Development of ferritic steel for fuel element cladding

B. A. Tarasov, I.I. Konovalov, M.D. Saveliev, M.S. Tarasova, D.P. Shornikov, N.S. Nikitin

JSC «VNIINM», NRNU MEPHI

Analysis VVER operating conditions with the oxide and nitride fuel with FR shows similarities НДС cladding:

- "Incompressibility" of fuel at the stage FCMI → the cladding follows the swelling fuel in warp speed ~ 10^{-6} h^{-1}
- Gassing from fuel at the end of the campaign (~ 10 at.%) does not exceed (15-25)% of the formed GPD

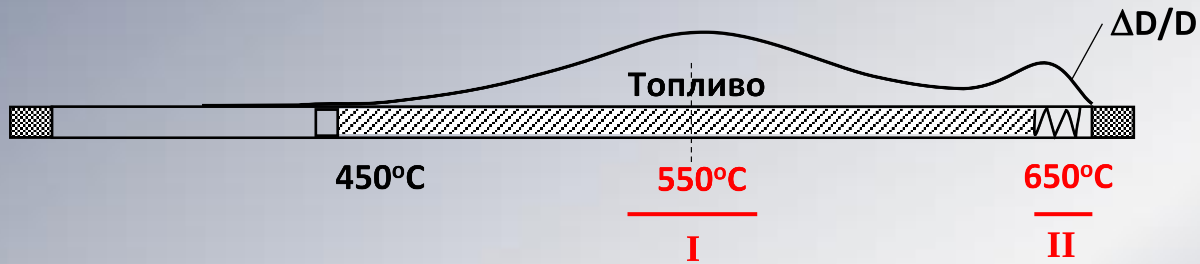
The development of the cladding material has a twofold direction: "tolerant" fuel for VVER and the BREST type nitride fuel rod for FR (burnout 6 at.% And 14 at%, respectively)

To ensure the efficiency of the fuel rod at the ultra-deep burn-up is required:

- Ensuring long-term strength in the upper hot part of the fuel (pressure GPD) and ensuring creep deformation in the middle of a fuel rod (maximum rate of fuel swelling)
- Corrosion resistance in the coolant
- Structural phase stability in the stressed state with overheating

The specification of requirements for the fuel cladding of the FR with nitride fuel is given in the next slide.

Criteria for the performance of BR nitride fuel elements - requirements for claddings properties



$$\frac{1}{3}\int \dot{S}_F \tau_{FSMI} < \varepsilon_{Lim}$$

$$\frac{2\delta}{D}\left(P_{He} + P_{FGP}^{Max} - P_{Ext}^{Min}\right) < \sigma_{5\cdot10^4}^{650}$$

For cladding $D \sim 10$ мм and shell thickness $\delta \sim 0{,}5$ мм , R- fuel / rod gap ~0,15 мм
(6 - year company, $q_l^{Max} \sim 48\ kW/m$, $B^{Max} \sim 14\ at.\%$)

- Ultimate creep deformation of the cladding $\varepsilon_{Lim} > 5\ \%$
- Optimal swelling of the cladding at the end of the campaign $S = (5-6)\ \%$
- Long durability of fuel cladding $\sigma_{5\cdot10^4}^{650°} > 20\ MPa$
- Maximum corrosion damage to the cladding on both sides, in the amount of $< 100\ \mu m$
- The structural and phase stability of the fuel cladding under overheating in the stressed state to ~ 720°C

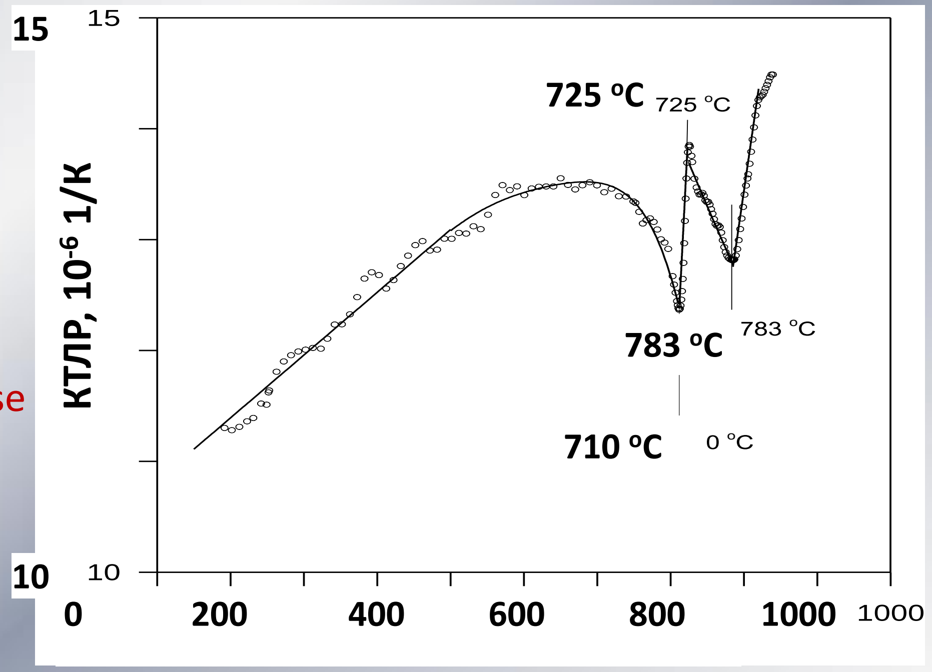
Disadvantages of fuel rod cladding material for the FR "BREST"

Steel	Ultimate creep deformation	Alignment swelling fuel / cladding	Long-term strength	Corrosion in Pb	The stability of the SPS
AS	YES	NO	YES	NO	YES
FMS	YES	NO	YES	YES	NO

Disadvantages

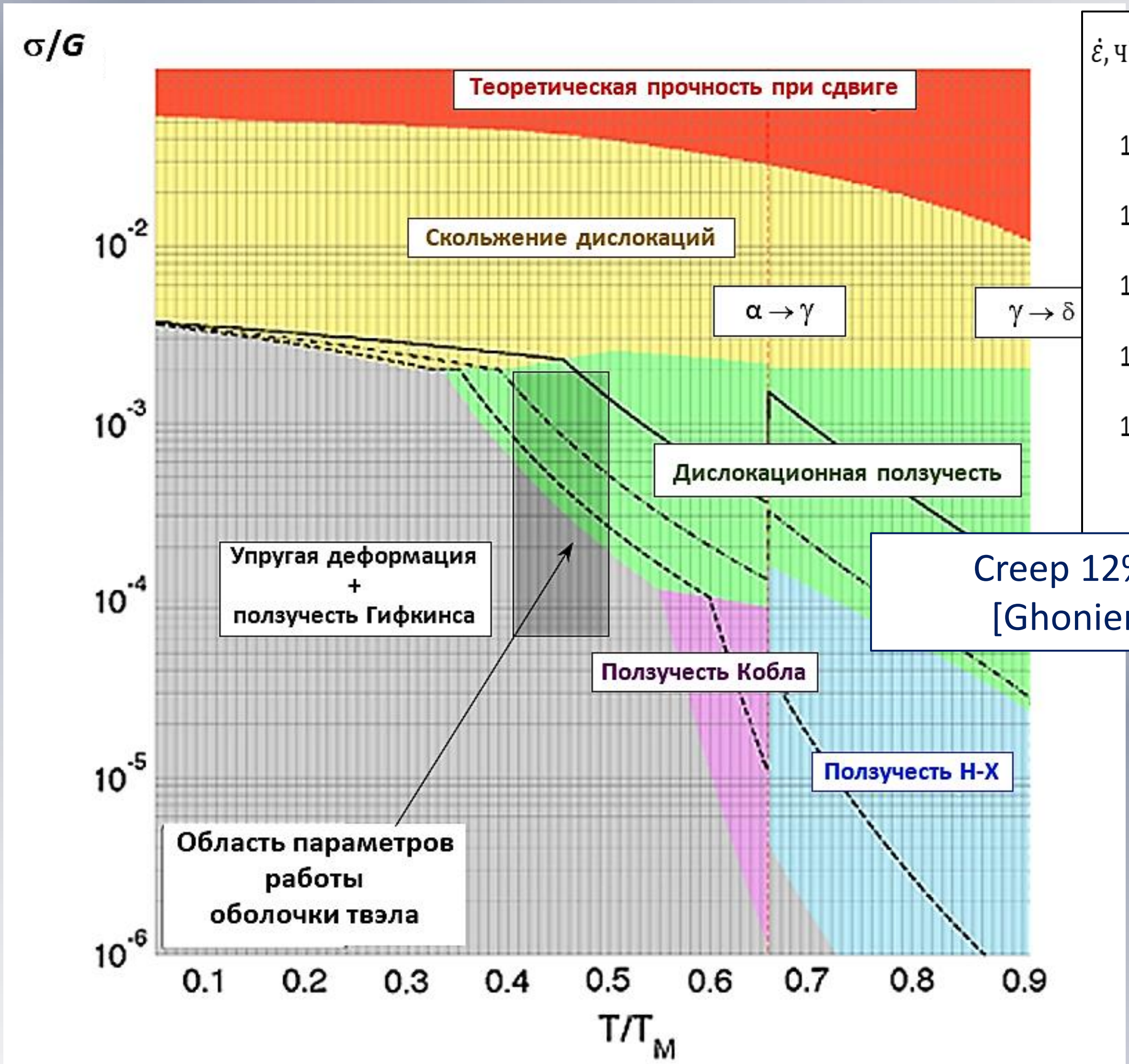
AS – the swelling is greater than that of the SNUP fuel
– the presence of Ni → low resistance in Pb

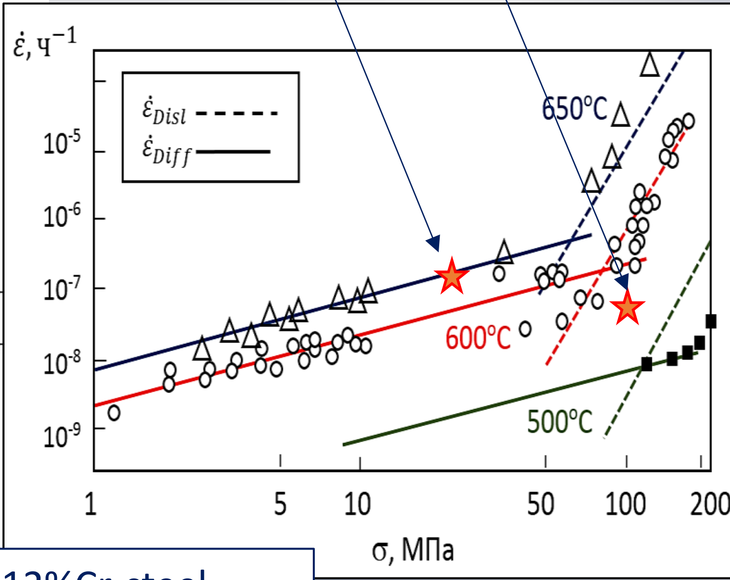
FMS – swelling is lower than that of SNUP fuel
– SPS instability (transition to structural and phase "superplasticity")



SPS instability ЭП-823
[MEPhI, 2014]

Steel cladding FR throughout the campaign will be in terms of diffusion creep:
elements of dislocation creep - the middle of the fuel rod(~100 МПа, 550 °C)
diffusion creep - the top of the fuel rod (~ 20 МПа, 650 °C)





Creep 12%Cr-steel [Ghoniem 2013]

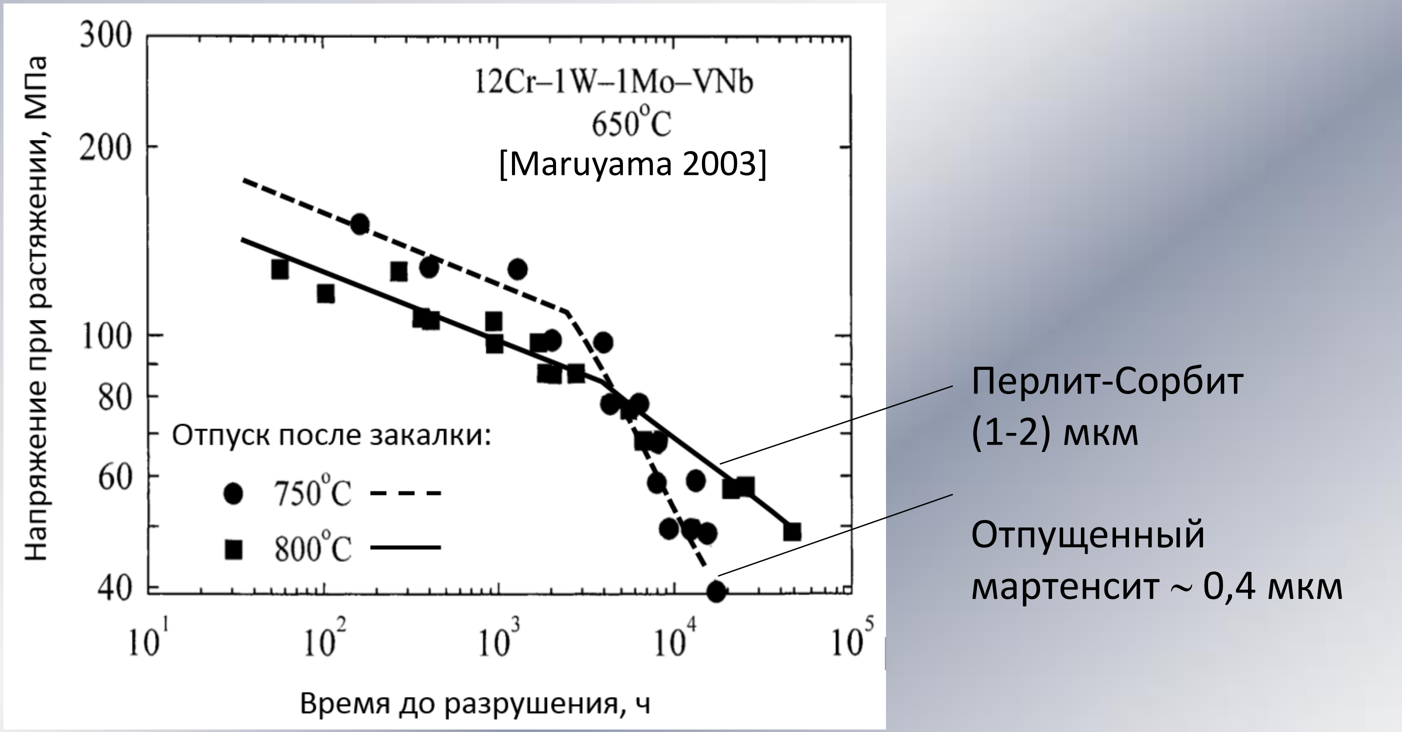
In general, the creep of the cladding FR is determined by:

$$\dot{\varepsilon} = \dot{\varepsilon}_{Disl} + \dot{\varepsilon}_{Diff}$$

With the coarsening of the structure, the diffusion creep resistance (heat resistance) increases, and the “dislocation” strength decreases

The obvious fact is that single-phase solid solutions with a large grain have the best resistance to diffusion creep.

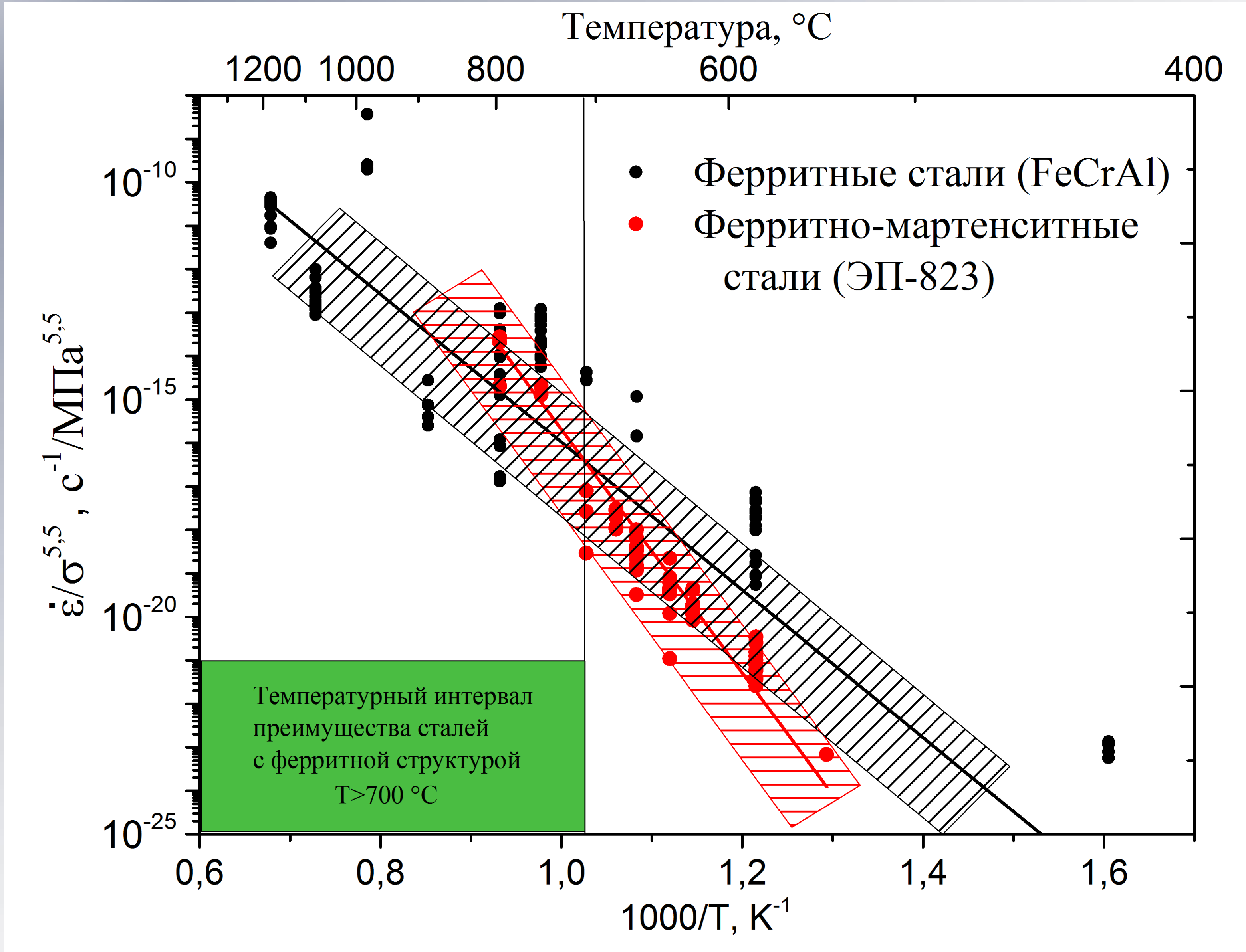
Example: Effect of SPS on the long-term strength of FM steel



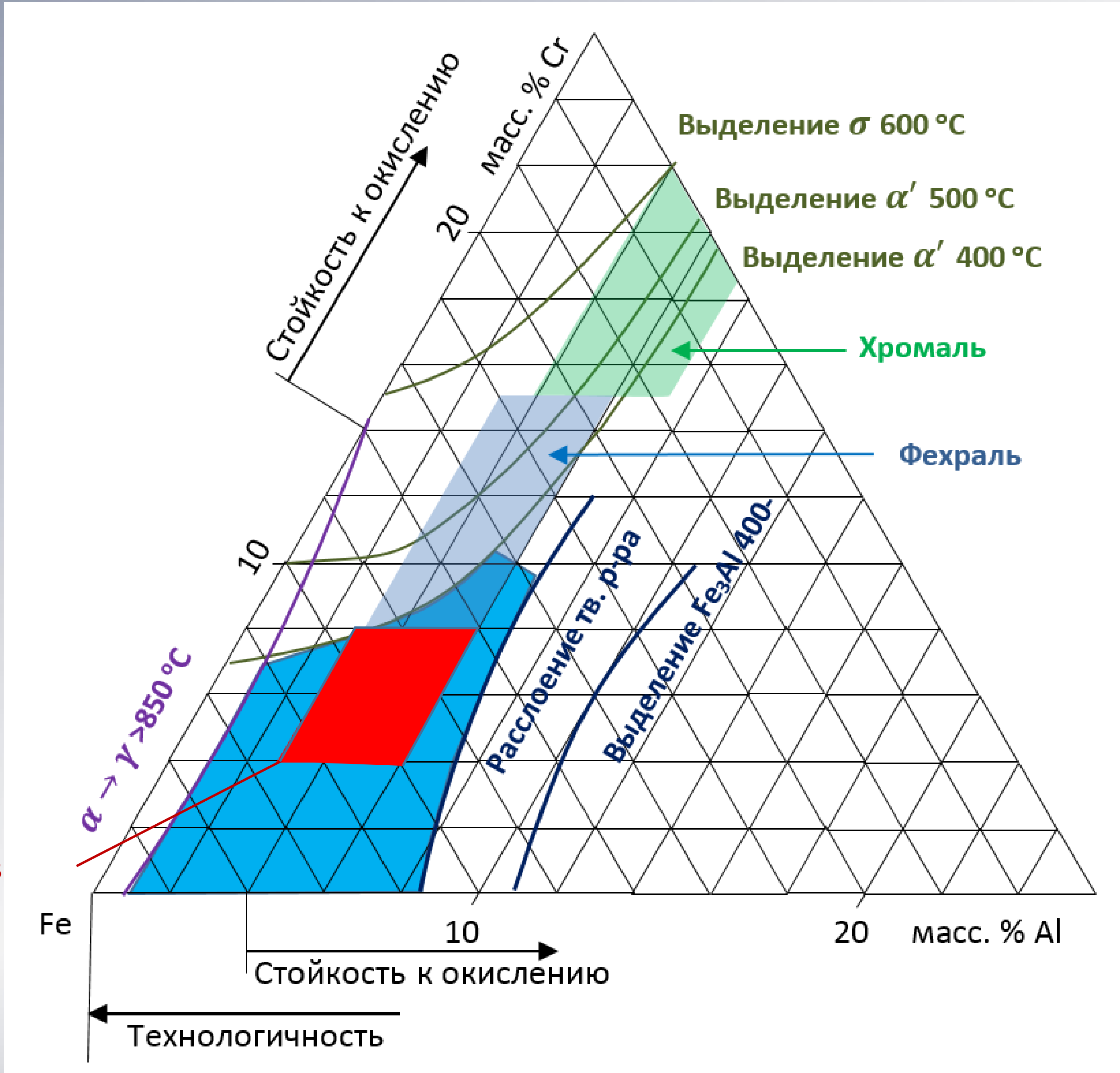
Search for candidate compositions was carried out in the single-phase area:

- Maximum creep deformation and best durability
- The best corrosion resistance
- Lack of structural and phase "superplasticity"

Comparison of the creep rate of ferritic and ferritic-martensitic steels



Field of study of ferritic steels (Fe-Cr-Al-Si)



studies ferritic steels

Model alloys Fe-Cr-Al-Si

Cr, %	Al, %	Si, %	Прокатанные (80% х.д.)			Отжиг 450°C, 1000 ч			Отжиг 650°C, 1000 ч		
			$\sigma_{0,2}$, МПа	$\sigma_в$, МПа	δ_{tot}, %	$\sigma_{0,2}$, МПа	$\sigma_в$, МПа	δ_{tot}, %	$\sigma_{0,2}$, МПа	$\sigma_в$, МПа	δ_{tot}, %
8	1	-	592	617	5,1	452	499	6,6	171	314	37,6
8	2	-	659	690	5,2	453	517	8,6	211	361	39,4
8	3	-	848	905	5,4	513	582	10,3	250	396	35,9
10	1	-	684	733	4,7	505	600	10,5	176	348	43,4
10	2	-	872	899	5,1	546	625	10,5	240	408	41,7
10	3	-	829	873	4,9	582	668	10,0	282	414	40,2
10	4	-	-	-	-	523	612	9,3	320	447	39,6
12	1	-	732	769	5,2	534	625	10,0	204	345	39,9
12	2	-	888	944	4,5	586	731	10,8	247	368	40,4
12	3	-	873	929	4,9	530	780	10,1	307	447	32,1
12	4	-	870	918	4,8	517	700	10,3	341	460	37,4
14	1	-	776	820	4,9	522	739	12,3	220	370	43,9
14	2	-	831	883	5,2	510	835	11,4	260	404	41,1
14	3	-	882	935	4,5	519	858	15,9	318	444	35,7
14	4	-	826	919	4,9	419	670	10,7	356	481	38,1
8	-	1	739	803	4,8	412	772	14,3	244	399	45,5
8	-	2	759	819	4,3	425	771	19,5	309	445	34,6
8	-	3	800	931	3,6	777	806	10,5	388	502	26,4
8	-	4	946	1000	4,3	849	897	10,8	474	589	25,1
10	-	1	690	741	4,6	630	670	11,9	236	385	35,9
10	-	2	746	935	4,7	734	796	13,0	334	461	32,1
12	-	3	703	853	4,7	707	778	11,0	255	392	40,2
14	-	1				849	905	10,1	411	525	24,7
14	-	2	856	901	4,5	724	787	10,7	328	454	31,7
14	-	3	824	1003	4,5	824	950	7,5	425	546	26,5
5	2	2	725	967	4,7	825	875	12,1	453	569	32,8
5	1	3	495	888	4,6	755	802	9,0	386	514	36,9
5	1	4	784,06	983,38	4,6	871	916	10,1	447	562	31,6

Model Alloy Fabrication

Ingot
- Preparation of the raw materials
- Melting and casting in an arc furnace with a non-consumable electrode

Tape
- Forging the resulting ingot (in the air)
- Vacuum Furnace Annealing
- Hot and cold rolling

Sample
- Ribbon cutting
- Surface grinding

Tests in still air:
- time – 60 h;
- temperature – 800 ^oC.

Tests in water:
- time – 300 h;
- temperature – 350 ^oC;
- pressure – 16 MPa.

Tests in steam:
- time – 72 h;
- temperature – 400 ^oC;
- pressure – 18 MPa.

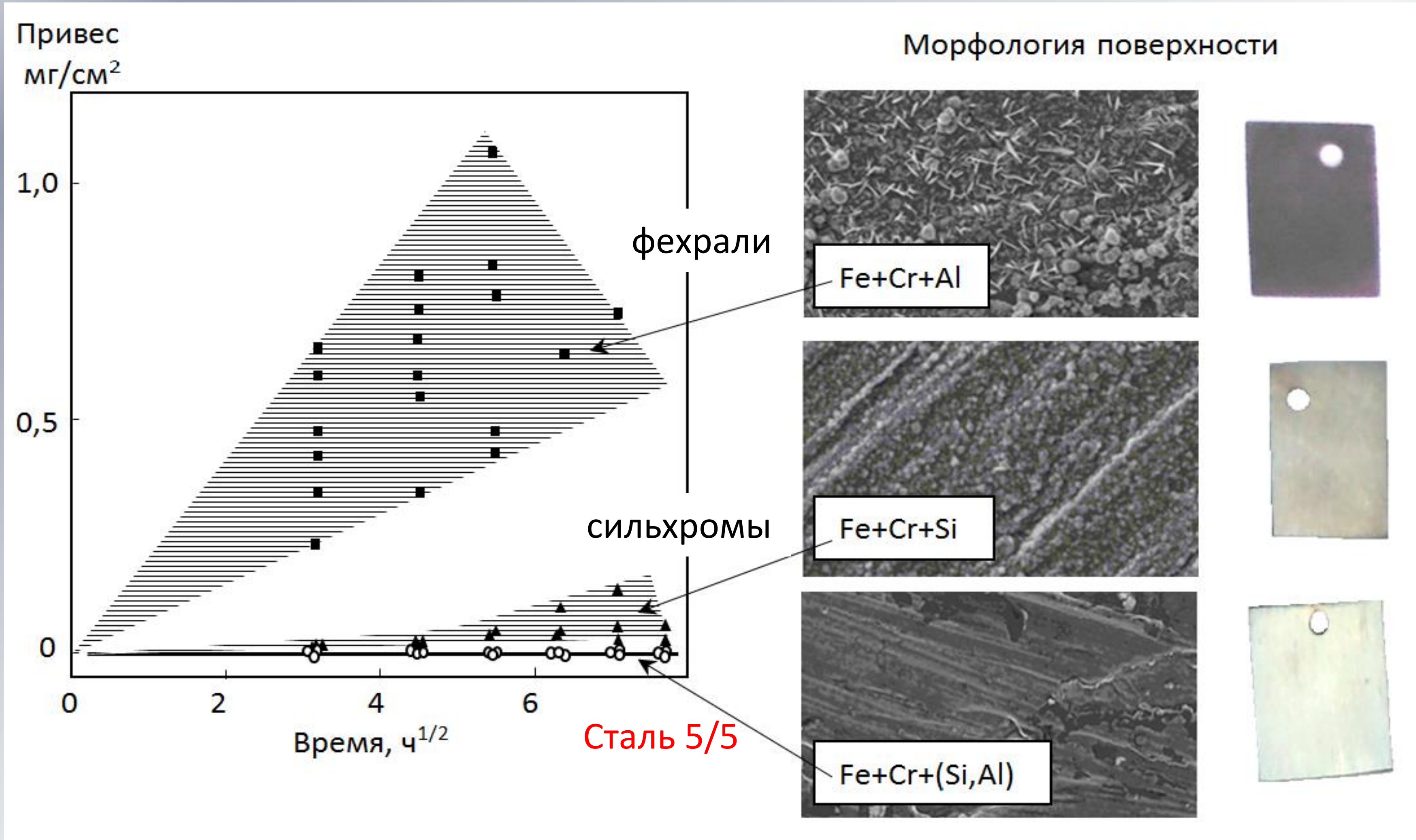
Tests in superheated steam :
- time – 4 h;
- temperature – 1100 ^oC;
- pressure – 0,1 MPa.

Selection of alloys: rapid test - oxidation in air at 800, 60 h (more than 30 alloys were investigated)

Resistance of Fehral confirmed

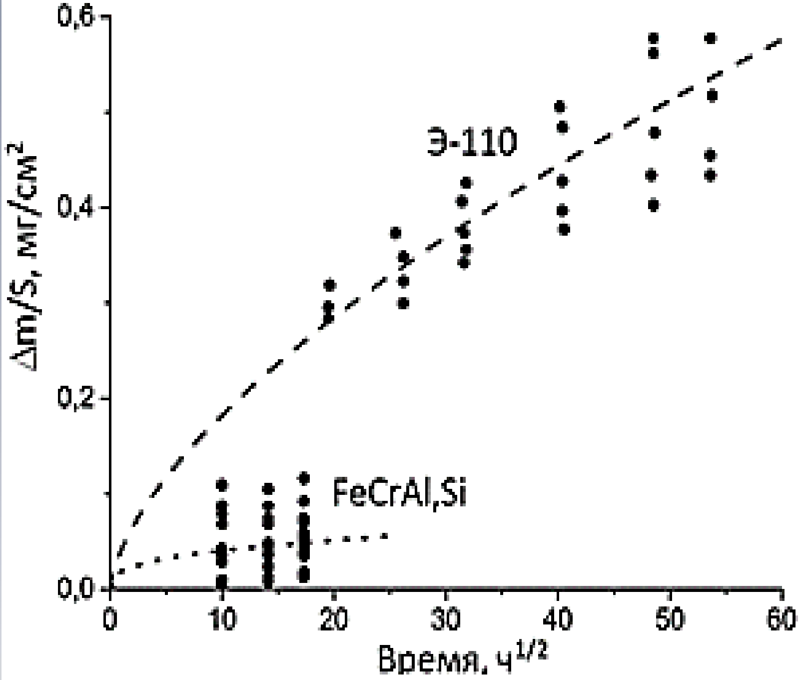
Single phase area with high durability are defined: so-called Steel 5/5 Fe+5Cr+5(Al,Si)

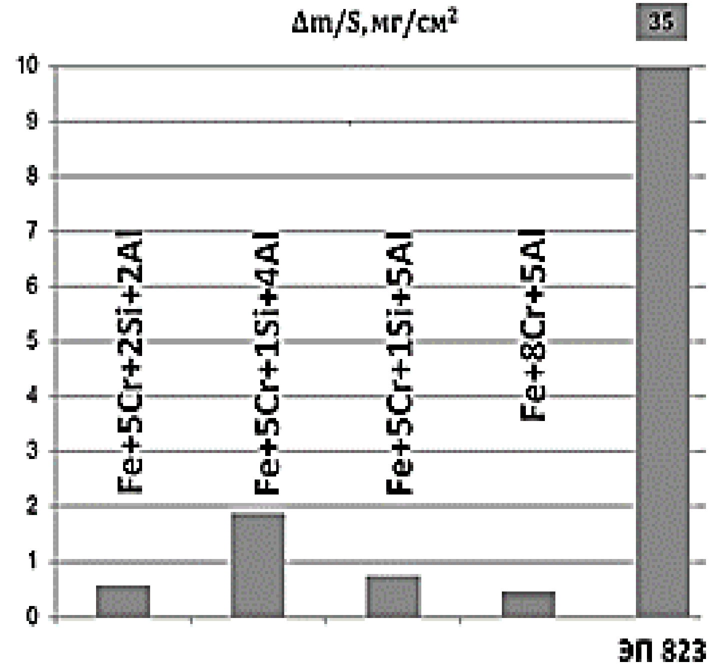
Corrosion of fehrales, silchromes and steel 5/5 in water and steam



Corrosion of steel in steam 400 °C, 18 MPa

Corrosion in superheated water and steam



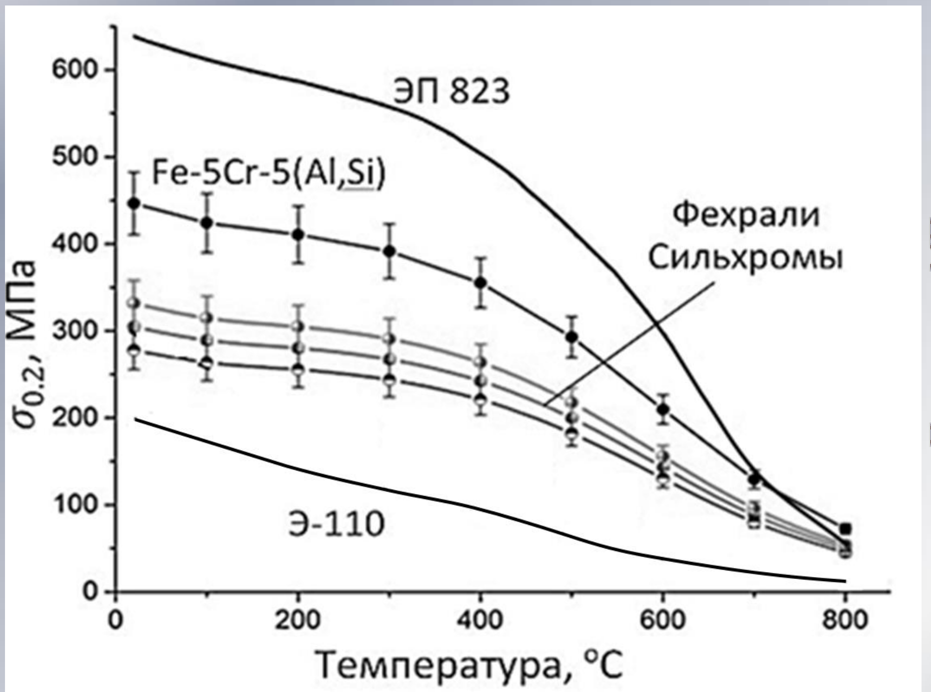


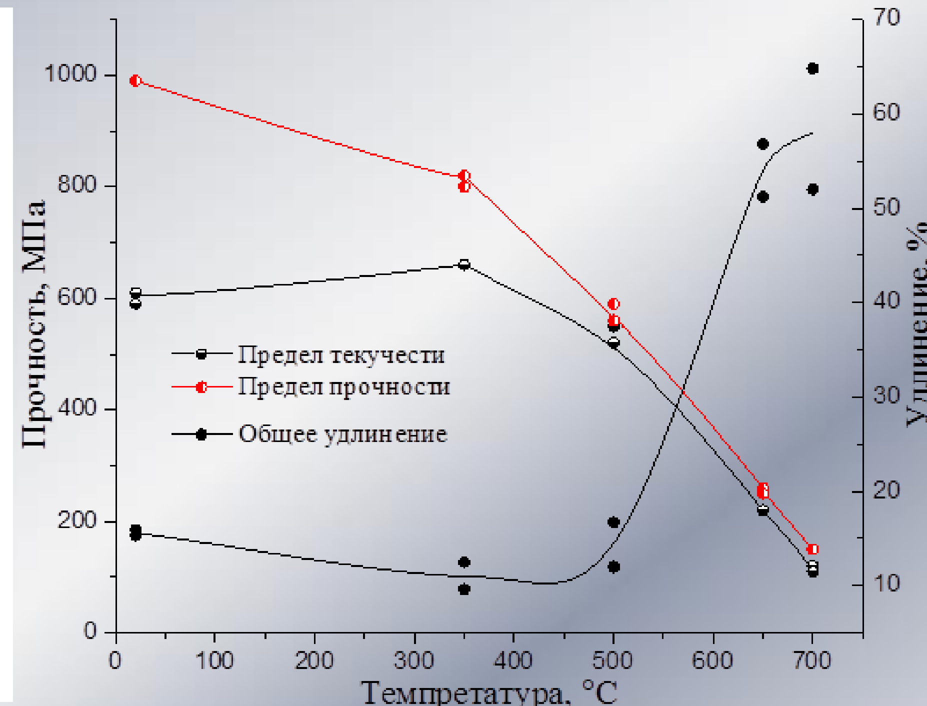
Water 360 °C, 16 MPa

Steam 1100 °C, 0,1 MPa

It is confirmed that single-phase steel has a high corrosion resistance

Mechanical properties

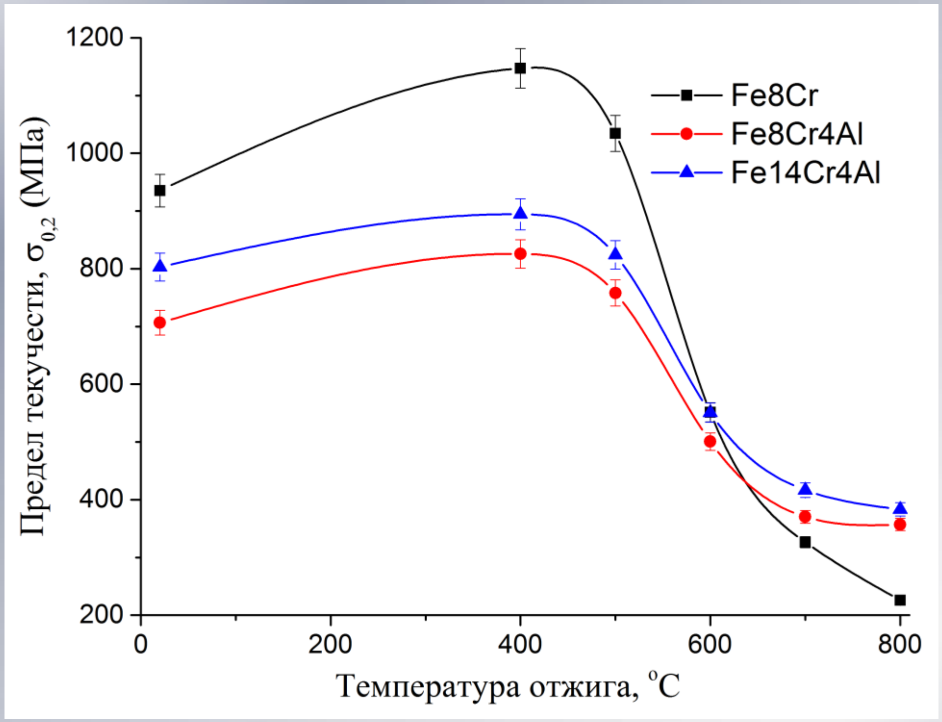


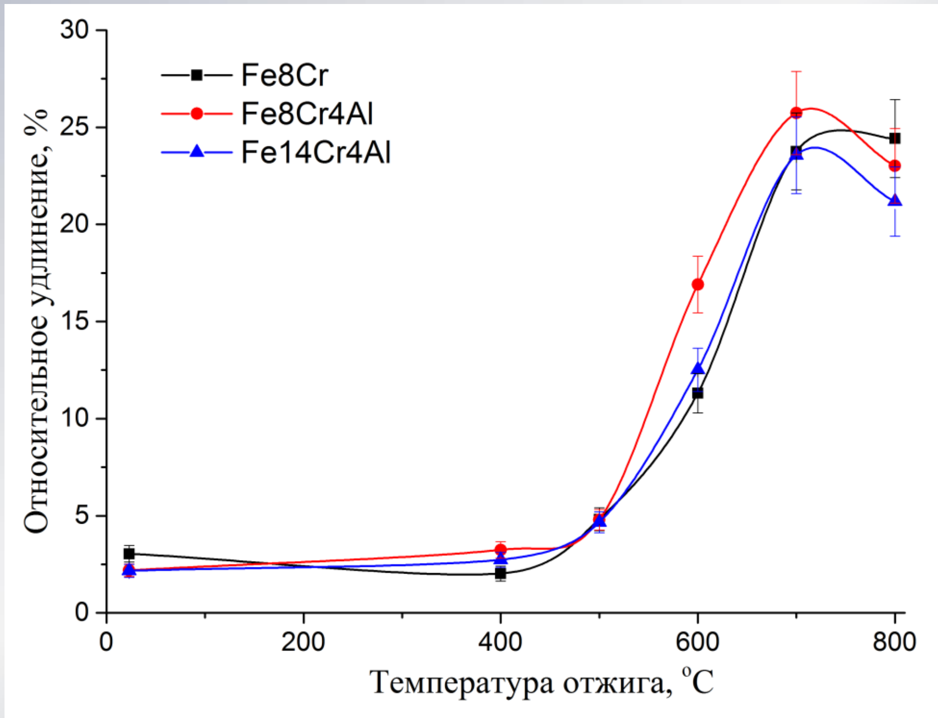


Yield Comparison

As applied to the WWER, based on the yield strength of the E-110 and Steel 5/5, the shell thickness can be reduced to 0.2 mm.
Strengthening (if required) is possible with additional doping.

Thermal stability (recrystallization)



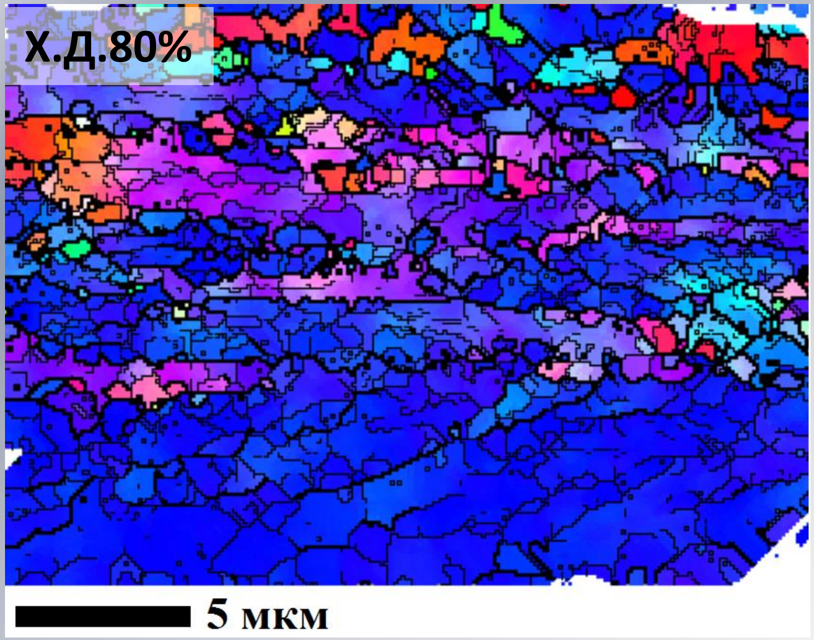


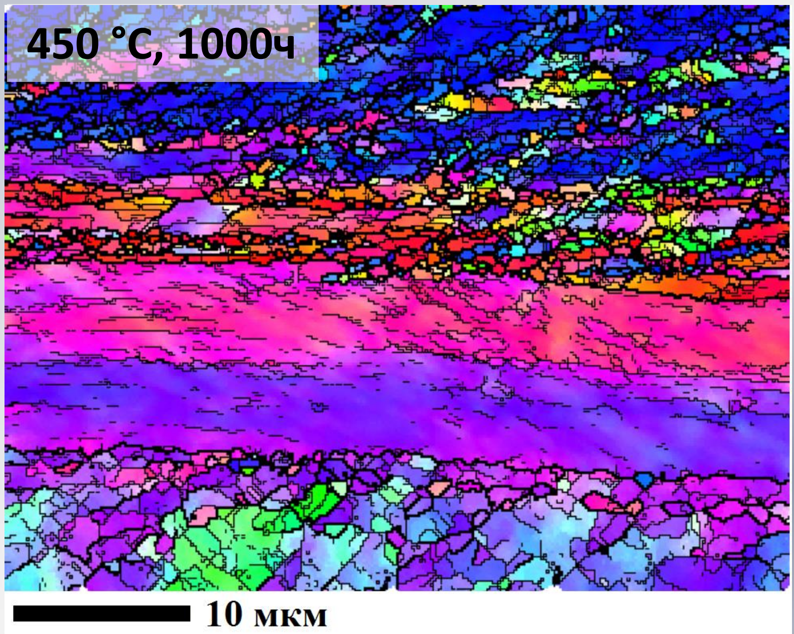
Recrystallization Study:

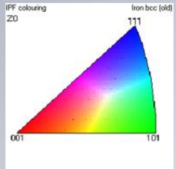
- Baseline - 80% C.D.
- Annealing time at each temperature 2 hours
- The temperature of the onset of secondary recrystallization >700 °C

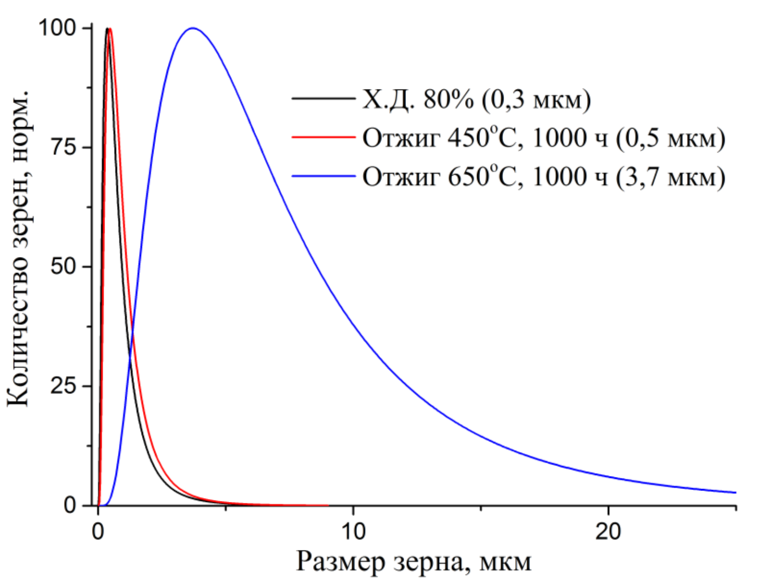
Авторы выражают благодарность Осинцеву А.В за помощь в проведении исследований.

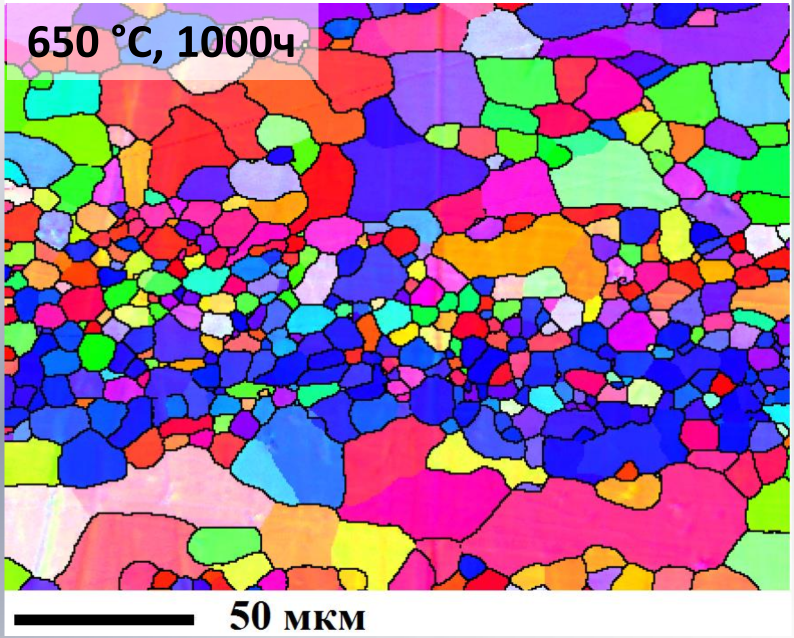
Thermal stability (recrystallization)











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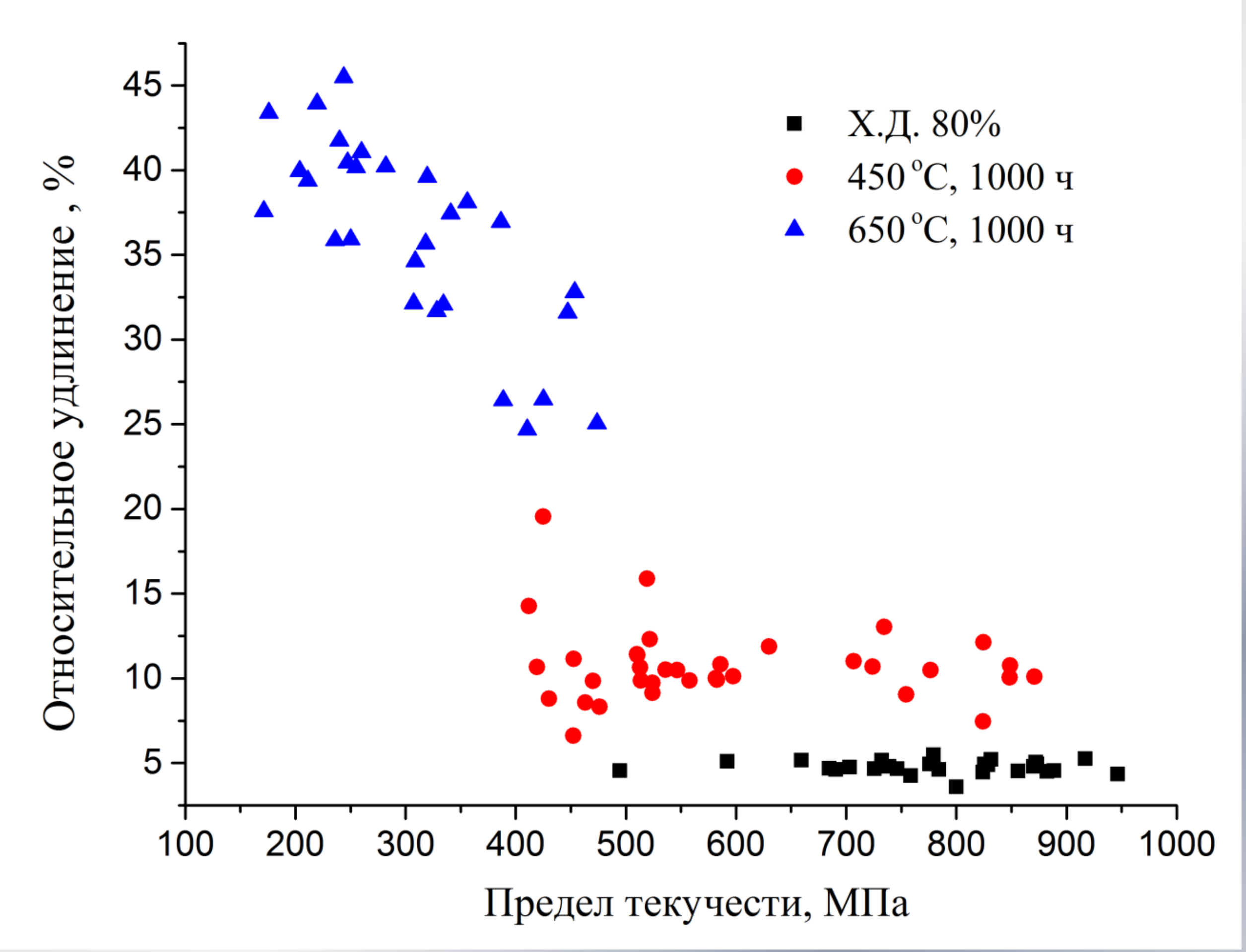
Thermal stability (ductility)



For all the compositions were not observed thermal aging and embrittlement!

Технологически-эксплуатационные свойства

Испытания на коррозионное растрескивание под напряжением. Насыщенный раствор $MgCl_2$, 413 К, 0,1 МПа >100 ч;

Время, обработка / №	300 ч., холоднодеформированные	300 ч., отожжённые
41/1		
41		
42		
43		

Проведены тесты на свариваемость (ручная аргонно-дуговая сварка пластин 50х50х1)
Полное удлинение сварных образцов ~3%.

Conclusion

Discovered "island" steel compositions $Fe + (4 \ldots 6)\%Cr + (4 \ldots 6)\%Al, Si$. It is single-phase in the range from operating temperature to melting temperature and combining high oxidation resistance (logarithmic kinetics) with a high level of mechanical properties ($\sigma_{0.2} > 200\ MPa$ and $\delta = (30 - 40)\%$ at 650 ℃) – so-called Steel 5/5.

Steels 5/5 can become the basis for the development of materials for fuel claddings of promising fast neutron reactors (BREST type), as well as thermal neutron reactors (such as VVER 3+ and SUPER-VVER).

Exploratory research phase is completed.

The absence of embrittlement of experimental alloys during thermal aging is shown.