

Characterization of the newly produced T91- fuel cladding tubes

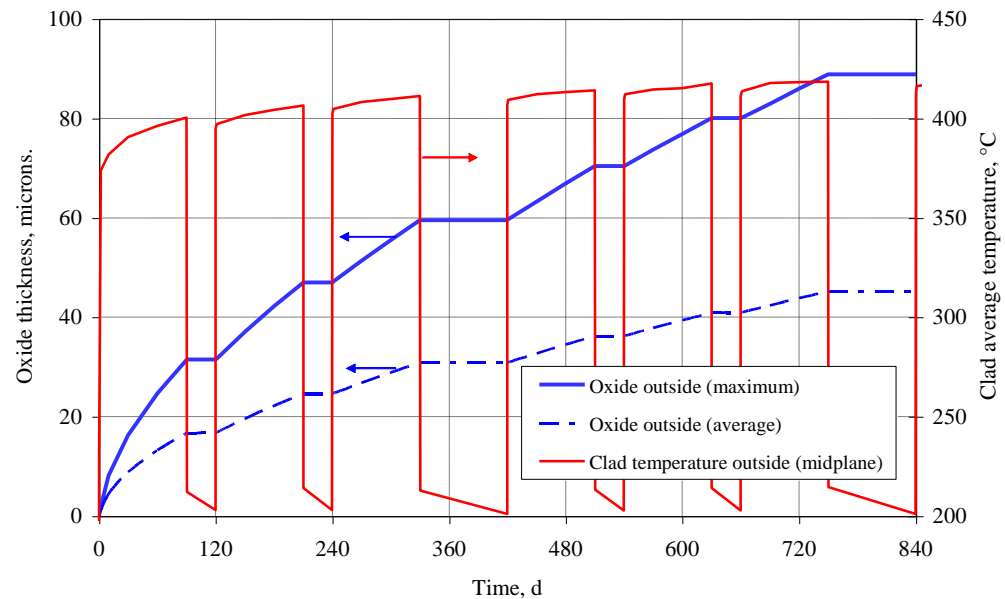
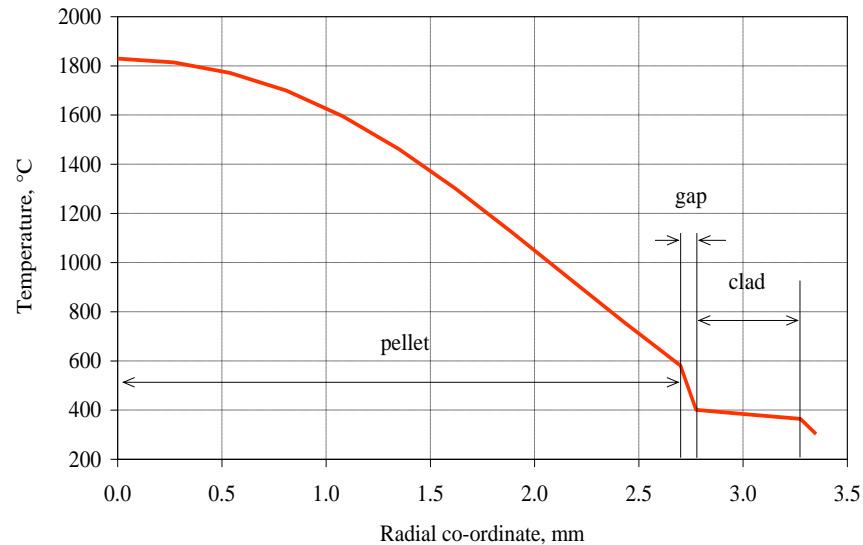
A. Almazouzi et al.

Outline

- Design requirements
- selection of the cladding material
- fabrication procedure
- Optimization of the tempering treatment
- microstructure of the produced clad
- mechanical properties
- comparison with plate materials and conventional stainless steel clad
- Conclusions and Outlook

Design requirements

Radial temperature distribution in the fuel rod at mid-plane of the hottest sub-channel at *BOL*.



Corrosion and temperature evolution of the hottest pin cladding

General approach to clad selection

Clad material requirements:

1. Keeping the adequate mechanical performances (strength, ductility, swelling, creep) at high doses and operation temperatures.
2. Resistance to corrosion/erosion attack of LBE flow
3. Resistance to cycling stresses caused by the trips and restarts of the proton beam.

→ *ferrite-martensitic or austenitic steels ?*

Mechanical properties of F/M claddings after irradiation in fast spectrum (Yano et al., JNM, 2007)

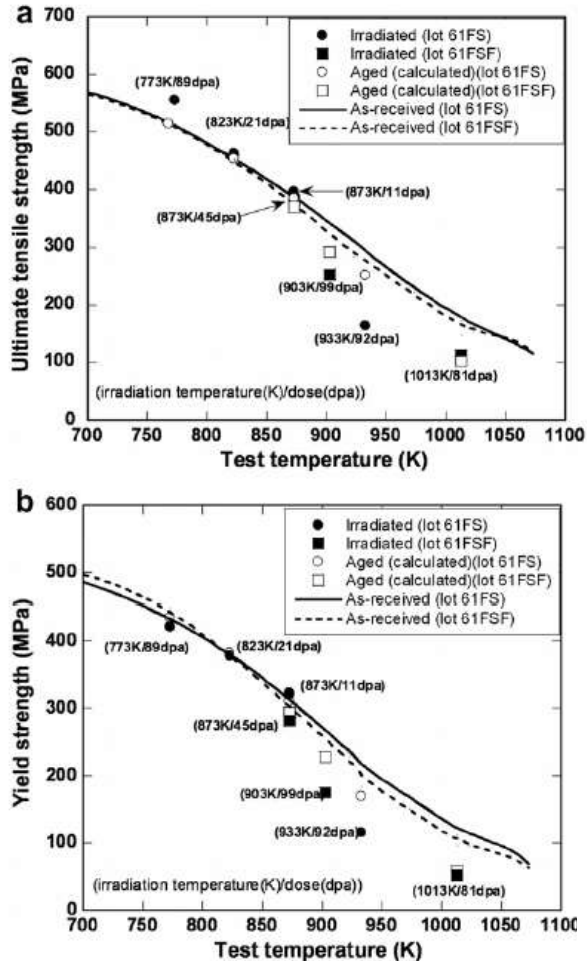


Fig. 2. Tensile strengths of irradiated PNC-FMS claddings: (a) ultimate tensile strength and (b) yield strength.

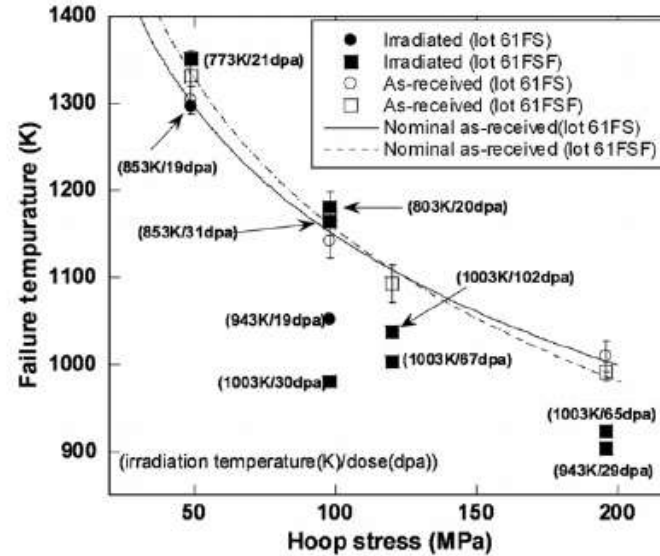


Fig. 4. Relationship between hoop stress and failure temperature of irradiated PNC-FMS claddings. The bar for as-received data shows the standard deviation.

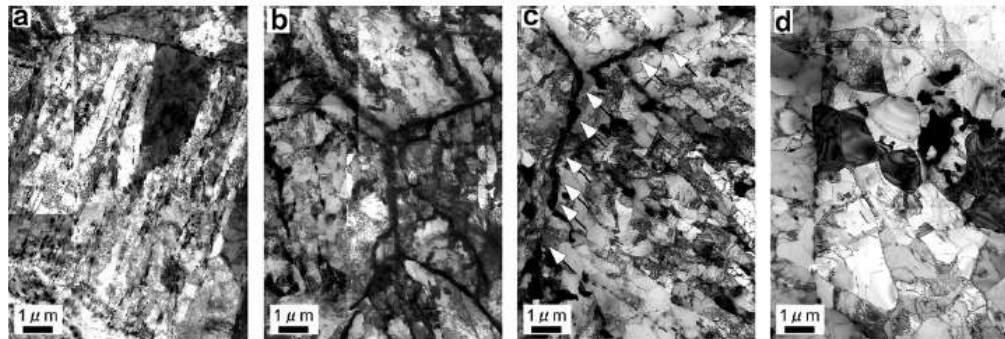
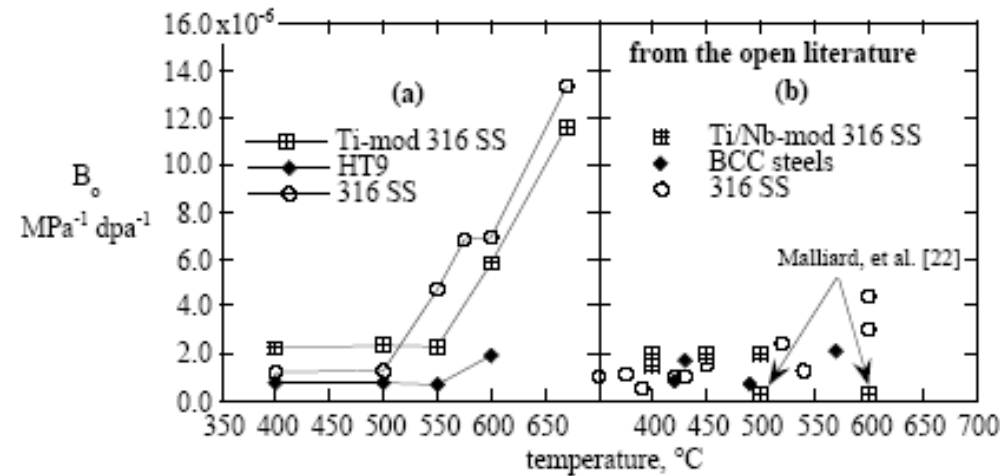


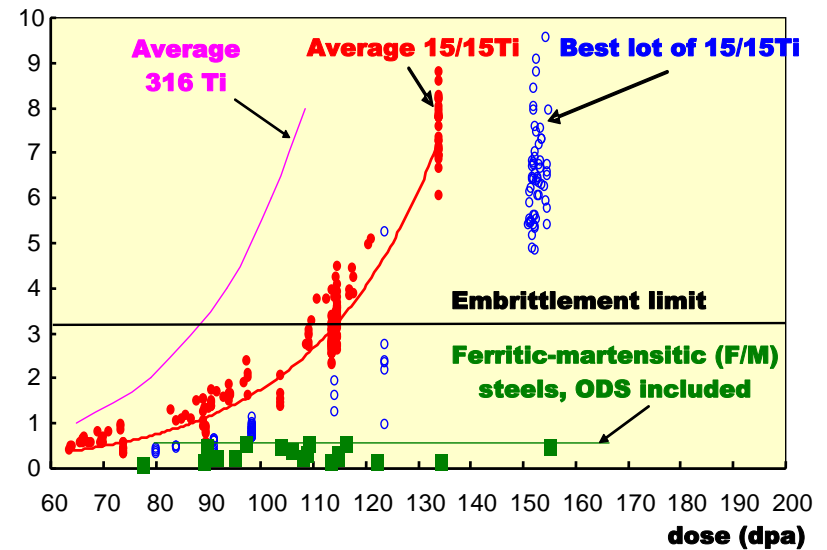
Fig. 5. TEM micrographs of PNC-FMS cladding (lot 61FS): (a) as-received specimen and following FFTE/MOTA irradiation at (b) 823 K to 97 dpa (c) 878 K to 102 dpa and (d) 948 K to 103 dpa.

Selection of cladding candidates

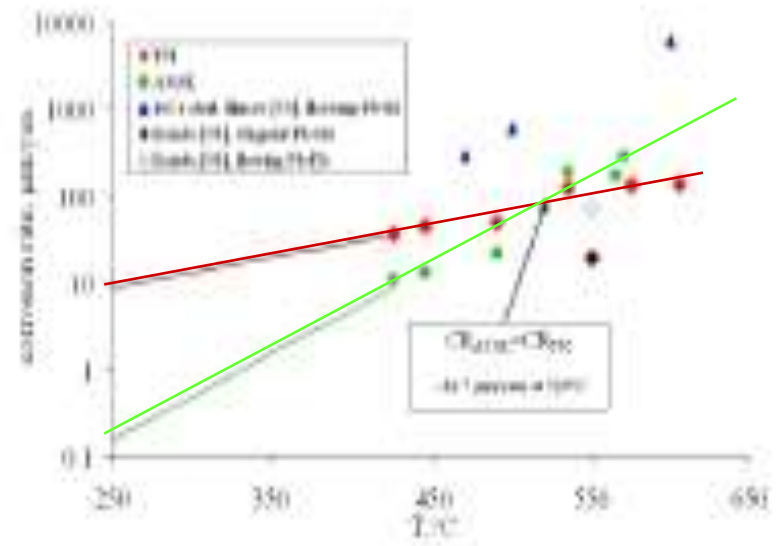
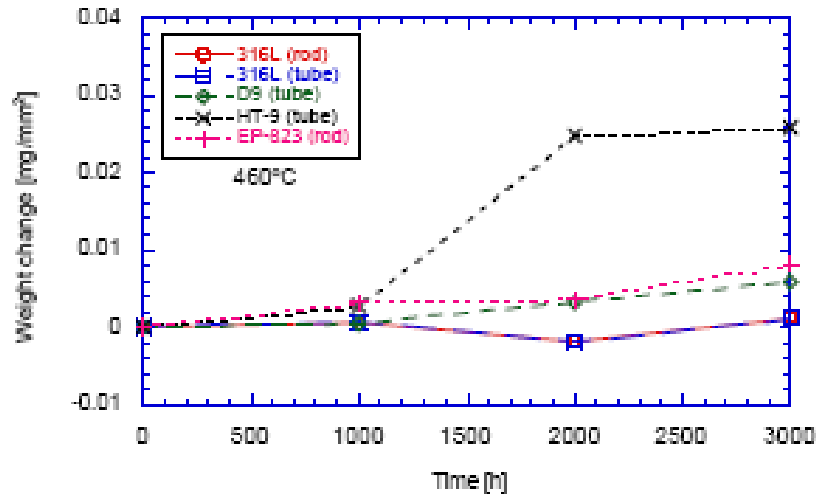
Creep under irradiation



Swelling



Corrosion in LBE



General approach to clad selection

Cladding parameters choice:

- o Material -> T91 MS (oxygen protection)
- o Allowed temperature -> 500 °C (normal operation)
600 °C (transients)
- o Allowed radiation damage -> ~100 dpa
- o Allowed swelling -> ~ 5 %
- o Allowed corrosion -> ~ 10 %

*SS 316 Ti (corrosion protected) is still kept as back-up solution.
...however, helium induced embrittlement can be a problem...*

Main geometrical parameters (*in mm*) of the fuel rods of few fast neutron reactors and of MYRRHA

	SPX	Phenix	SNR-300	BN-600*	EFR	MYRRHA
Diameter	8.50	6.55	6.00	6.90	8.65	6.55
Total length:	2700	1793	2475	1100	3600	1200
-upper gas-plenum	162	93	50	20	1700	60
-upper breeder/reflector	300	(0)**	400	50	250	100
-active part	850	900	950	500	1400	600
-lower breeder/reflector	300	(300)**	400	50	150	100
-lower gas-plenum	852	442	650	421	545	300

* experimental fuel rod with the annular pellets;

** experimental design.


Procurement within ISTC-2048 (in collaboration with FZK and IPPE) start: 2005-

- Specification of the starting tubes in terms of ovality and surface finish
- Definition and procurement of the needed amount
- Clear documentation of cladding production history
- Requirement of a reference specimen after each production step
- Definition of a qualification roadmap with the necessary tests



STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

Cladding materials: starting tubes

 VAM VALLOUREC & MANNESMANN TUBES <small>V & M FRANCE Tubero de St Sauve</small>		MATERIAL TEST REPORT INSPECTION CERTIFICATE EN 10204 3.1.B M. T. R.			ISO 9001																																																																							
<small>rue du Galibot ZI n°4 - BP 2 99880 Saint-Sauve-FRANCE</small>		<small>tel: 03.27.23.13.01 fax: 03.27.23.13.63</small>		<small>SA03/Ref: 26-01-003048 1 / 3 SA05/NV&M: SA2724/01 877/2117.5</small>																																																																								
<p>(A00) Purchaser / Client :</p> <p>(A07) Order n° / N° de commande : 285-PROO-2142</p> <p>(B01) SEAMLESS STEEL PIPE, HOT FINISHED (KILLED STEEL) / TUBES SANS SOUDURE LAMINES A CHAUD (ACIER CALME)</p> <p>(B04) NORMALIZED / NORMALISES 1060°C 20MN TEMPERED / REVENU 780°C 60MN</p> <p>(B02) Specification / Spécification : ASTM A 335 (99) + ASME SA 335 (98) + GRADE P91</p> <p>(B06-007) Die stamping / Marquage poinçon: K A/SA335 P91 HYDROSTATIC TEST NDE HEAT NUMBER LENGTH</p> <p>QUANTITY PER ITEM / QUANTITES PAR POSTE</p> <table border="1"> <thead> <tr> <th>Y/R v/Ref</th> <th>Q/R n/Ref</th> <th>(B11-B12) Size Dimensions</th> <th>(B13) single length long, unitaire</th> <th>(B10) Quantity Nombre</th> <th>length long. m</th> <th>(B14) Weight Poids kg</th> </tr> </thead> <tbody> <tr> <td>01</td> <td>01</td> <td>26.70 X 2.87 MM</td> <td>5/8 M</td> <td>67</td> <td>490.27</td> <td>864</td> </tr> </tbody> </table>							Y/R v/Ref	Q/R n/Ref	(B11-B12) Size Dimensions	(B13) single length long, unitaire	(B10) Quantity Nombre	length long. m	(B14) Weight Poids kg	01	01	26.70 X 2.87 MM	5/8 M	67	490.27	864																																																								
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<p>(C71-C92) LADLE ANALYSIS / ANALYSE SUR COULEE</p> <table border="1"> <thead> <tr> <th>(C70) Process Procédé</th> <th>(B08) Heat coulée</th> <th>C</th> <th>Si</th> <th>Mn</th> <th>P</th> <th>S</th> <th>Cr</th> <th>Mo</th> <th>Ni</th> <th>Al</th> <th>Nb</th> <th>V</th> <th>N</th> </tr> </thead> <tbody> <tr> <td>MIN</td> <td></td> <td>0.08</td> <td>0.20</td> <td>0.30</td> <td></td> <td></td> <td>8.00</td> <td>0.85</td> <td></td> <td></td> <td>0.06</td> <td>0.18</td> <td>0.030</td> </tr> <tr> <td>MAX</td> <td></td> <td>0.12</td> <td>0.50</td> <td>0.60</td> <td>0.020</td> <td>0.010</td> <td>9.50</td> <td>1.05</td> <td>0.40</td> <td>0.040</td> <td>0.10</td> <td>0.25</td> <td>0.070</td> </tr> <tr> <td></td> <td></td> <td>%</td> <td>%</td> <td>%</td> <td>%</td> <td>%</td> <td>%</td> <td>%</td> <td>%</td> <td>%</td> <td>%</td> <td>%</td> <td>%</td> </tr> <tr> <td>E</td> <td>58158</td> <td>0.10</td> <td>0.32</td> <td>0.45</td> <td>0.013</td> <td>0.002</td> <td>8.53</td> <td>0.93</td> <td>0.14</td> <td>0.014</td> <td>0.06</td> <td>0.22</td> <td>0.045</td> </tr> </tbody> </table>							(C70) Process Procédé	(B08) Heat coulée	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Nb	V	N	MIN		0.08	0.20	0.30			8.00	0.85			0.06	0.18	0.030	MAX		0.12	0.50	0.60	0.020	0.010	9.50	1.05	0.40	0.040	0.10	0.25	0.070			%	%	%	%	%	%	%	%	%	%	%	%	E	58158	0.10	0.32	0.45	0.013	0.002	8.53	0.93	0.14	0.014	0.06	0.22	0.045
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<p>(C10-C03-C03) RECTANGULAR SPECIMEN LONGITUDINAL TENSILE TEST AT ROOM TEMPERATURE / TRACTION PRISMATIQUE LONG TEMP AMBIANTE</p> <p>***** ECHANTILLONS PRELEVES SUR TUBES EN LONGUEUR DE FABRICATION *****</p> <p>***** SPECIMEN PICKED ON PIPES IN MANUFACTURING LENGTH *****</p> <table border="1"> <thead> <tr> <th>(C00) Test</th> <th>(B08) Heat coulée</th> <th>width larg.</th> <th>thick. épais</th> <th>sect.</th> <th>(C11) Y.S. lim élast.</th> <th>(C12) T.S. résistance</th> <th>(C13) Elong. 2" Allong. 2"</th> </tr> </thead> <tbody> <tr> <td>MIN</td> <td></td> <td></td> <td></td> <td></td> <td>415</td> <td>586</td> <td>14</td> </tr> <tr> <td>MAX</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td>mm</td> <td>mm</td> <td>mm²</td> <td>MPa</td> <td>MPa</td> <td>%</td> </tr> <tr> <td>DK731 01</td> <td>58158</td> <td>15.4</td> <td>3.1</td> <td>52.15</td> <td>496</td> <td>686</td> <td>19</td> </tr> <tr> <td>DK731 02</td> <td>58158</td> <td>15.4</td> <td>3.1</td> <td>53.02</td> <td>522</td> <td>699</td> <td>19</td> </tr> </tbody> </table>							(C00) Test	(B08) Heat coulée	width larg.	thick. épais	sect.	(C11) Y.S. lim élast.	(C12) T.S. résistance	(C13) Elong. 2" Allong. 2"	MIN					415	586	14	MAX										mm	mm	mm ²	MPa	MPa	%	DK731 01	58158	15.4	3.1	52.15	496	686	19	DK731 02	58158	15.4	3.1	53.02	522	699	19																						
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Starting from 26.7 x
2.87 mm of T91
(ASTM A335)

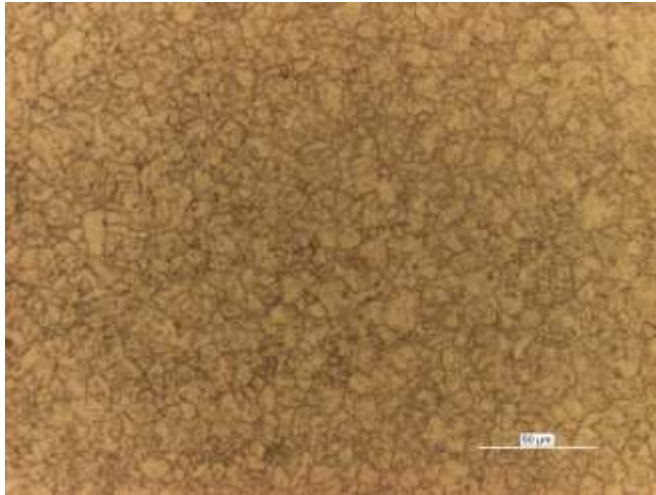
Fabrication procedure: 1st route

Pass No.	Tube size, mm	Rolling-out	Strain, ϵ_p , %	Total rolling-out $\frac{F_{n-1}}{F_n}$	Total strain, %	$\frac{t_{n-1}}{t_n}$	$\frac{d_{n-1}}{d_{mp(n)}}$
0	24.5x3.25	~1.2	Route No.	1	52	1.08	1.18
1	22x2.5	1.417	17.2	2.09		1.11	1.3
2	20x2.25	1.22	29			1.11	1.11
3			18				
	h.t. at 760°C, 1 hour						
4	18x2	1.248	19.9	2.13		1.11	1.14
5	16x1.75	1.283	22		53	1.125	1.143
6	14x1.5	1.330	24			1.143	1.167
	h.t. at 760°C, 1 hour						
7	12x1.25	1.4	28.67	1.616	38	1.167	1.2
8	10.5x1.0 (1.2)	1.244	19.63			1.143	1.136
	h.t. at 760°C, 1 hour						
9	9.5x0.75	1.639	39	2.687	62.8	1.105	1.467
10	8.5x0.5	1.64	39			1.117	1.5

Fabrication procedure: 2d route

Pass No.	Tube size, mm	Rolling-out	Strain, ϵ_p , %	Total rolling-out $\frac{F_{n-1}}{F_n}$	Total strain, %	$\frac{t_{n-1}}{t_n}$	$\frac{d_{n-1}}{d_{mp(n)}}$
0	24.5x3.25	~1.2	Route No.	2	52	1.08	1.18
1	22x2.5	1.417		2.09		1.11	1.3
2	20x2.25	1.22	17.2			1.11	1.11
3			29				
	h.t. at 760°C, 1 hour		18				
4	18x2	1.248	19.9	1.664	39.9	1.11	1.14
5	16x2	1.143	12.5			1.125	1.0
6	14x2	1.677	14.28			1.143	1.0
	h.t. at 760°C, 1 hour						
7	12x1.5	1.524	34.3	2.13	55	1.12	1.333
8	10.5x1.2 (1.1)	1.465	36.7			1.143	1.364
	h.t. at 760°C, 1 hour						
9	9.5x0.75	1.639	39	2.987	62.8	1.117	1.5
10	8.5x0.5	1.64	33				

Cladding tubes

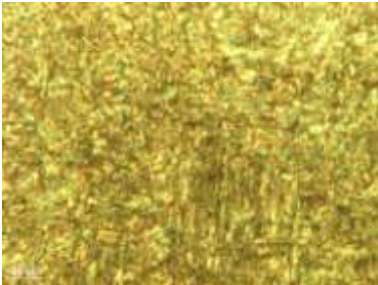



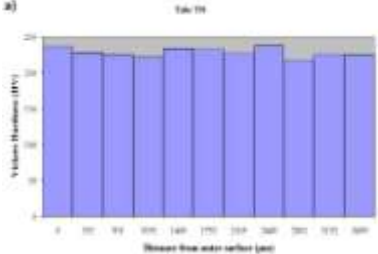
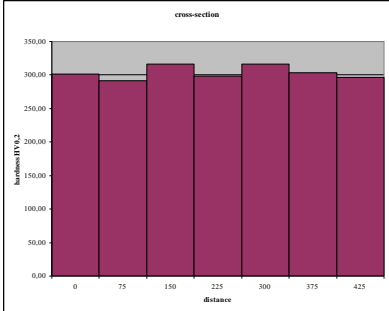
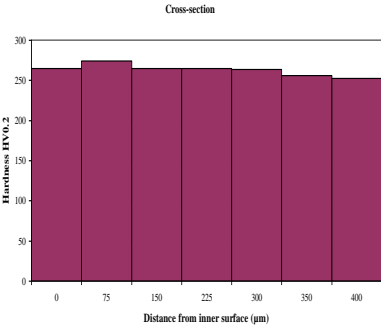
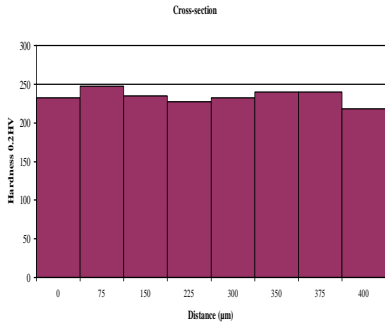


Microstructure: ferrite with small amount of perlite in grain boundaries

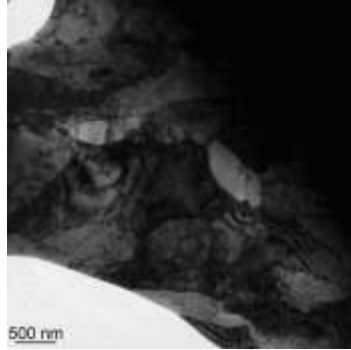
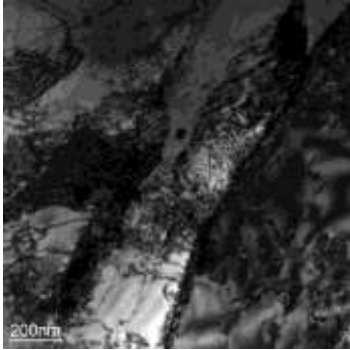
	initial	After thinning
Hardness	240 Hv	276Hv
Yield stress	510 MPa	607MPa

Need of an optimised heat treatment

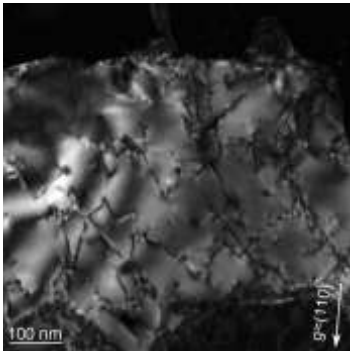
definition of the final heat treatment

Initial tubes (26.5mm)	As-fabricated 8.5mm tubes	treatment: 730°C, 1h and furnace cooling	Final treatment: 7300C, 4h followed by rapid air cooling
 <p>Fully martensite, grain size~25µm</p>	 <p>Not homogenous+Ferrite grain size~10-100µm</p>	 <p>Not homogenous+Ferrite grain size~10-50µm</p>	 <p>homogenous+F/M grain size~15µm</p>
 <p>Average HV: 228</p>	 <p>Average HV: 303</p>	 <p>Average HV: 260</p>	 <p>Average HV: 230</p>

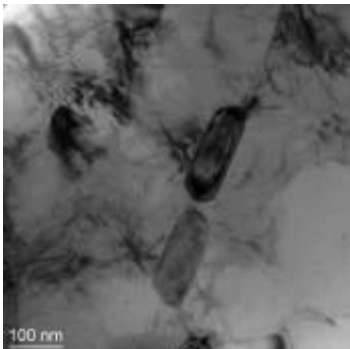
Final Microstructure



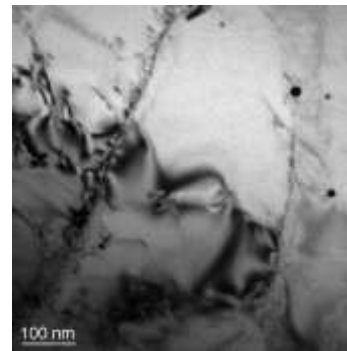
Martensitic laths were found throughout the specimen.
Width of the order of few 100 nm, length several μm



Average dislocation density $(3\pm 1)\times 10^{14}/\text{m}^2$. The projected dislocation directions correspond mostly with $\langle 111 \rangle$ type directions, but also $\langle 110 \rangle$ type directions are found. Majority appears to be screw dislocations with some edge ones

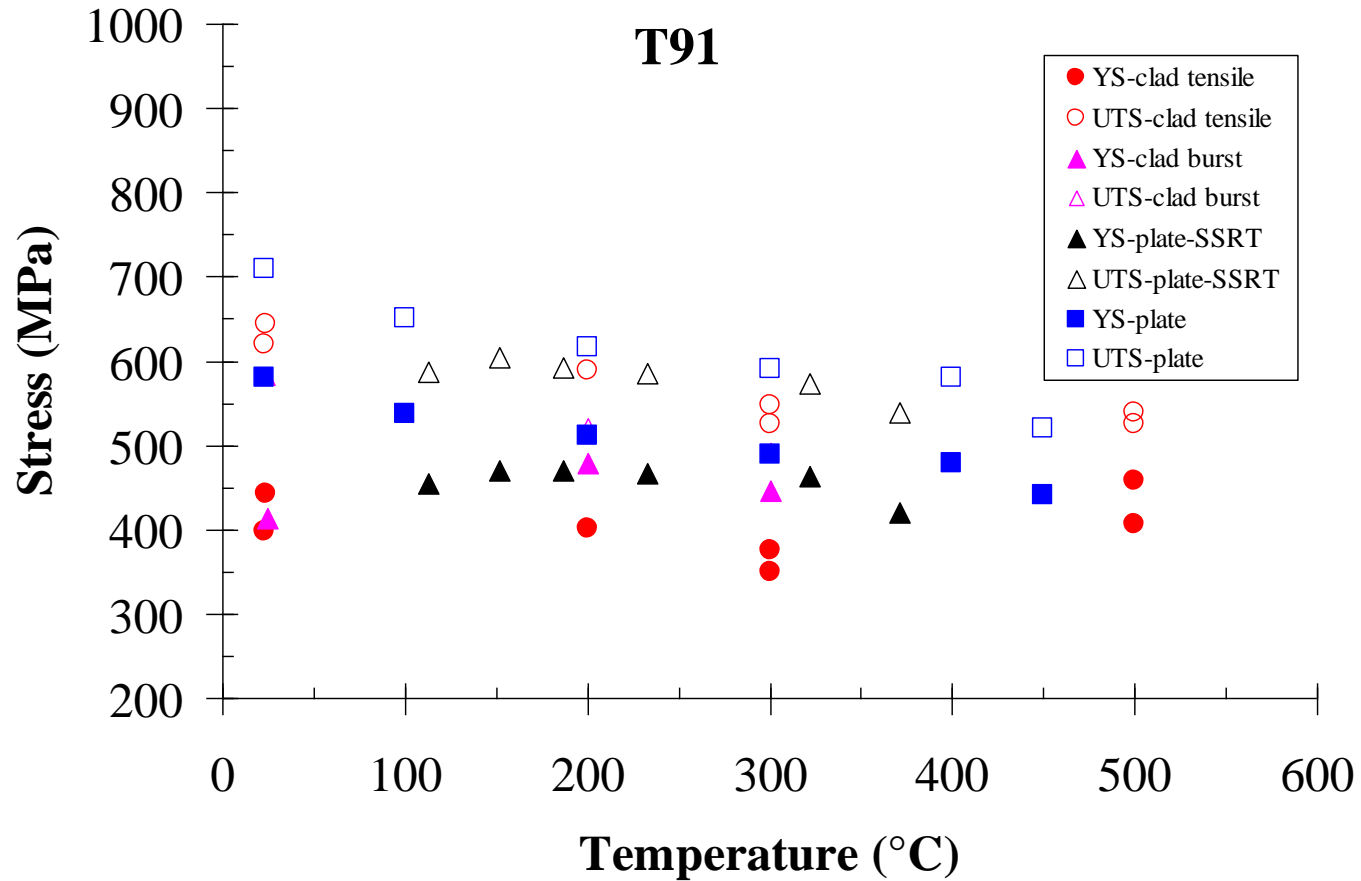


At the grain boundaries,
M₂₃C₆ carbides are found



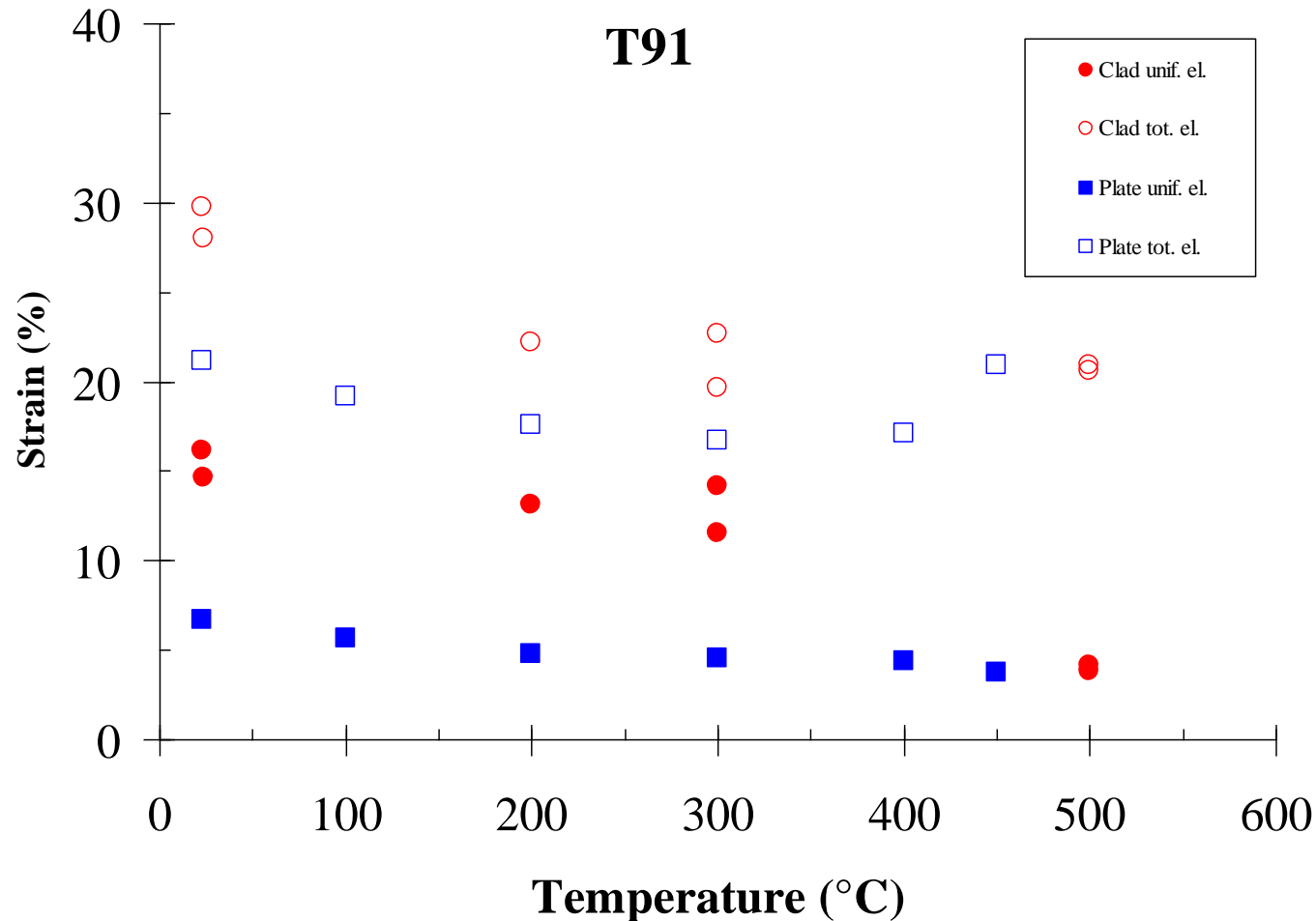
In the interior of the
laths, a second type of
precipitates is found.
They are (NbV)C.

Tensile properties



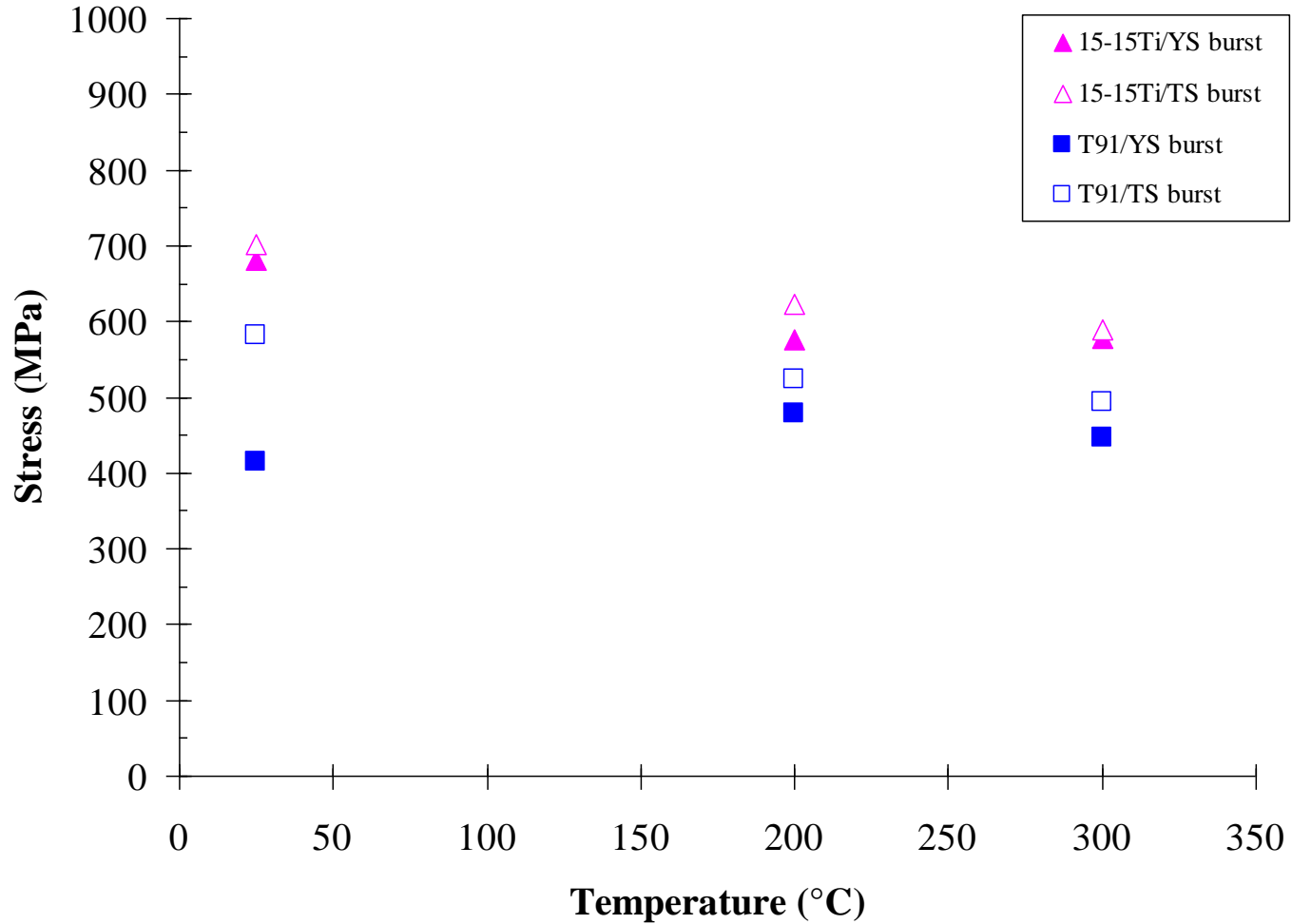
Similar properties as certified plates of the same material

Uniform and total elongation

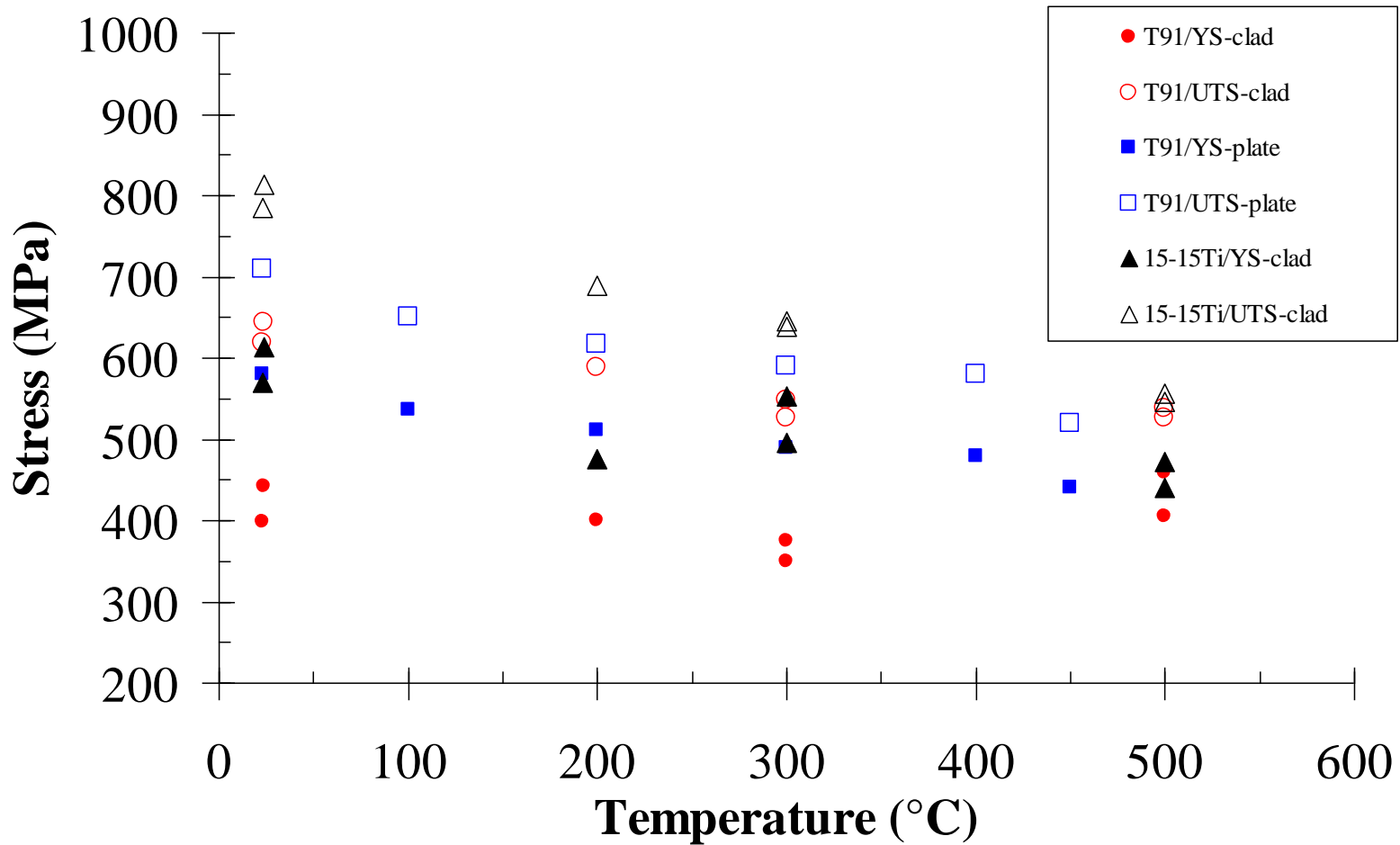


The cladding tubes perform as good as (if not better due to lower thickness) as the certified plate of T91

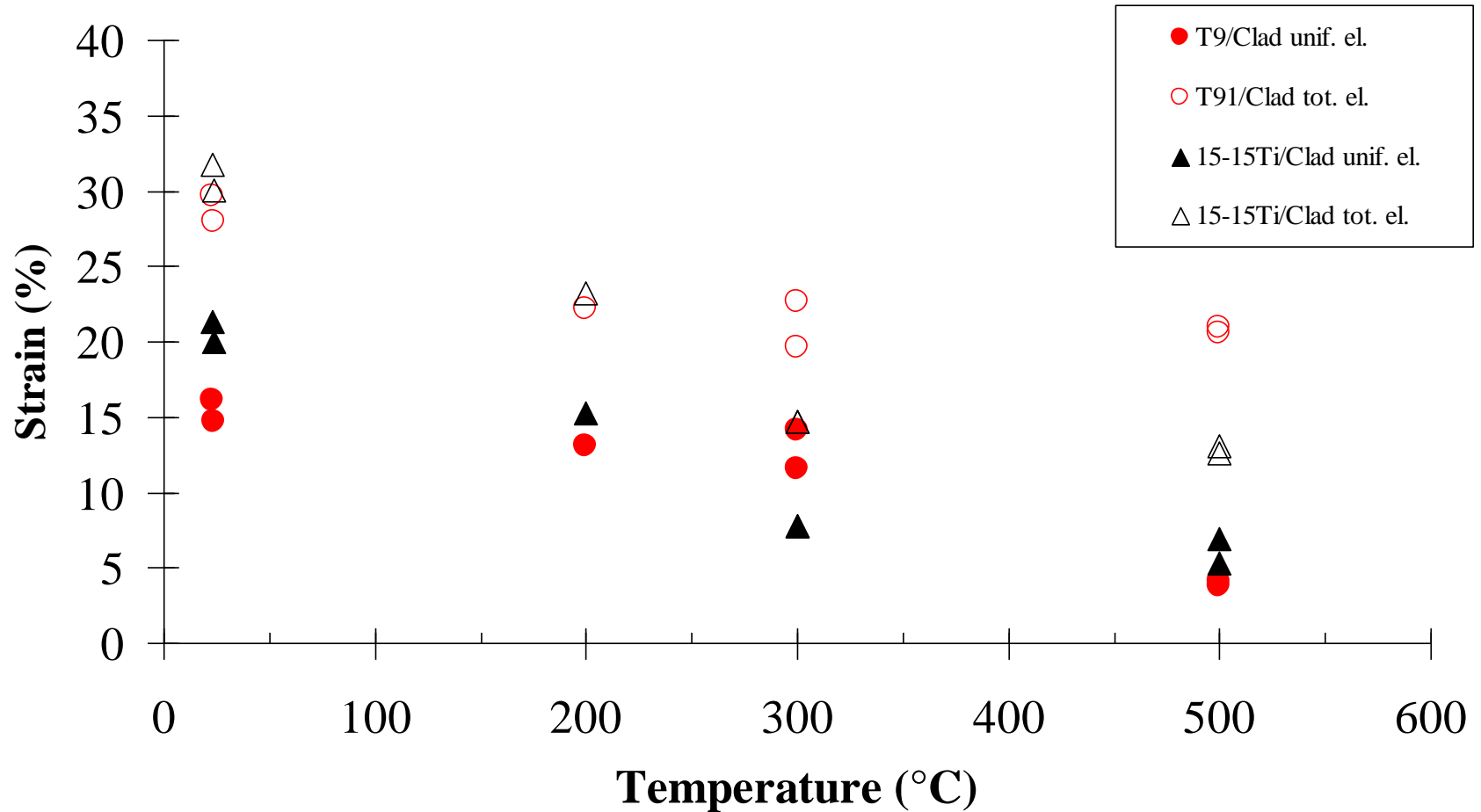
Comparison T91/15-15Ti: Burst tests



Comparison T91/15-15Ti: tensile tests



Comparison T91/15-15Ti: Elongation



Conclusion and the work still needed

- Specification of the starting tubes in terms of ovality and surface finish was performed
- Adequate thermal heat treatment was determined
- Microstructure of the produced tubes is very similar to the plate material
- The tensile properties are comparable to the plate material
- The Burst tests indicate that the material possesses good properties compared to 15-15Ti SS
- Reference specimens after each production step need to be investigated
- Clear documentation of cladding production history is still pending
- Definition of a qualification roadmap with the necessary tests has to be made in close collaboration with the fuel community