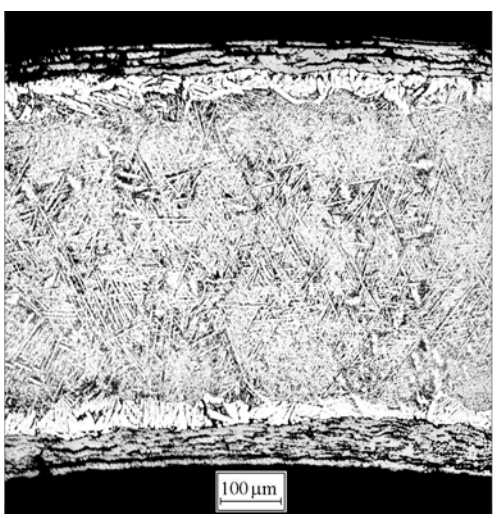
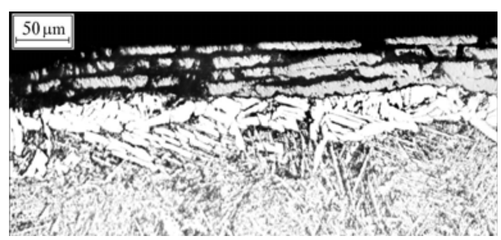
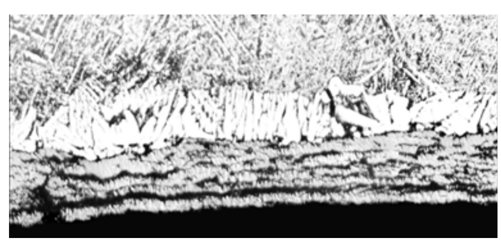
#130-5 ECR=3.9%	*Etched* 	*Etched*  
#131-5 ECR=6.7%	*Etched* 	*Etched*  
#142-5 ECR=12.3%	*Etched* 	*Etched*  

Fig. D-6. Microstructure of E110 standard as-received tubes after a double-sided oxidation at 900°C and F/F combination of heating and cooling rates

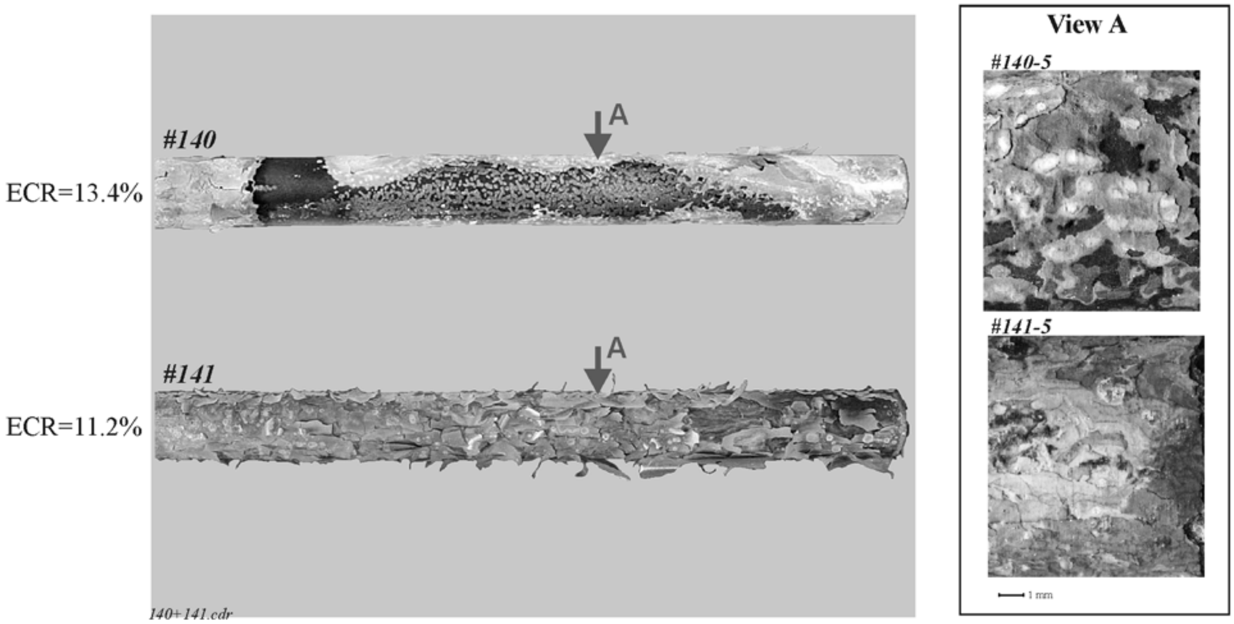


Fig. D-7. Appearance of E110 standard as-received tubes as a function of the ECR after a double-sided oxidation at 950 C and F/F combination of heating and cooling rates

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ECR=13.4%</td>
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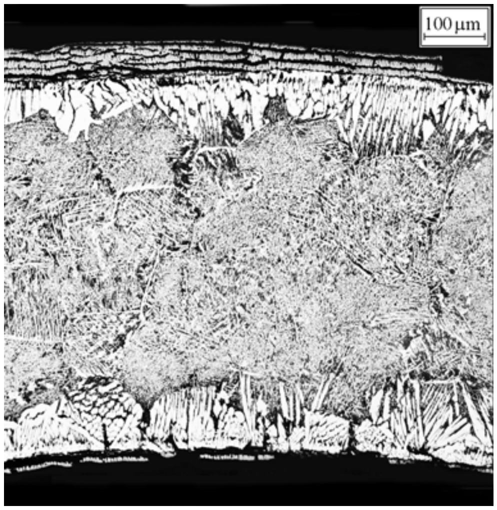</td>
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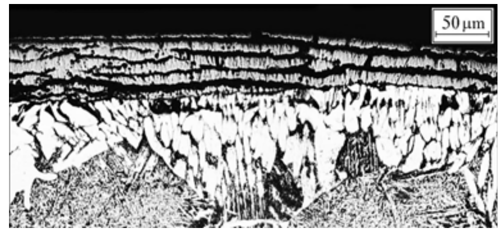
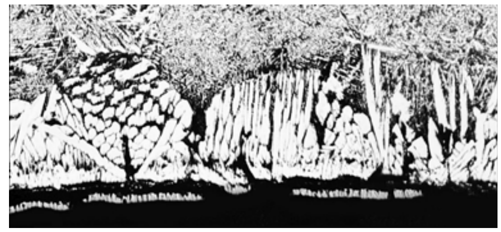</td>
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<tr>
<td>#141-5
ECR=11.2%</td>
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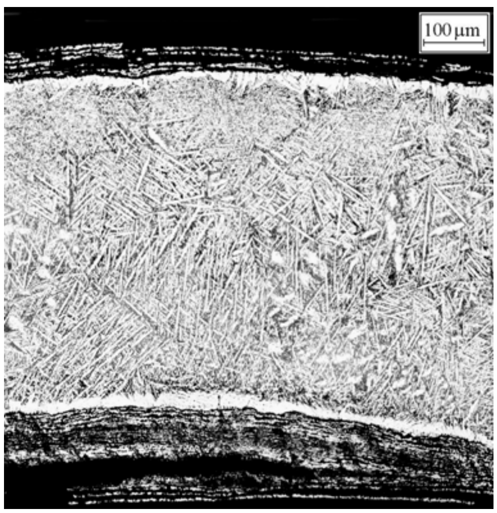</td>
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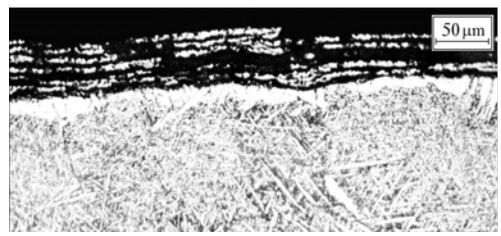
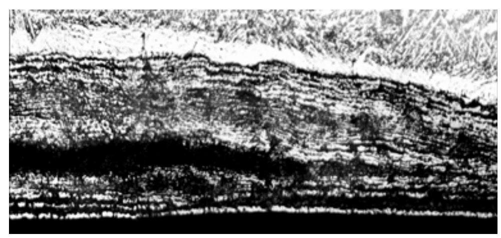</td>
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Fig. D-8. Microstructure of E110 standard as-received tubes after a double-sided oxidation at 950°C and F/F combination of heating and cooling rates

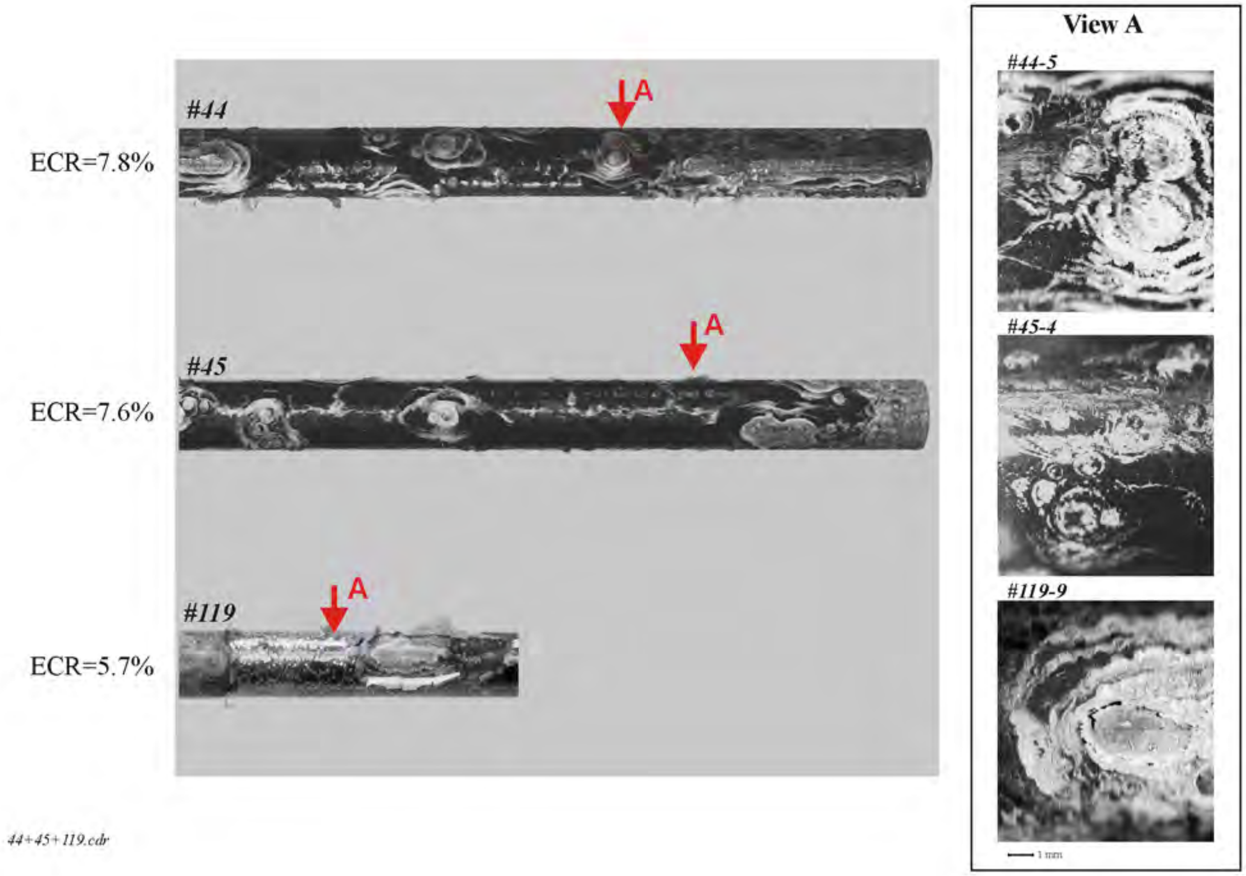
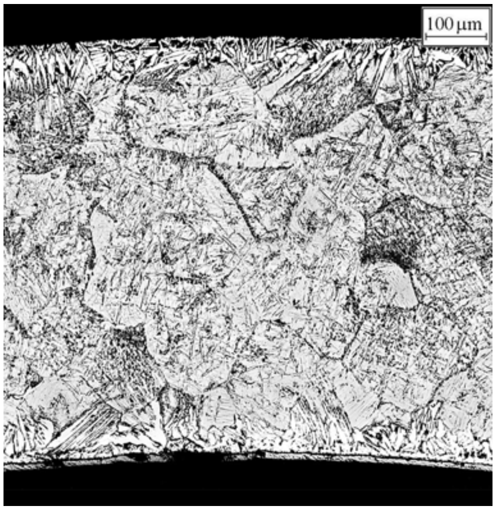


Fig. D-9. Appearance of E110 standard as-received tubes as a function of the ECR after a double-sided oxidation at 1000 C and F/F combination of heating and cooling rates

#119-2
(as-received)
ECR=5.7%

Etched



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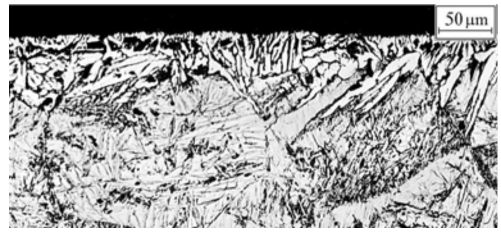
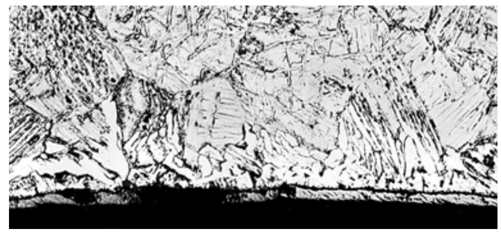
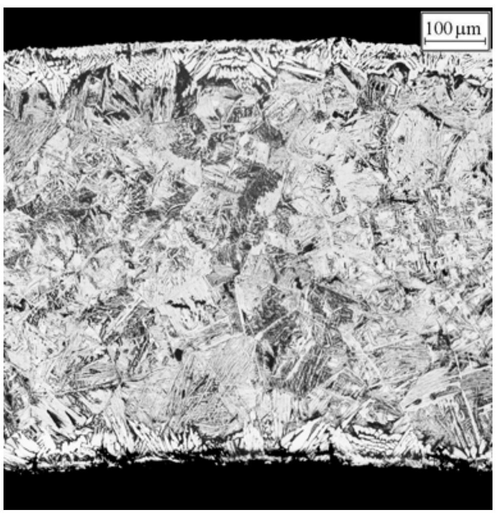




#45-5
ECR=7.6%

Etched



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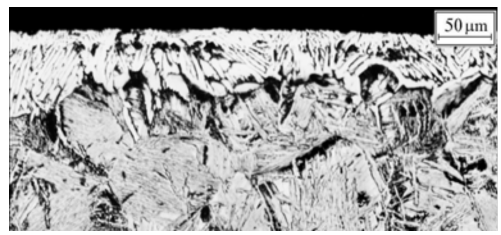
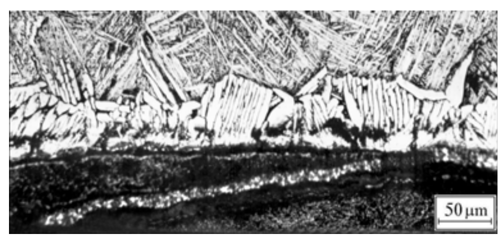
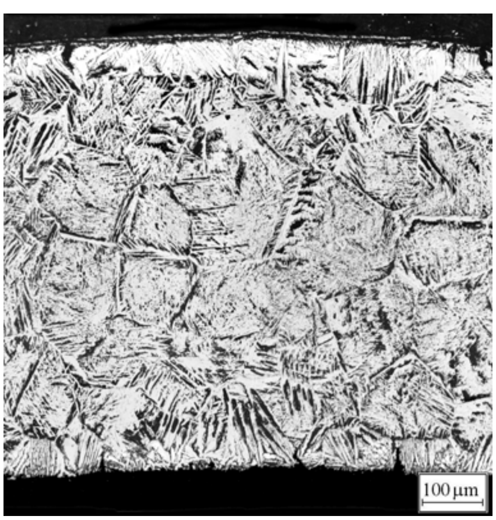




#44-5
ECR=7.7%

Etched



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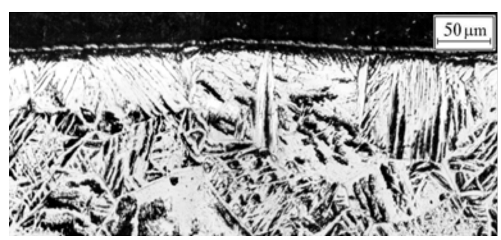


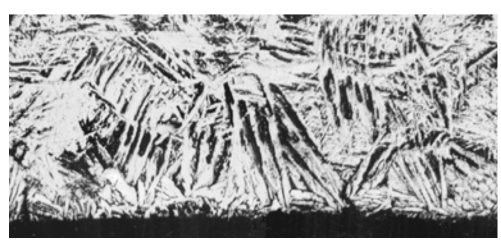


Fig. D-10. Microstructure of E110 standard as-received tubes after a double-sided oxidation at 1000°C and F/F combination of heating and cooling rates

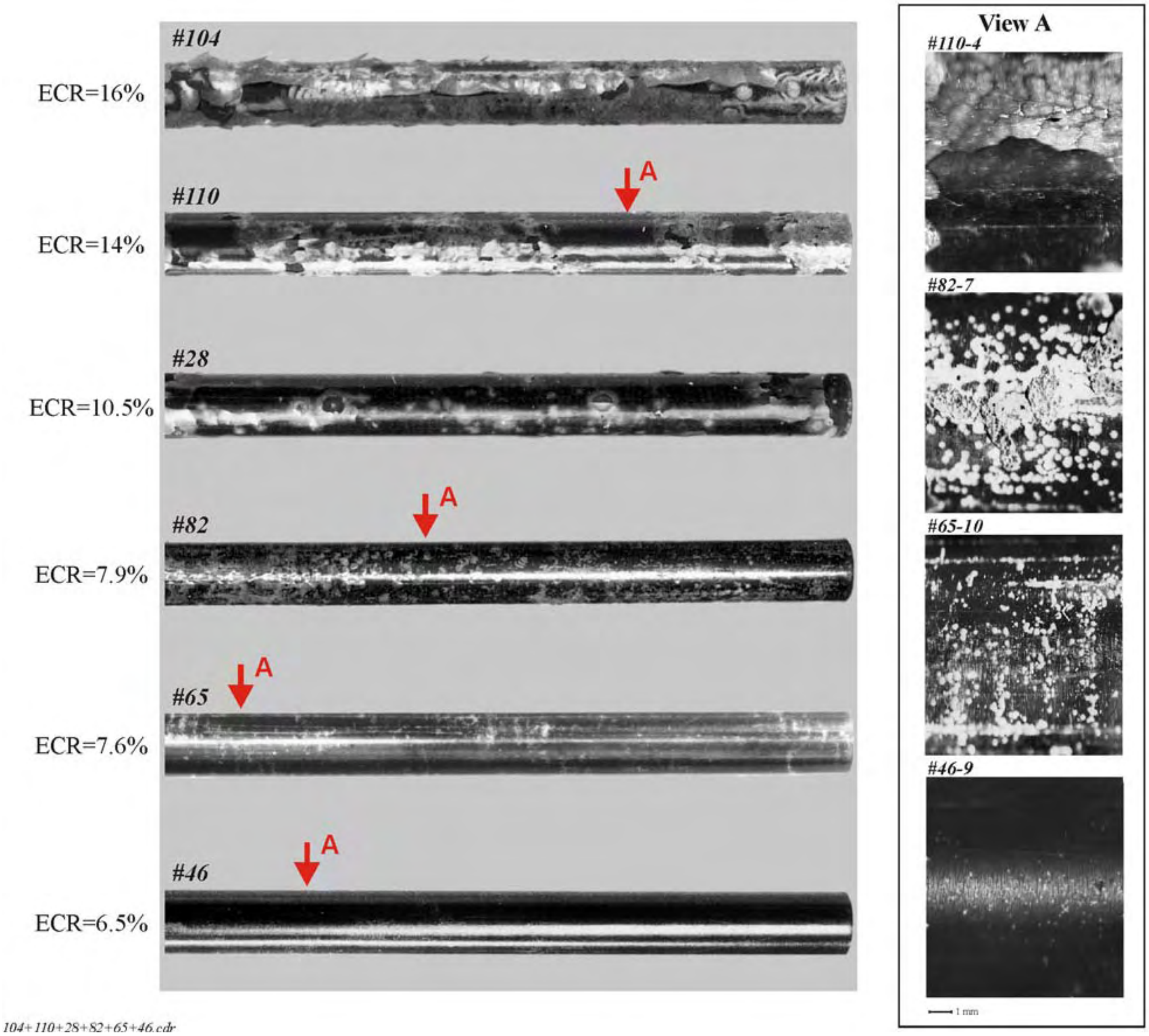


Fig. D-11. Appearance of E110 standard as-received tubes as a function of the ECR after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

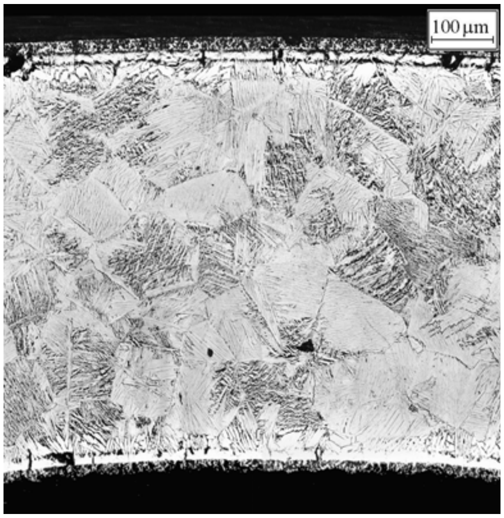
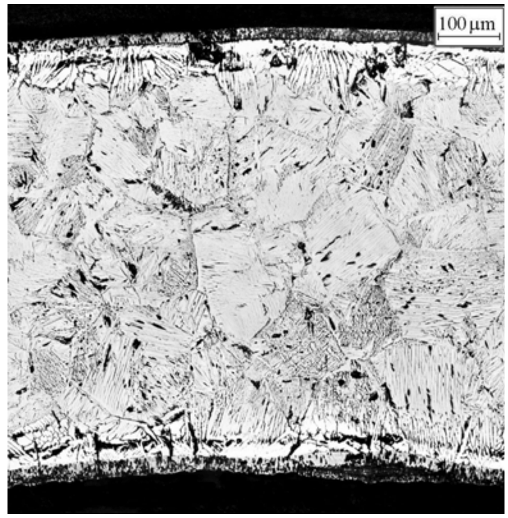
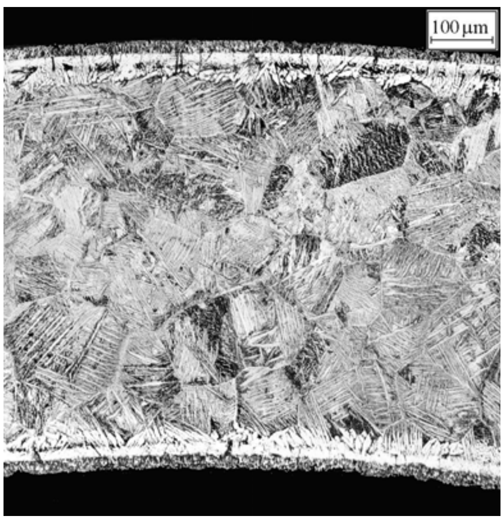
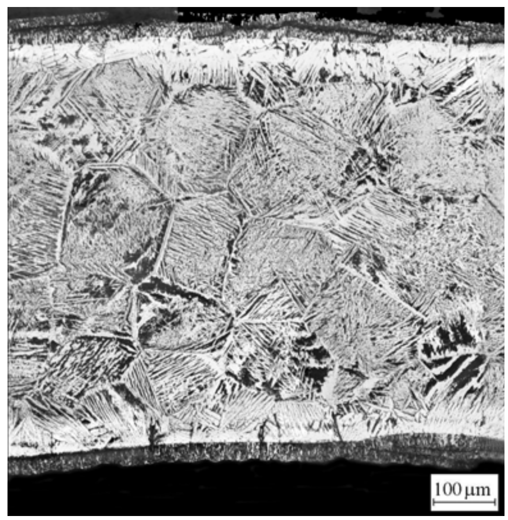
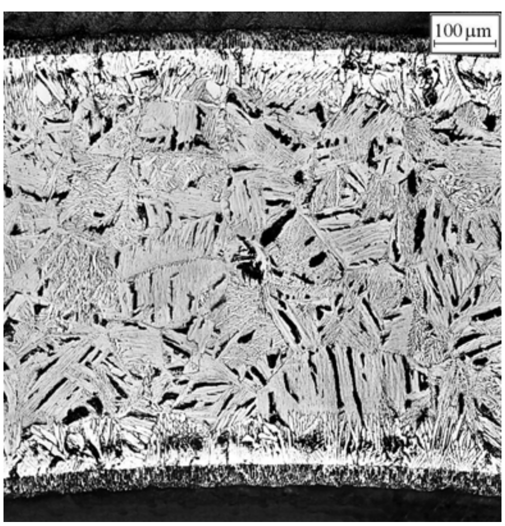
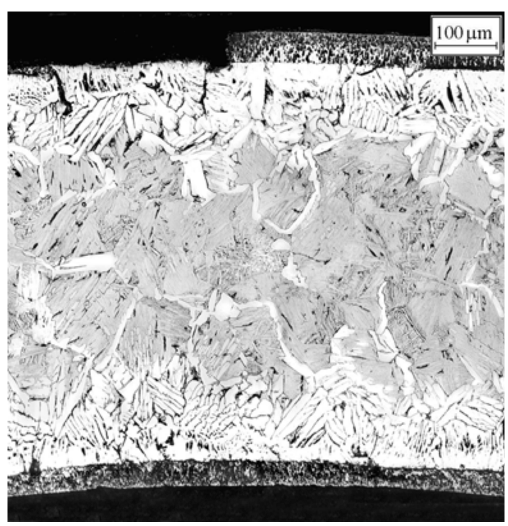
Etched	
#46-5 ECR=6.5 %  	#65-5 ECR=7.6 % 
#41-5 ECR=8.2 %  	#30-5 ECR=8.9 % 
#68-5 ECR=10.0 %  	#110-5 ECR=14.0 % 

Fig. D-12. Microstructure of E110 standard as-received tubes after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates (ECR=6.5–14 %)

<table>
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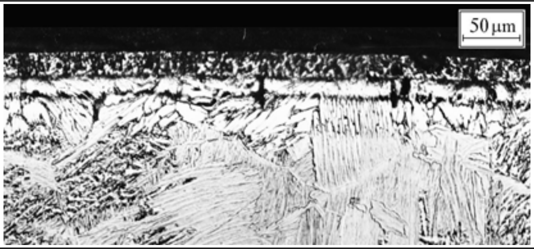
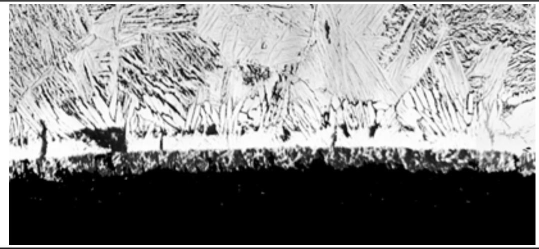
ECR=6.5 %</td><td>
</td><td></td></tr>
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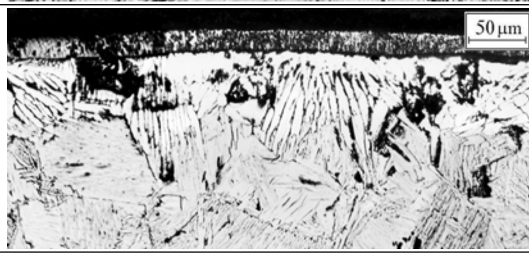
ECR=7.6 %</td><td>
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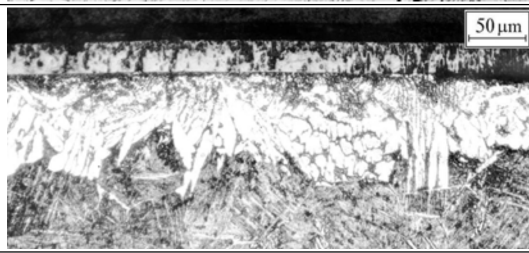
ECR=8.1 %</td><td>
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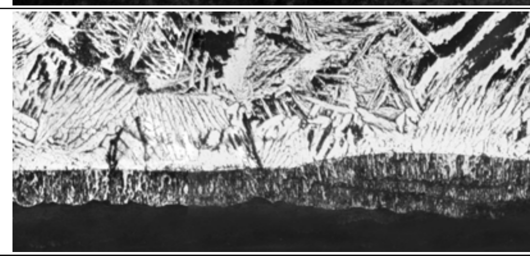
</td><td></td></tr>
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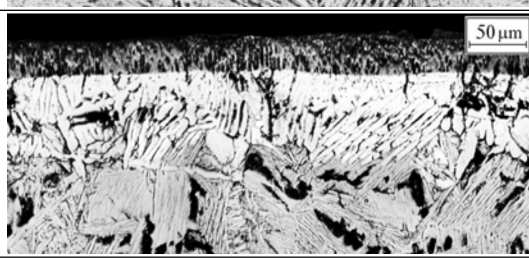
ECR=10 %</td><td>
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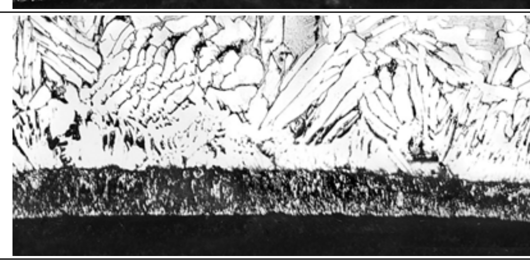
</td><td></td></tr>
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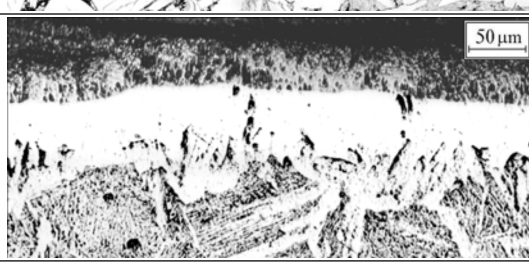
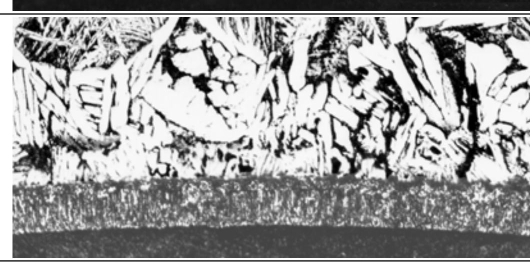
ECR=16 %</td><td>
</td><td></td></tr>
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Fig. D-13. Microstructure of ZrO_2 and α-Zr(O) layers in E110 standard as-received tubes after a double-sided oxidation at 1100 C and F/F combination of heating and cooling rates

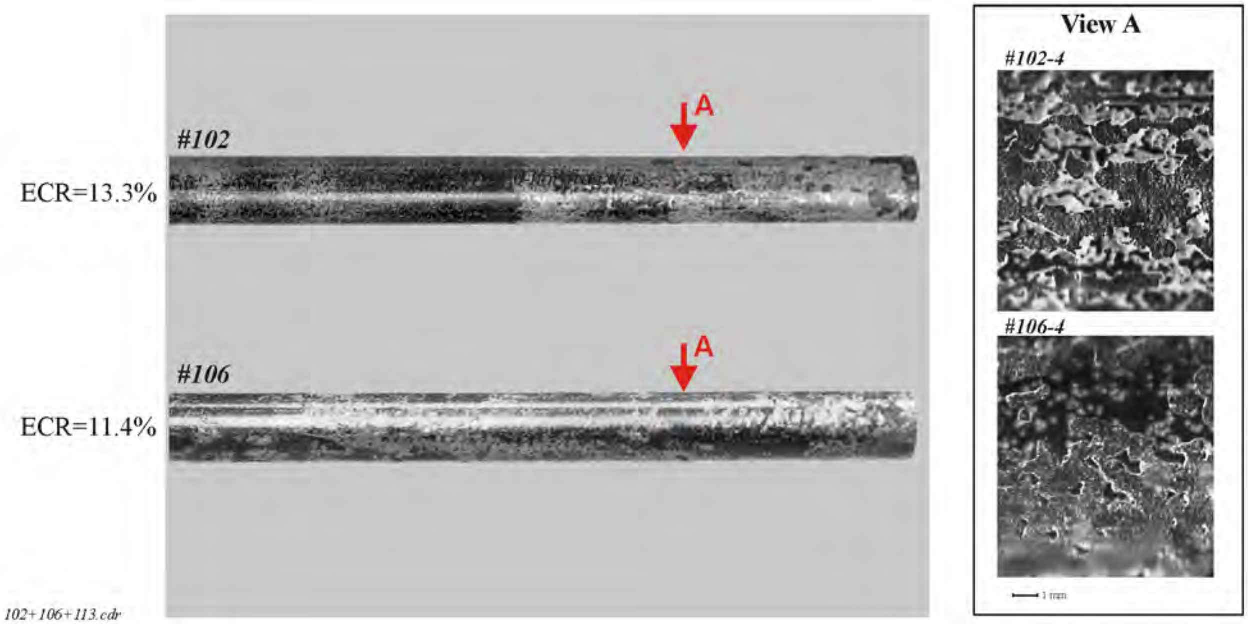

Fig. D-14. Appearance of E110 standard as-received tubes as a function of the ECR after a double-sided oxidation at 1200 C and F/F combination of heating and cooling rates

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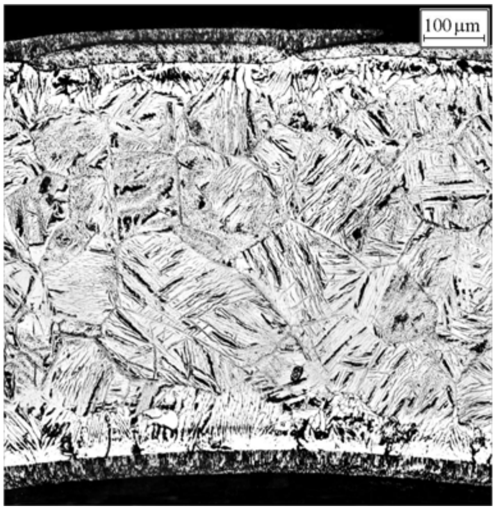
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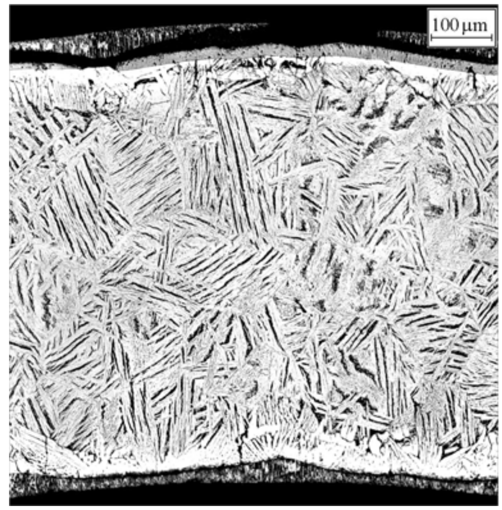
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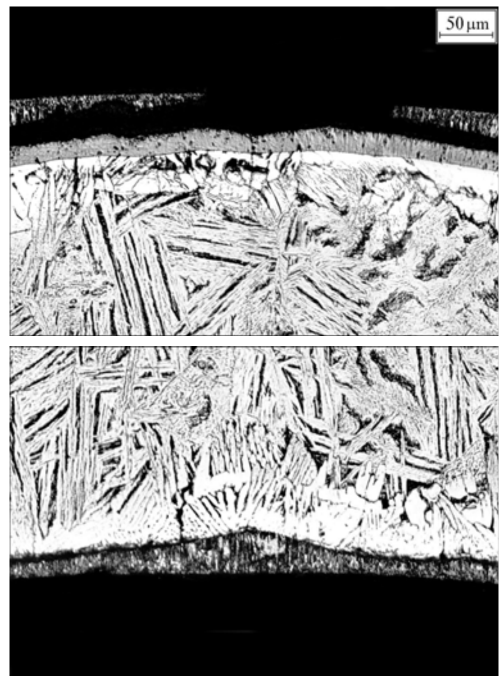
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Fig. D-15. Microstructure of E110 standard as-received tubes after a double-sided oxidation at 1200°C and F/F combination of heating and cooling rates