STATE SCIENTIFIC CENTER –RESEARCH INSTITUTE OF ATOMIC REACTORS

ПРЕДПРИЯТИЕ ГОСКОРПОРАЦИИ «РОСАТОМ»

MECHANICAL PROPERTIES AND STRUCTURE OF IRRADIATED ULTRA-FINE GRAINED STEEL 08X18H10T PRODUCED BY EQUAL-CHANNEL ANGULAR PRESSING

©V.K. Shamardin[1], T.M. Bulanova[1], A.A. Karsakov[1], A.V. Obukhov[1], L.A. Evseyev[1], E.P. Belan[1], R.Z. Valiev[2], N.A. Enikeyev[2], I.V. Alexandrov[2], M.M. Abramova[2], and A.K.Glushkova[3]

[1] Joint Stock Company “State scientific Center –Research Institute of Atomic Reactors”, Dimitrovgrad, Russia

[2] Ufa State Aviation Technical University, Ufa, Russia

[3] Dimitrovgrad Engineering and Technology Institute –Affiliated Branch of Federal State Autonomous Educational Institution for Higher Education “MEPhI”, Dimitrovgrad, Ulyanovsk region, Russia

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Introduction

To date the main opportunities for creating new materials with the required properties have been identified by varying their chemical composition. Therefore, a radical increase the properties of already existing materials due to the modification of their microstructure and phase state is of particular importance.

A promising way to implement this approach is to move to:

- ultra-fine grained (UFG) materials with a grain size from 100 nm to 500 nm;
- nanostructured (NS) materials with a grain size of ≤100 nm.

Technologically, the production of such structures is provided by using severe plastic deformation (SPD) processes :

-equal-channel angular pressing (ECAP);

-high pressure torsion;

-all-around isothermal forging, etc.

In the process of SPD the high dislocation density and the occurrence of non-equilibrium low-angle and high-angle grain boundaries are provided. That makes it possible to change the complex of physical and mechanical properties. There is a crucial possibility to minimize the development of such phenomena as irradiation embrittlement, irradiation-induced swelling, stress-corrosion cracking initiated by irradiation due to the increase of sink concentration in UFG-structures.

Introduction (continued)

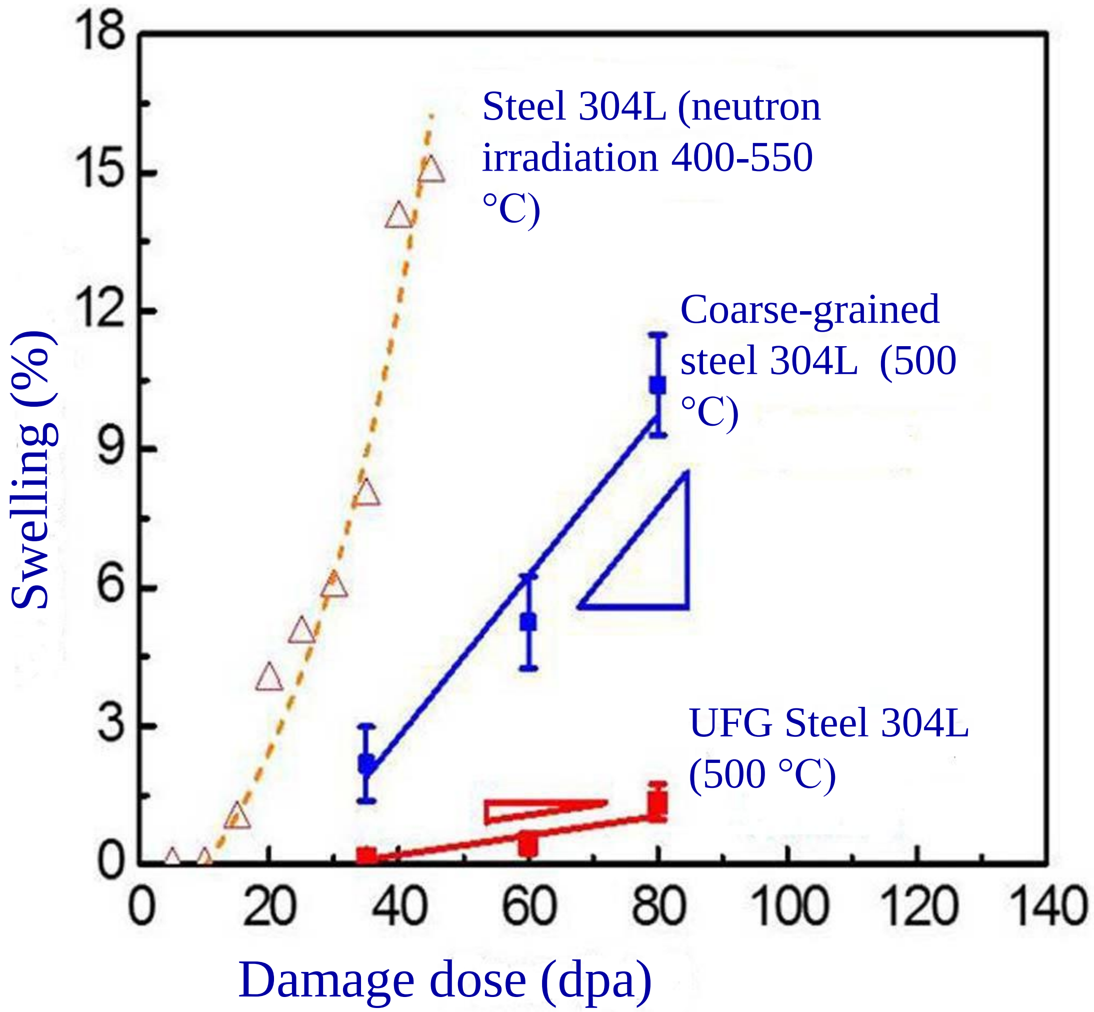
A combination of increased mechanical properties of UFG materials and thermal and irradiation stability can make these materials quite attractive for use in reactor engineering, so studies of the radiation stability of UFG materials have high scientific and applied value.

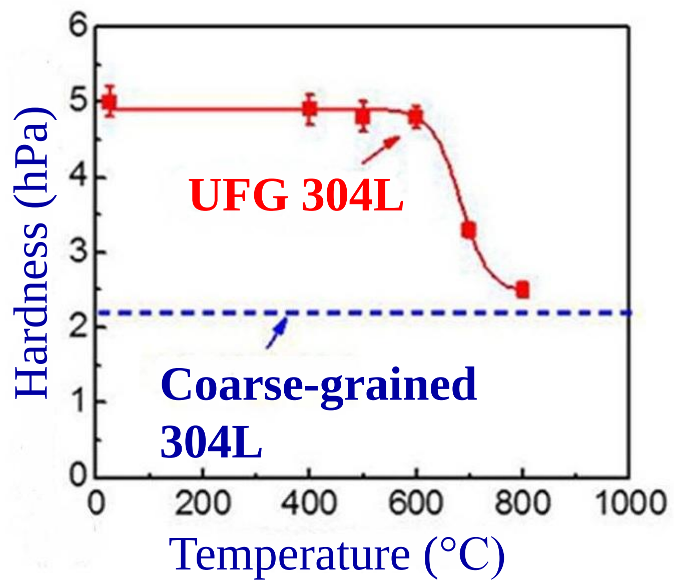
Austenitic stainless steels is the basic material used during the fabrication of core elements and BN internals, as well as water-cooled reactors. There are few experimental data about the peculiarities of mechanical property changes of stainless steels with UFG structure, irradiated by neutrons.

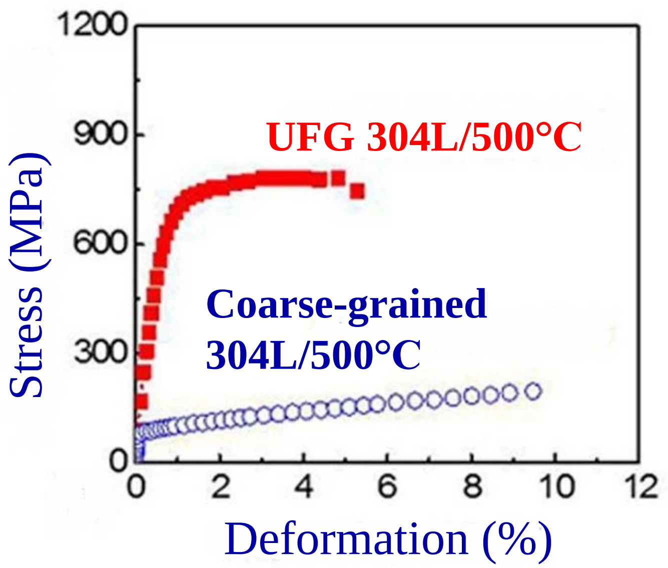
The paper describes results of studying the effect of neutron irradiation on the properties of austenitic stainless steel 08X18H10 T in the UFG-state.

Effects revealed during irradiation with Fe ions (1,5 meV) in steel 304L UFG- and NS (~100 nm) in comparison with the coarse-grained (CG) (35 μm) state. *)

- decrease of swelling value about 10 times at 80 dpa;
- thermal stability of hardening in the UFG-and nano-structures up to a temperature of 600°C;
- suppression of $M_{23}C_6$ precipitate formation due to the great number of high-angle grain boundaries.







*) C/SAN, S.ZHENG,C.C.WEI AT ALL 'SUPERIOR RADIATION-RESISTANT NANOENGINEERED AUSTENITIC 304L STAINLESS STEEL FOR APPLICATIONS IN EXTREME RADIATION ENVIRONMENTS', SCIENTIFIC REPORTS 5:7801 DOI 10.1038SREP07801, January 2015

Flow stress vs. grain size

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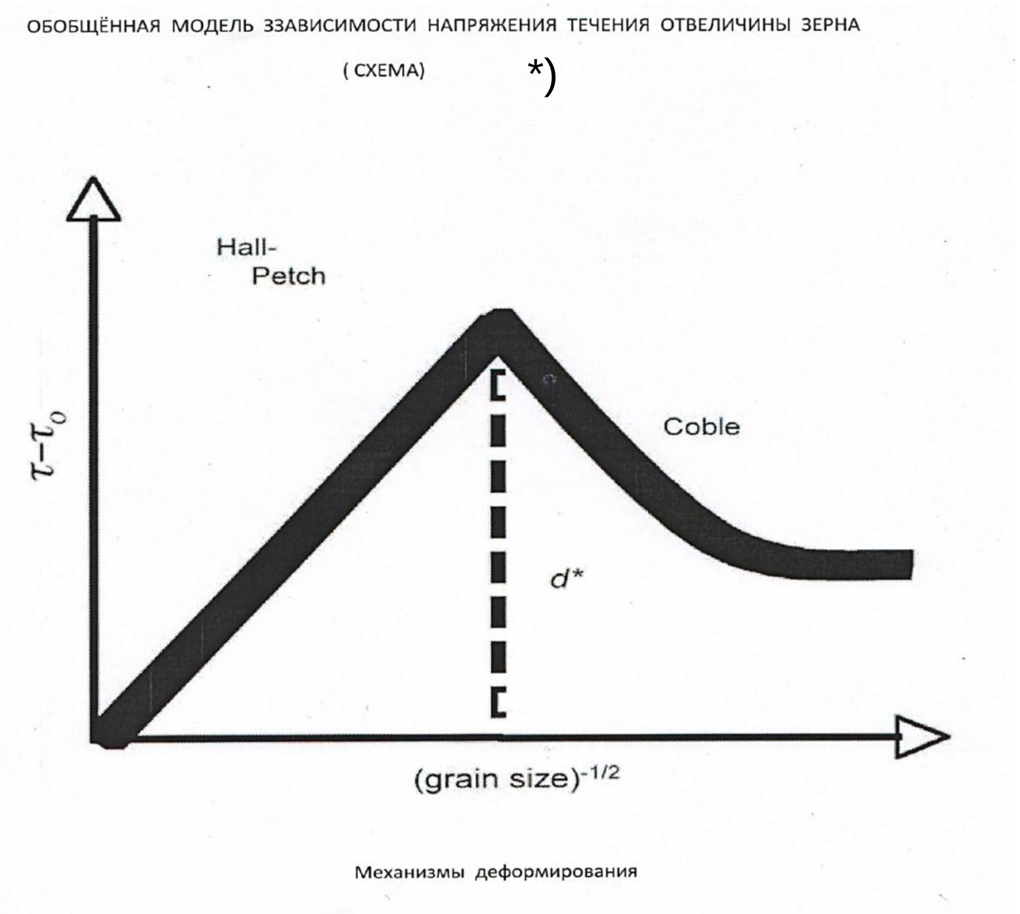
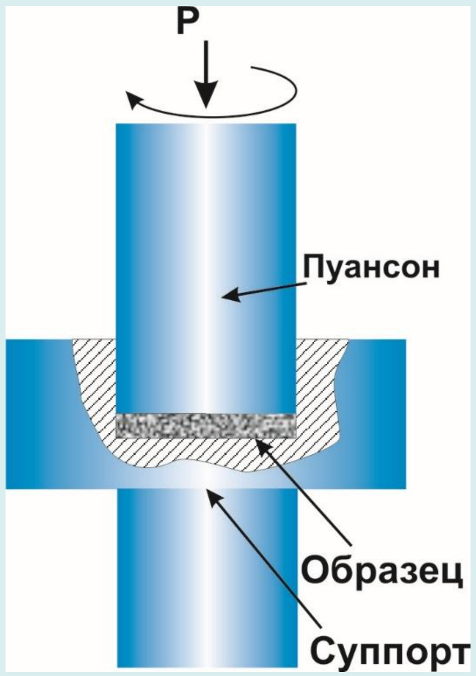


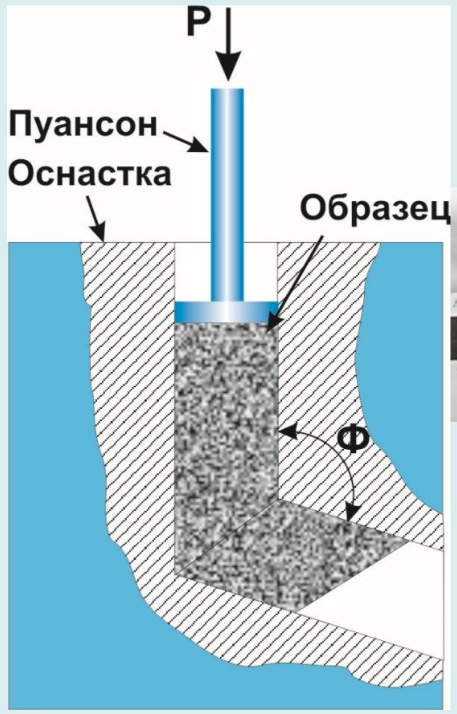
*). Nanomechanics of Hall-Petc hrelationship in nanocrystalline materials, C.S.Pande, K.P.Cooper
**) Mechanical behavior of nanocrystaline metals and alloy, K.S.Kumar, H.Van Swygenhoven, S.Surech

Severe plastic deformation (SPD)

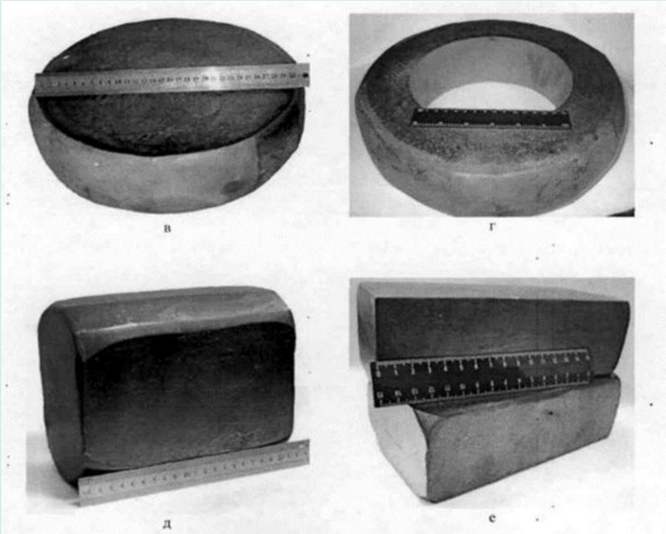
High pressure torsion



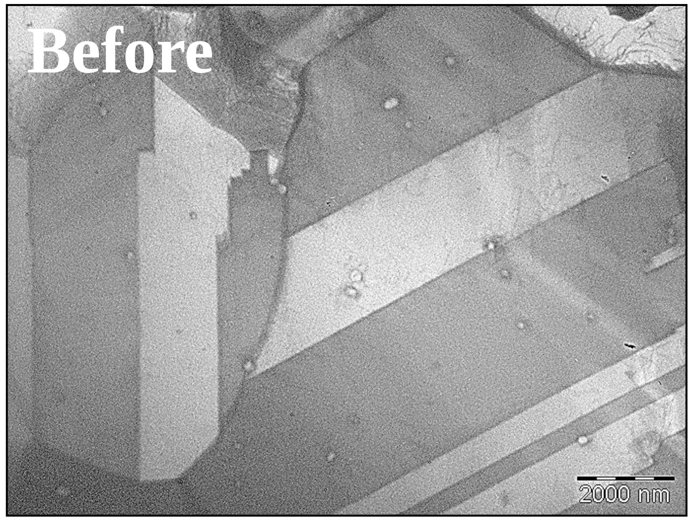
Equal-channel angular pressing

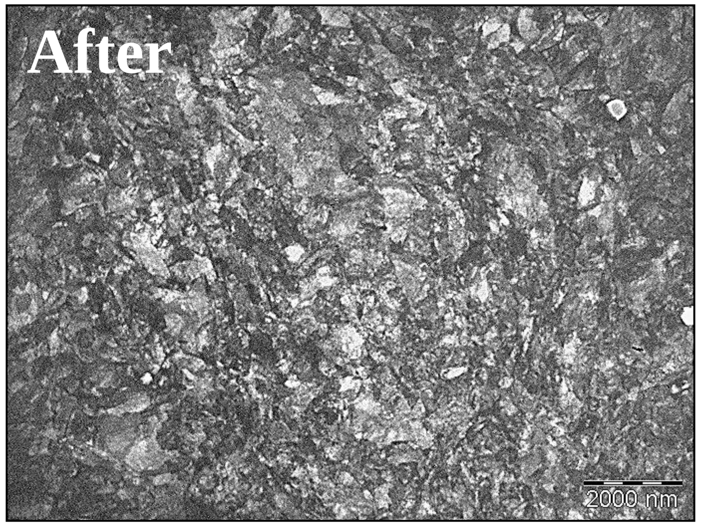


All-around isothermal forging



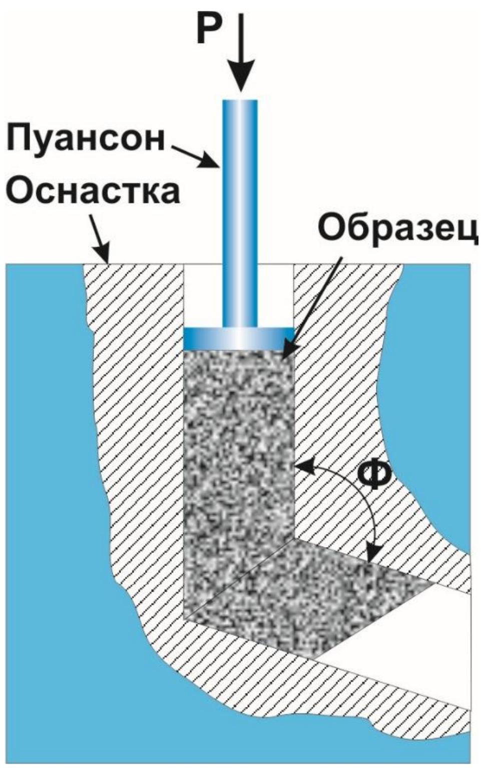
Microstructure of steel 08X18H10T before and after SPD



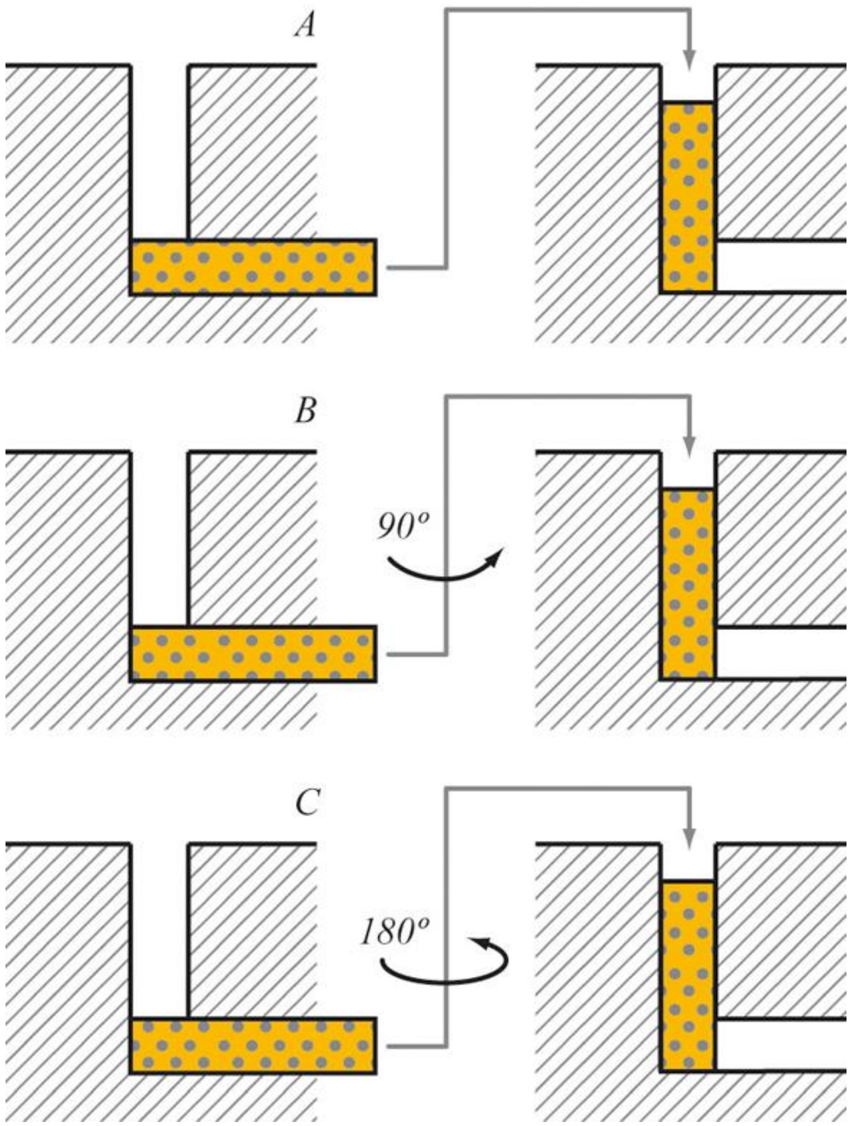


Materials and techniques of investigations

The research has been carried out on steel 08X18H10T in two states:
-as-received state;
-state after SPD with the use of equal-channel angular pressing (ECAP).



Steel rods with a diameter of 10 mm and a length of 60 mm were subjected to equal channel angular pressing (ECAP) at a temperature of 400°C.



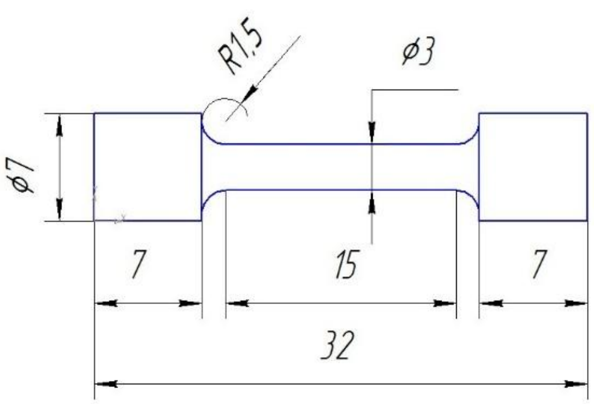
Schematic representation of ECAP modifications

Bulky bar steel obtained by severe plastic deformation

$$\varepsilon = N \cdot \frac{2ctg(\phi/2)}{\sqrt{3}}$$

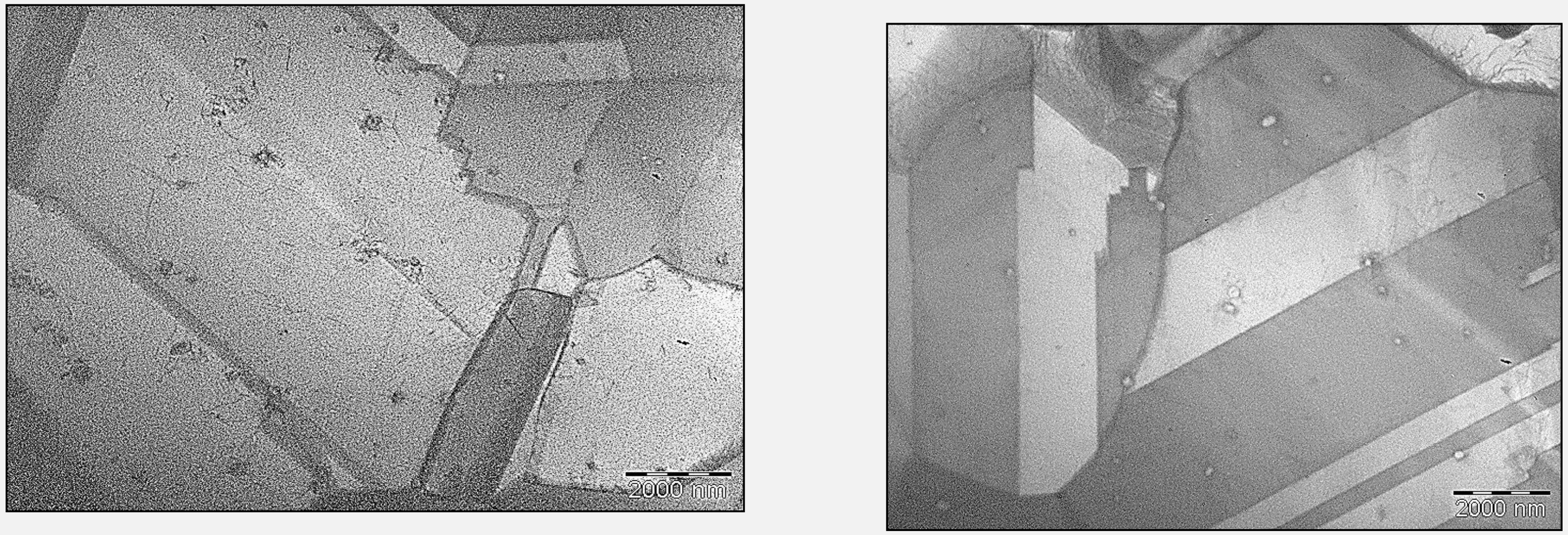
where
N- number of runs,
φ - crossing angle of channels.

Final deformation degree ε~7.1

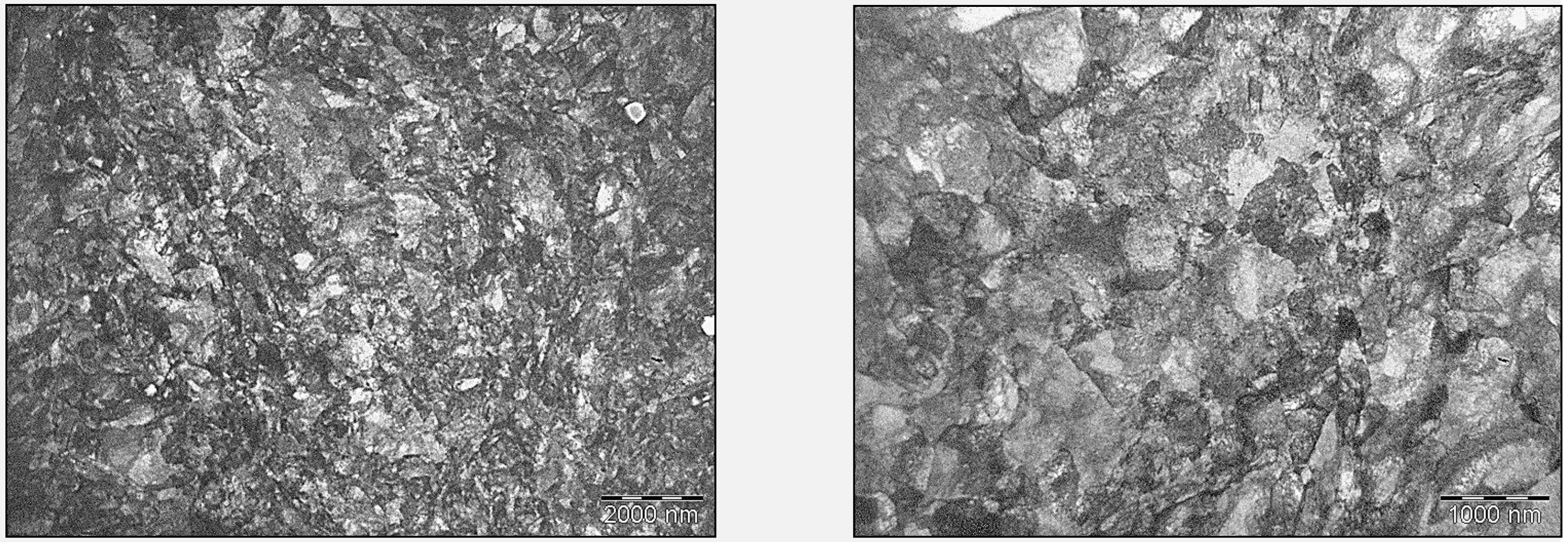


Sample for tensile test

Examined structure of unirradiated steel 08X18H10T



As-received material



Material after ECAP

Microstructure examined by means of EBSD

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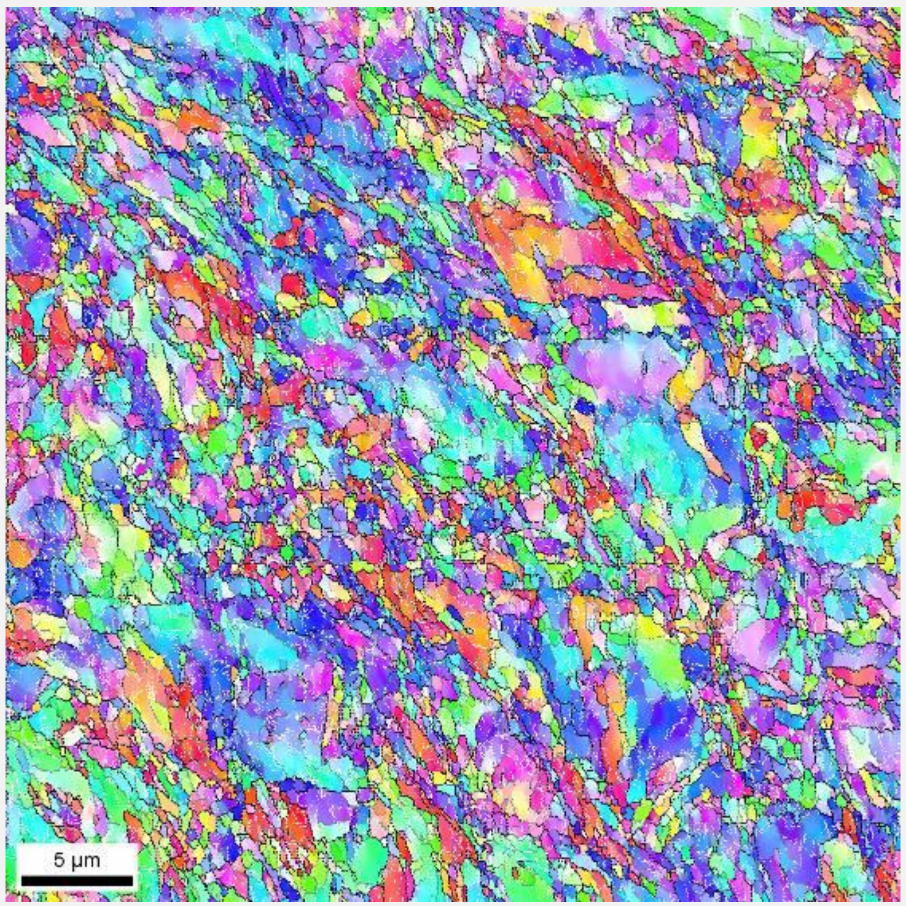
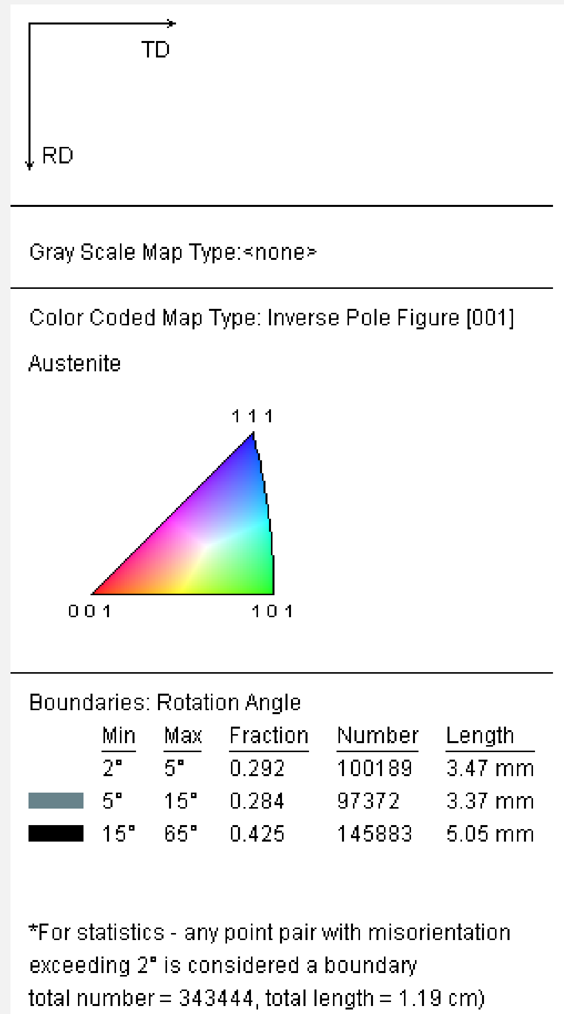
Fig. 4- Low-angle grain boundaries of unirradiated 08X18H10T after ECAP EBSD





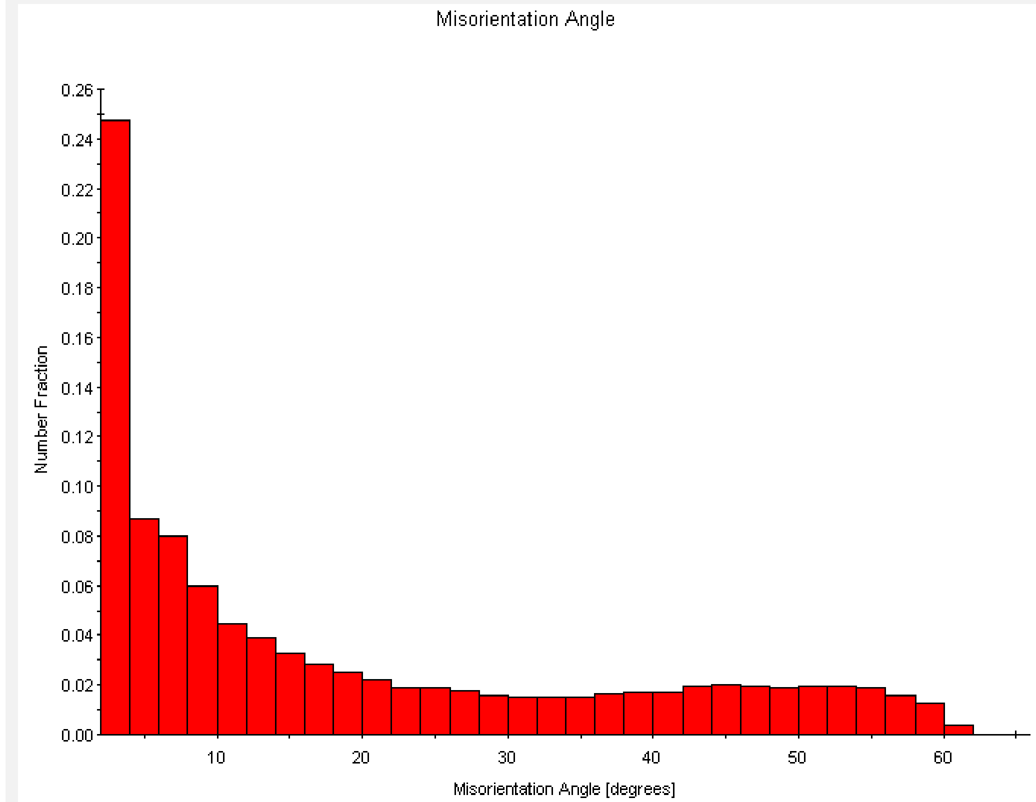
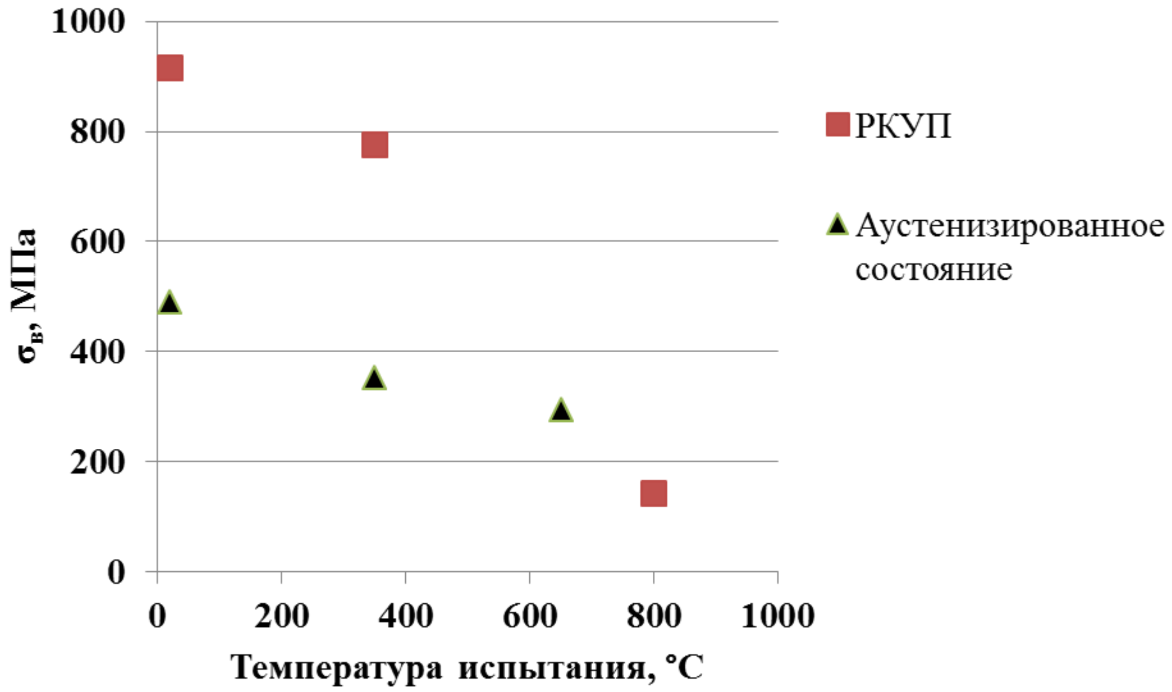
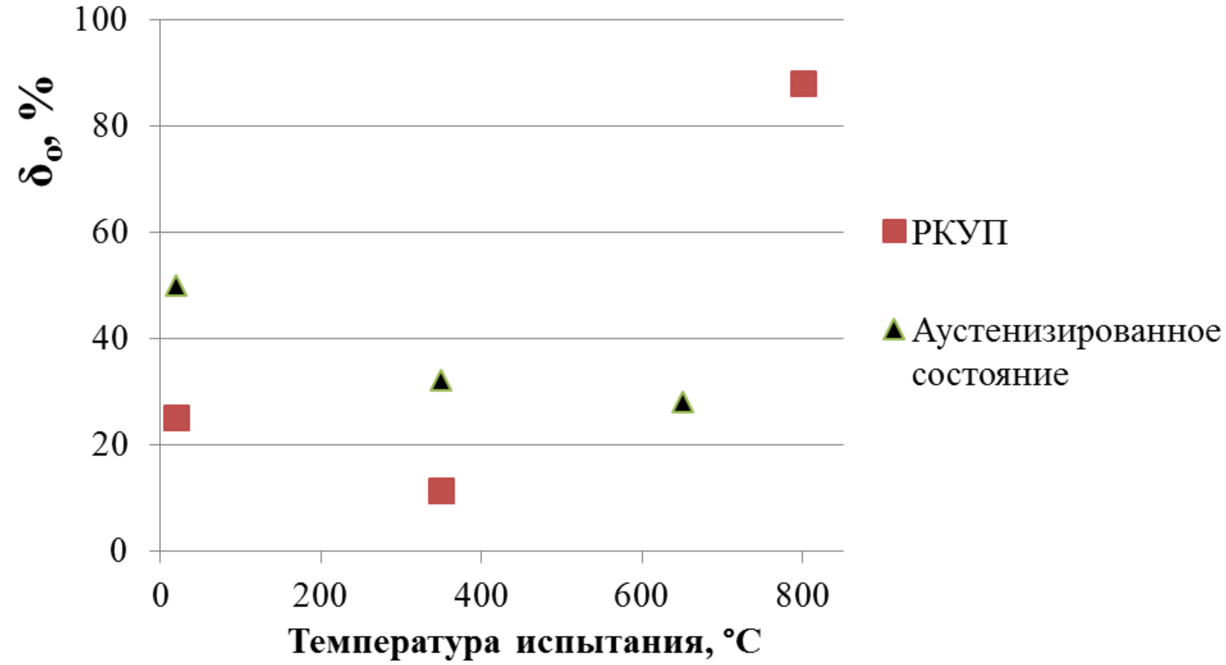


Figure 5. Low-angle grain boundaries distribution

Short-term tensile tests (no irradiation)

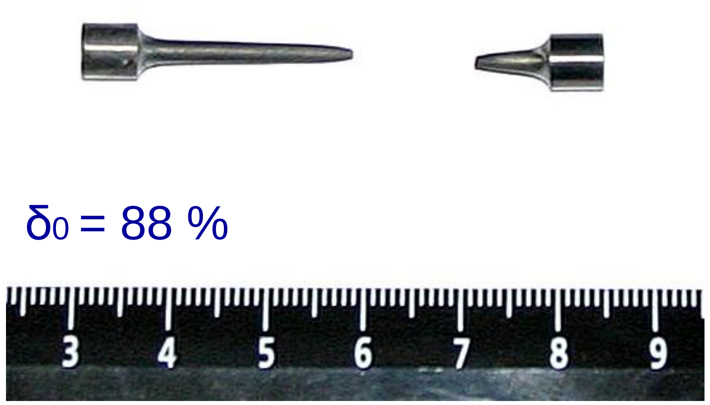


Yield strength vs. tests T

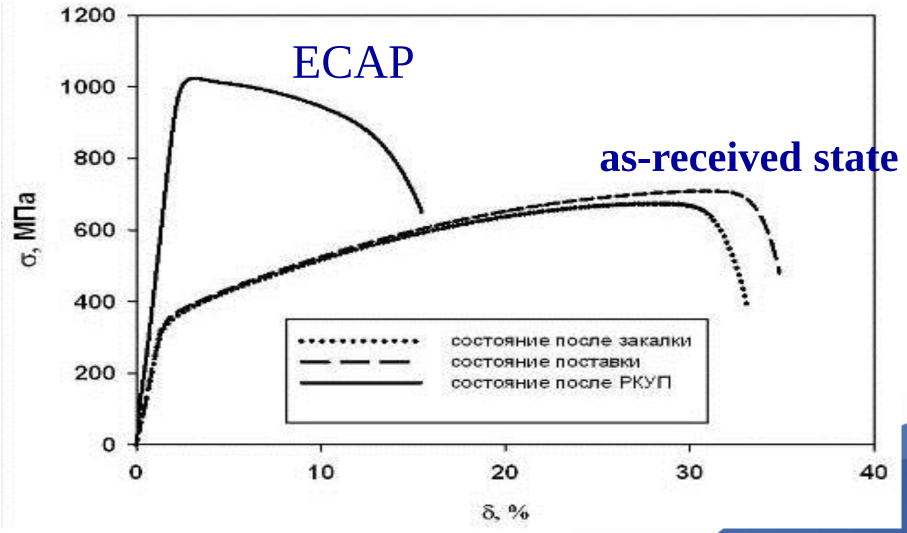


Total relative elongation vs. test T

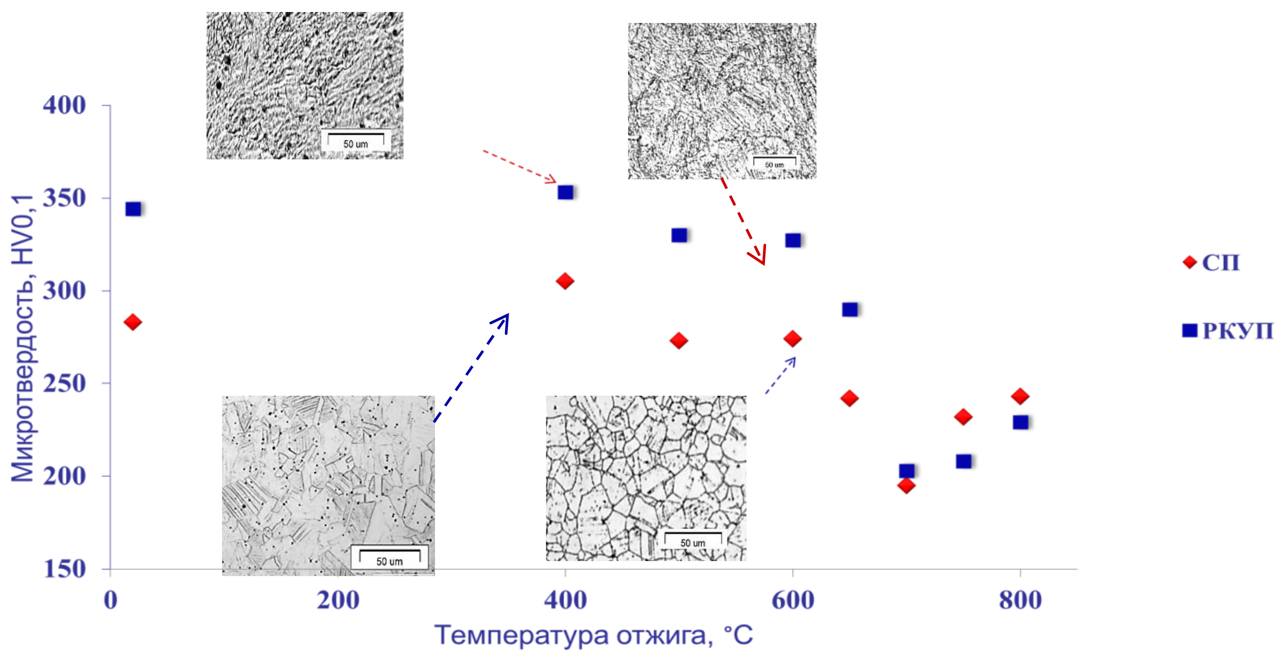
ECAP, T_{test}= 800 °C



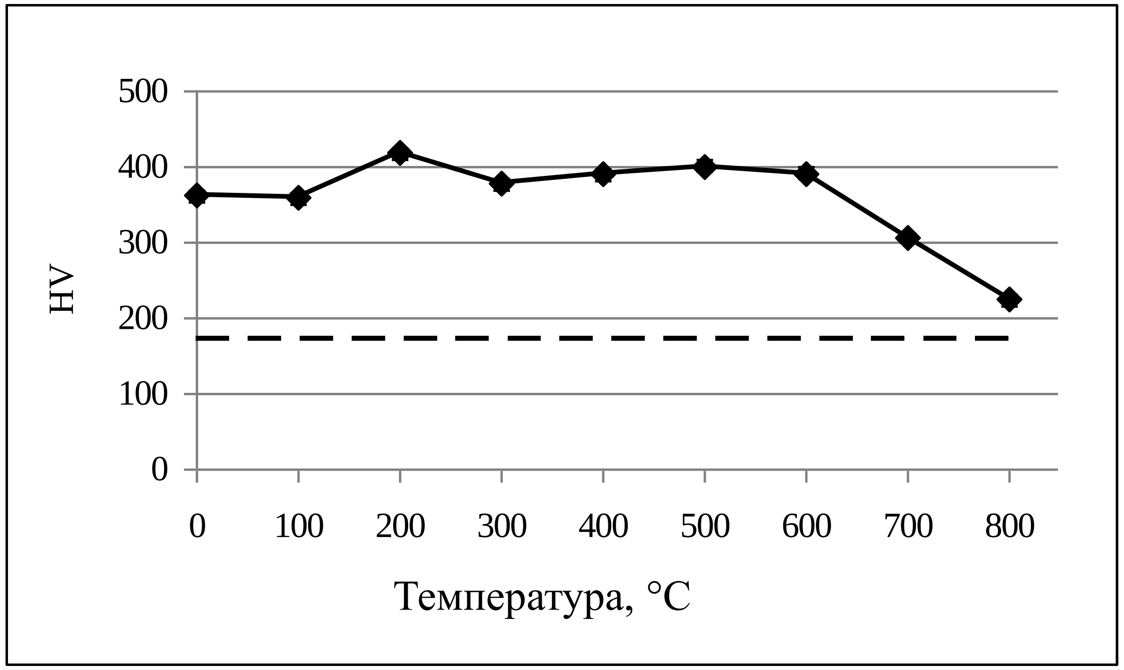
δ_0 = 88 %



Microhardness vs. annealing temperature

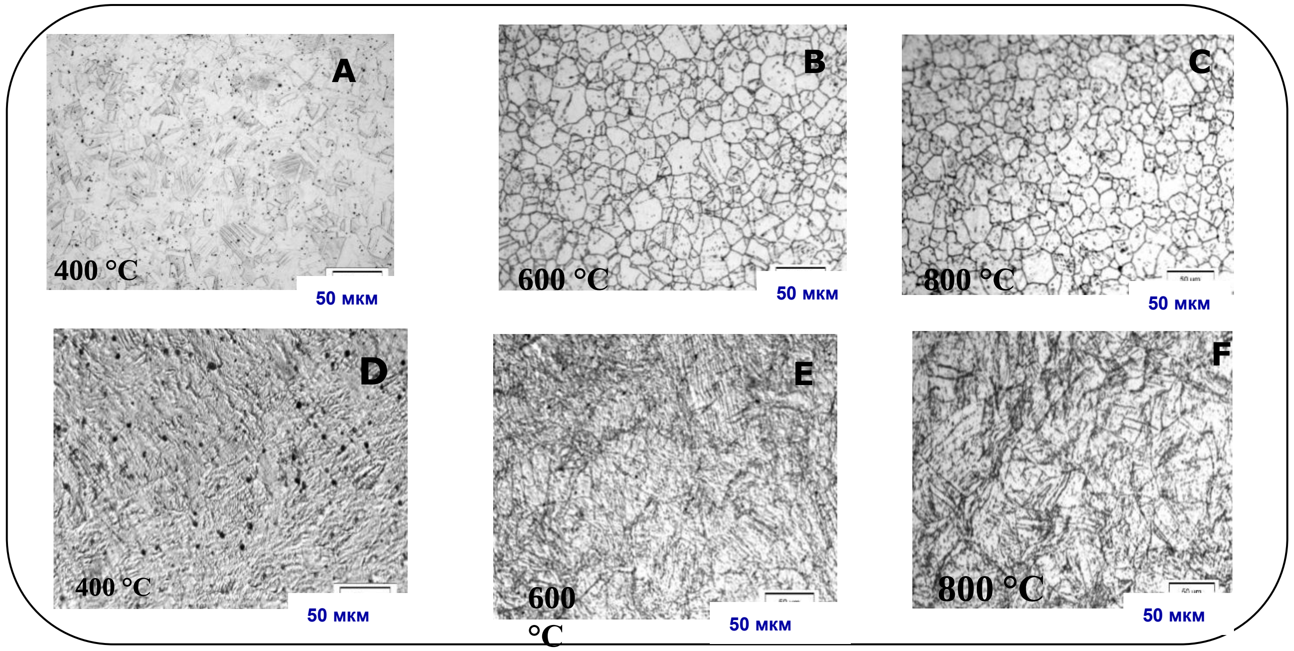


Microhardness (after ECAP, 4 series) vs. annealing T



Microhardness of UFG steel 08X18H10T samples vs. annealing T (ECAP 8 series)

- - - - Steel properties before ECAP

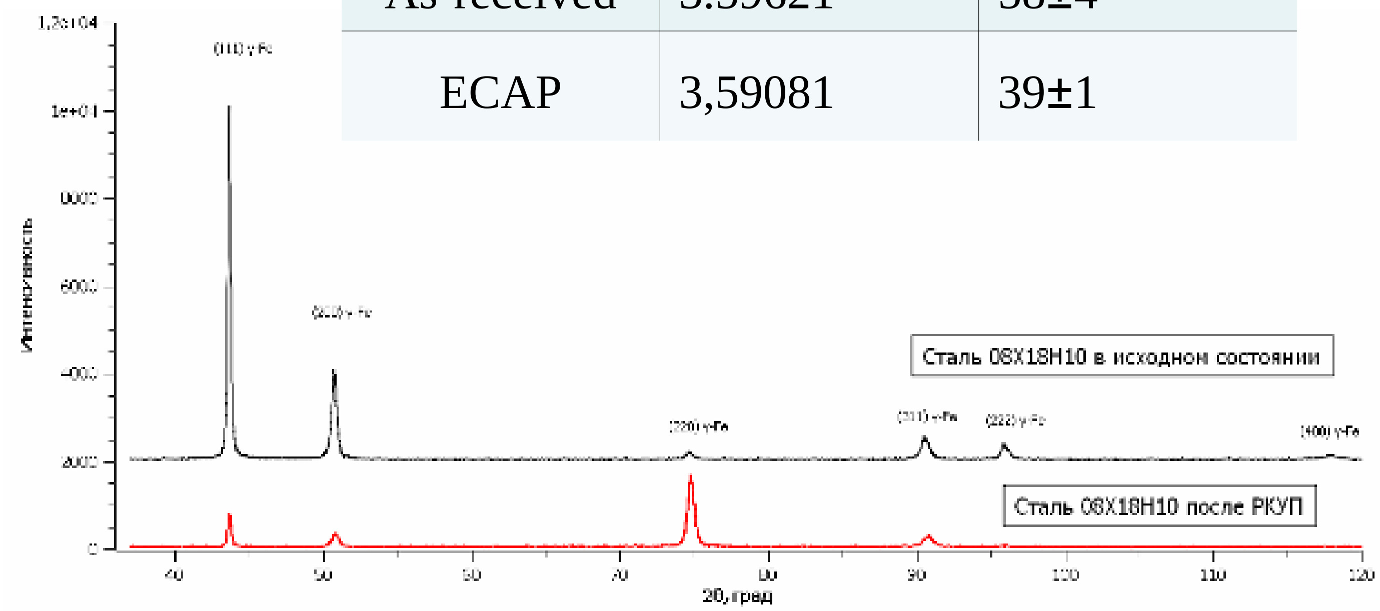


Microstructure of steel 08X18H10T after annealing, where

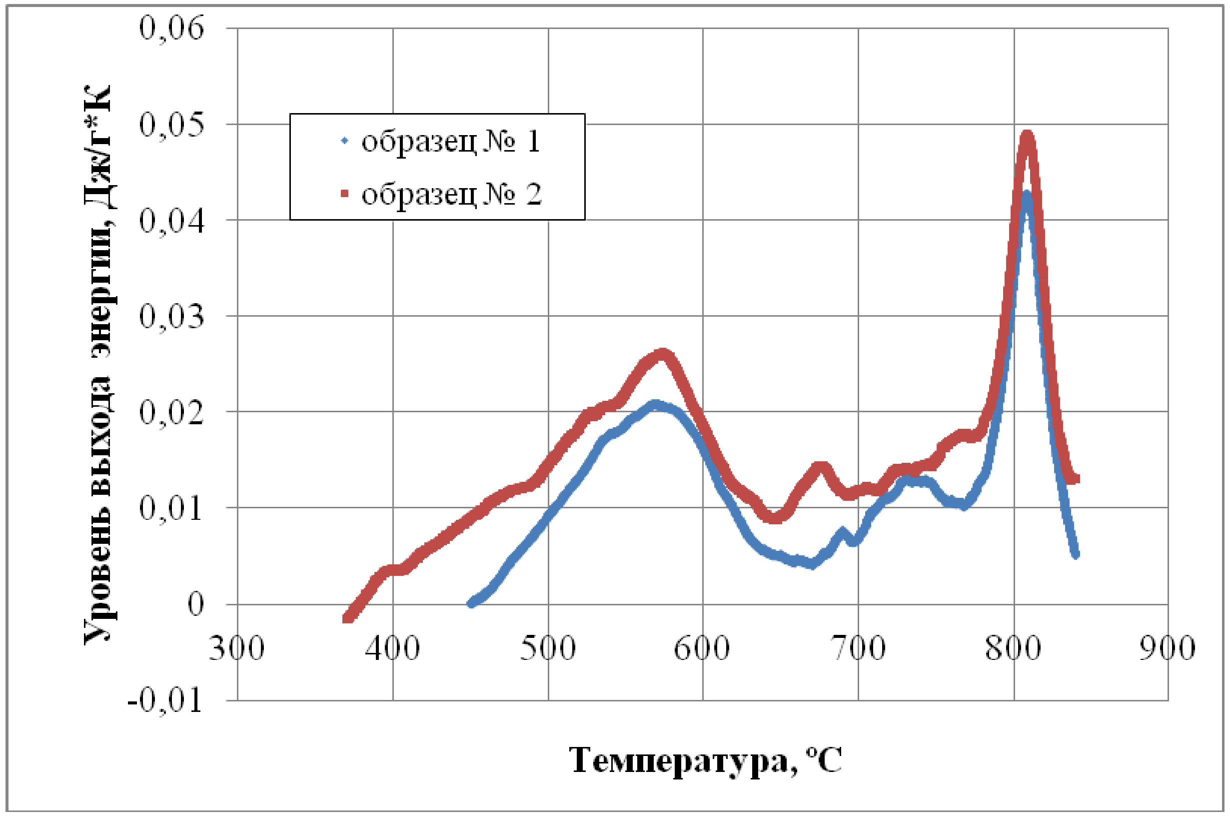
A – as-received state 400 °C;
B – as-received state 600 °C;
C – as-received state 800 °C;
D – ECAP 400 °C ;
E – ECAP 600 °C;
F – ECAP 800 °C

X-Raying and DSC

State	a, A	d, nm
As-received	3.59621	58±4
ECAP	3,59081	39±1



X-Ray patterns of steel 08X18H10Tin the as-received state and after ECAP.



Energy release when heating two strained steel samples (ν_{heat}=20°C/min.)

Irradiation in reactors BOR-60 and SM-3

Table 1. BOR-60 and SM-3 irradiation conditions

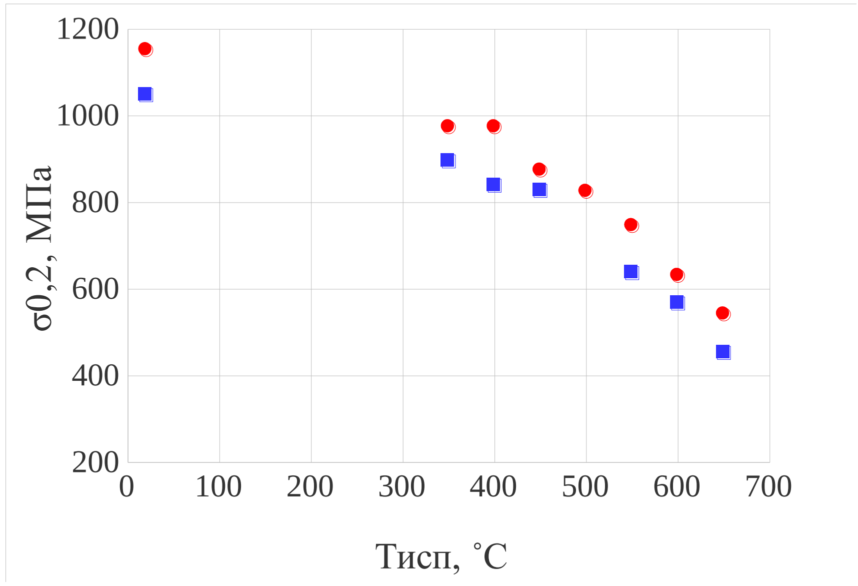
№	Irradiation T, ˚C	Damage dose, dpa	Sample type
1	350 ˚C	5 dpa	Samples for mechanical tests
2	350 ˚C	12 dpa	- Samples for mechanical tests - TEM discs
3	450 ˚C	15 dpa	Samples for mechanical tests
4	100 °C (SM-3)	~50 dpa	Samples for mechanical tests

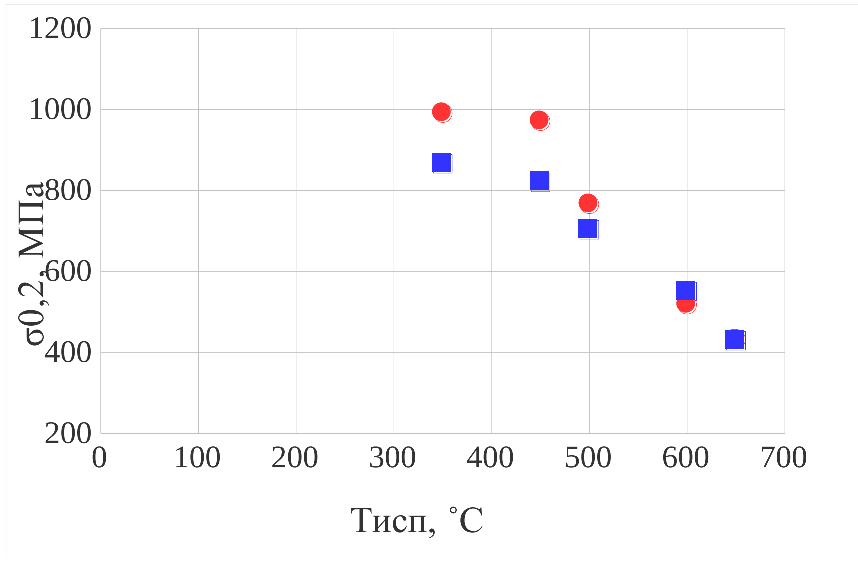
Results of short-term tensile tests after irradiation in BOR-60

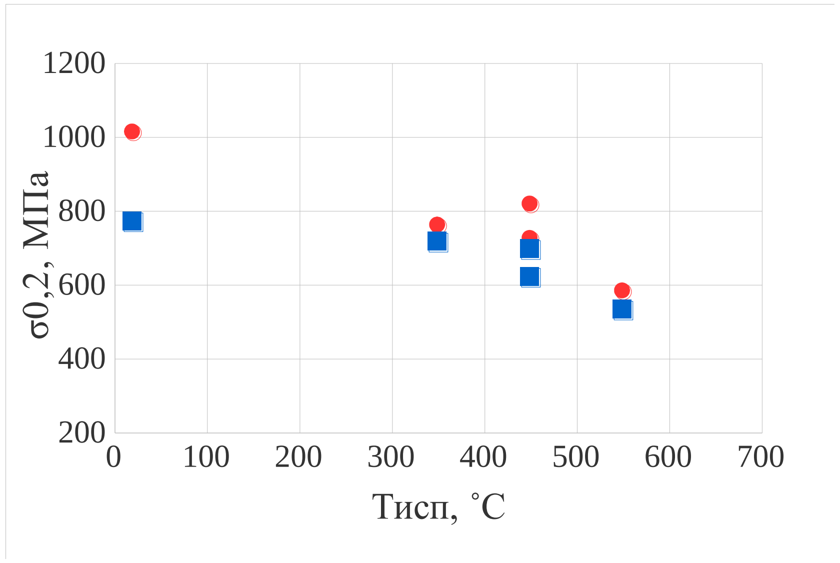
BOR-60, $T_{обл}$=350 ºC, 5 dpa

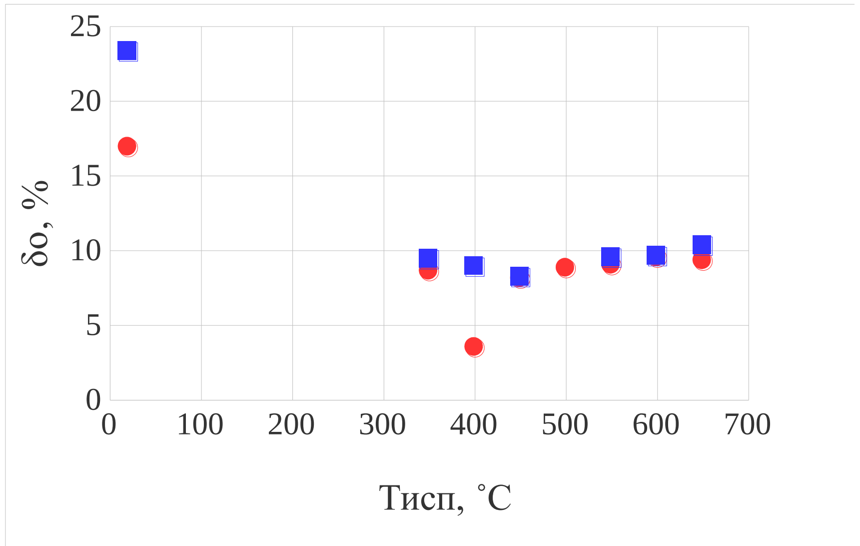
BOR-60, $T_{обл}$=350 ºC, 12 dpa

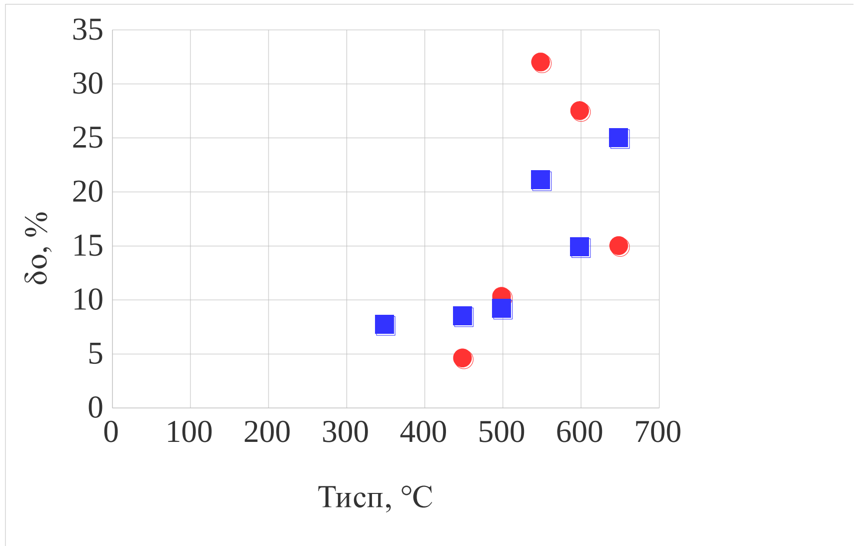
BOR-60, $T_{обл}$=450 ºC, 15 dpa

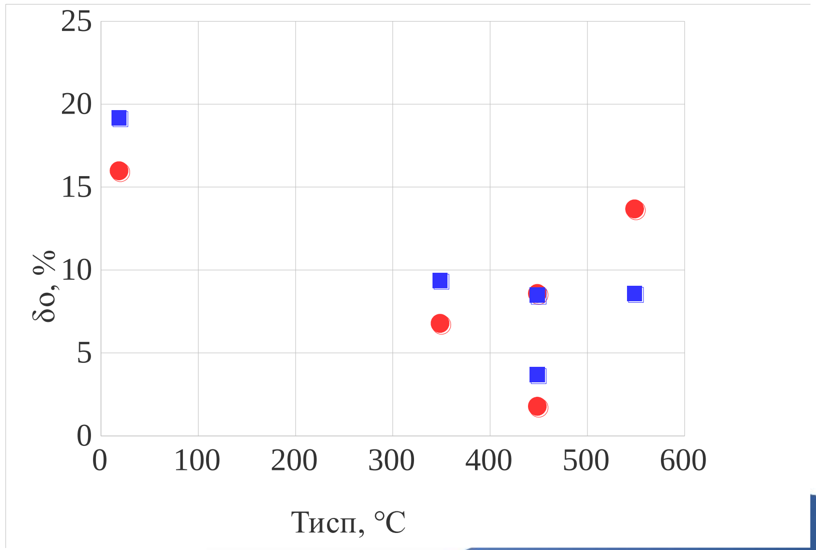






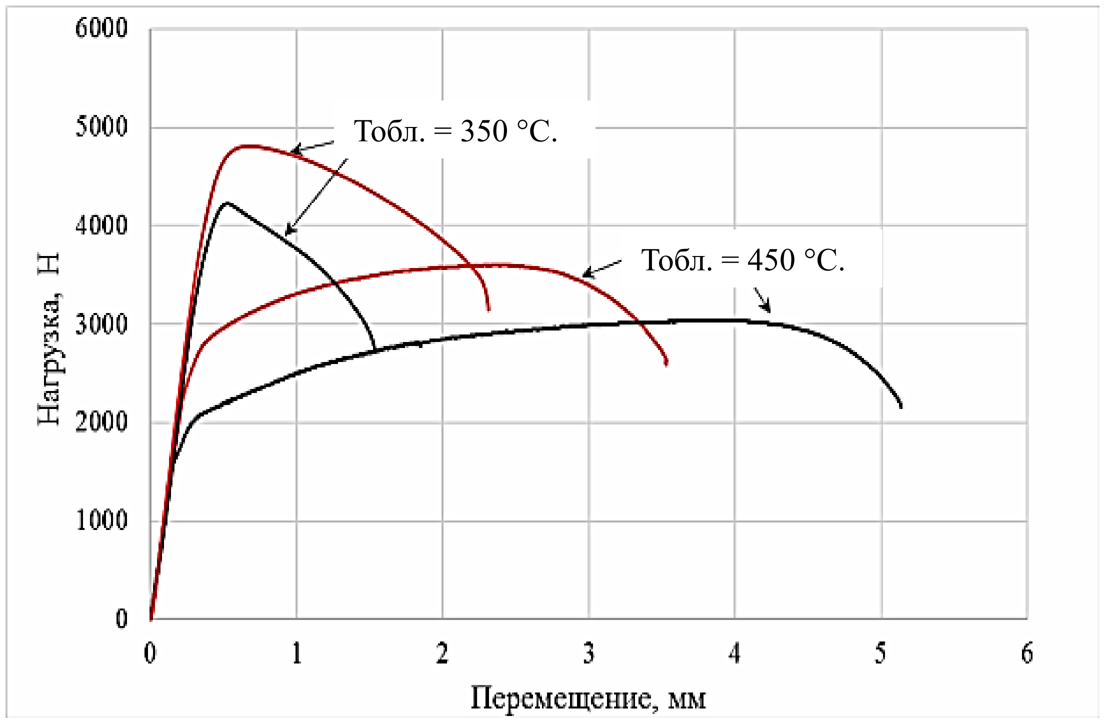




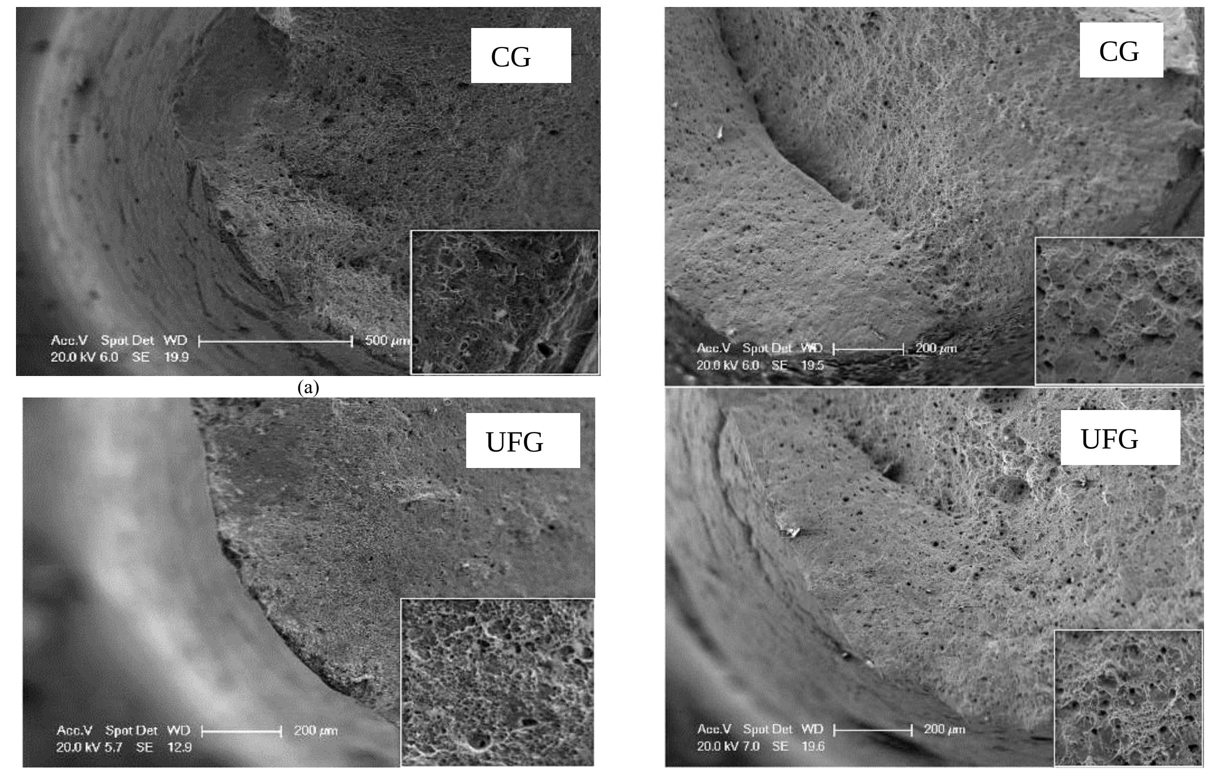


- ECAP   - as-received

Fractography



Tensile diagrams of steel 0X18H10T samples (T_{test}= 550˚C) irradiate at~ 350˚C up to 12dpa and at ~450˚C up to 15dpa; UFG (in red) and CG (in black).

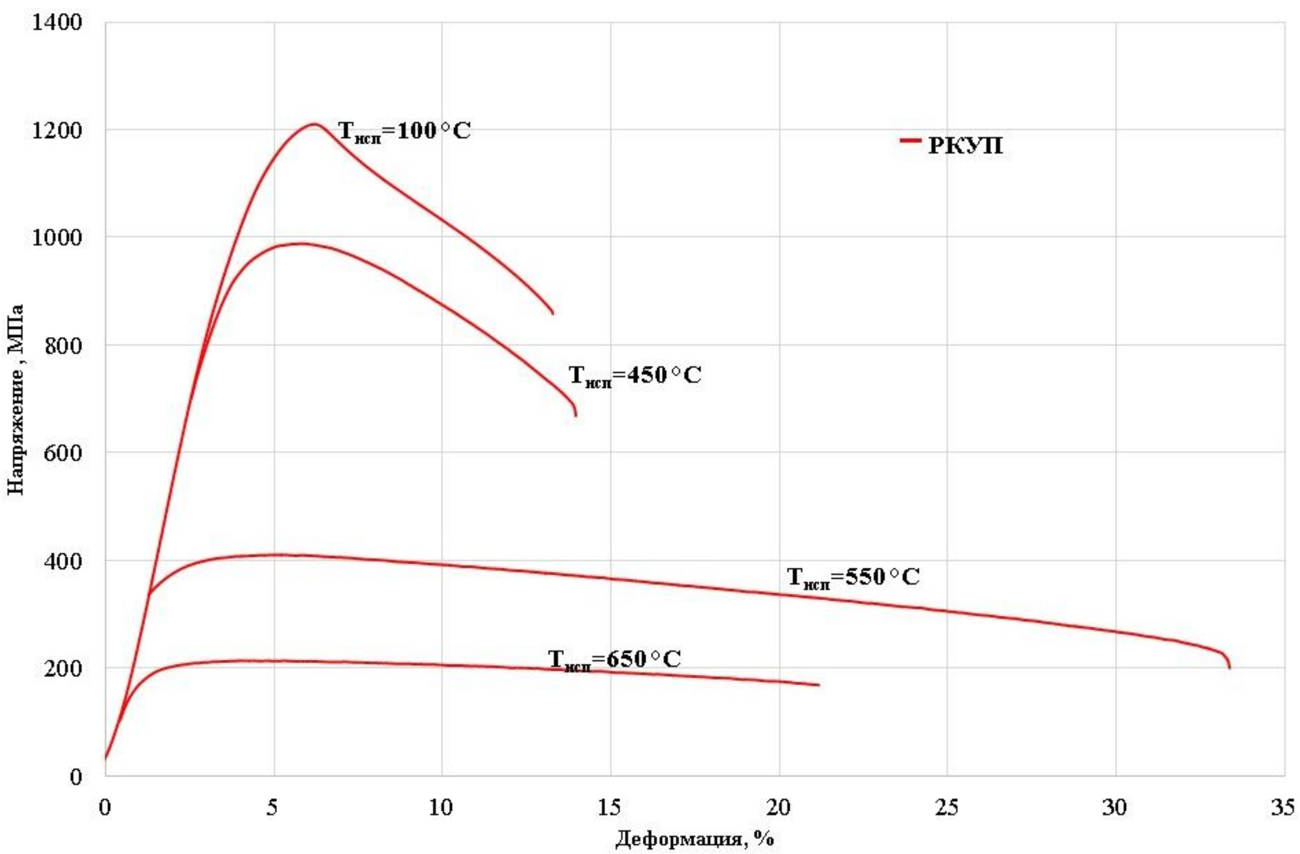


T_{irr}= 450 °C T_{irr}= 350 °C

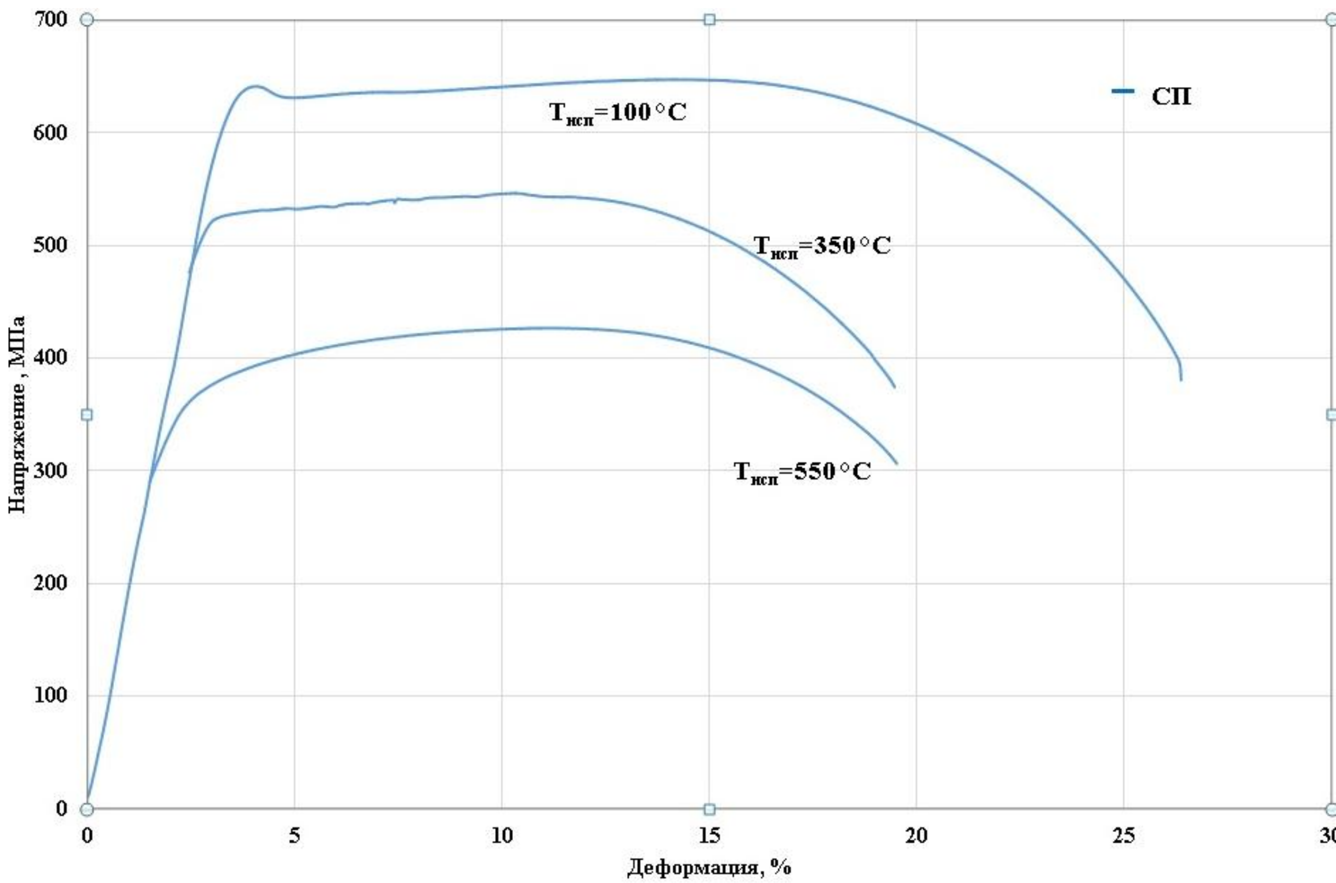
Fracture surface micro-pattern, Ttest = 500°C

Pit micro-pattern of the fractur surface of a sample irradiated at 450°C is characterized by a higher size of the pits than at 350° C

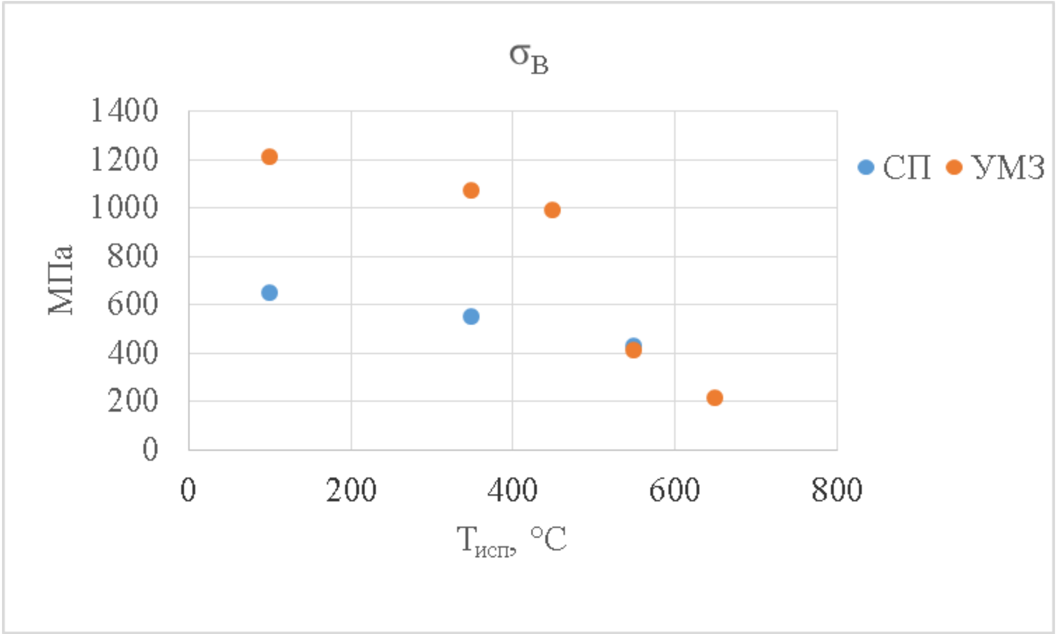
Reactor SM-3 (T_{irr}=100 °C). Tensile diagrams (0,1 mm/min)

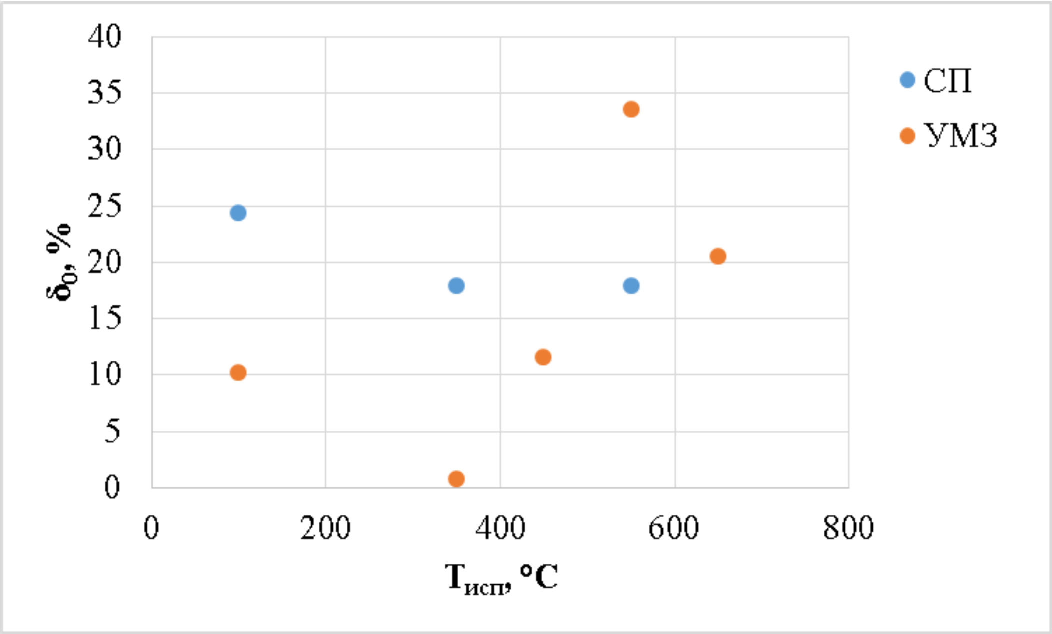


ECAP



as-received

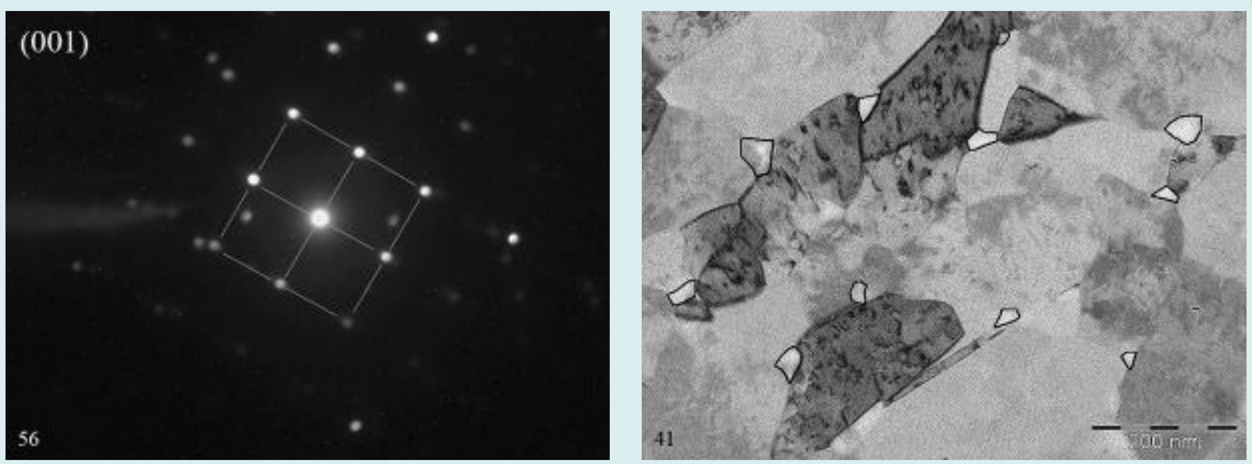




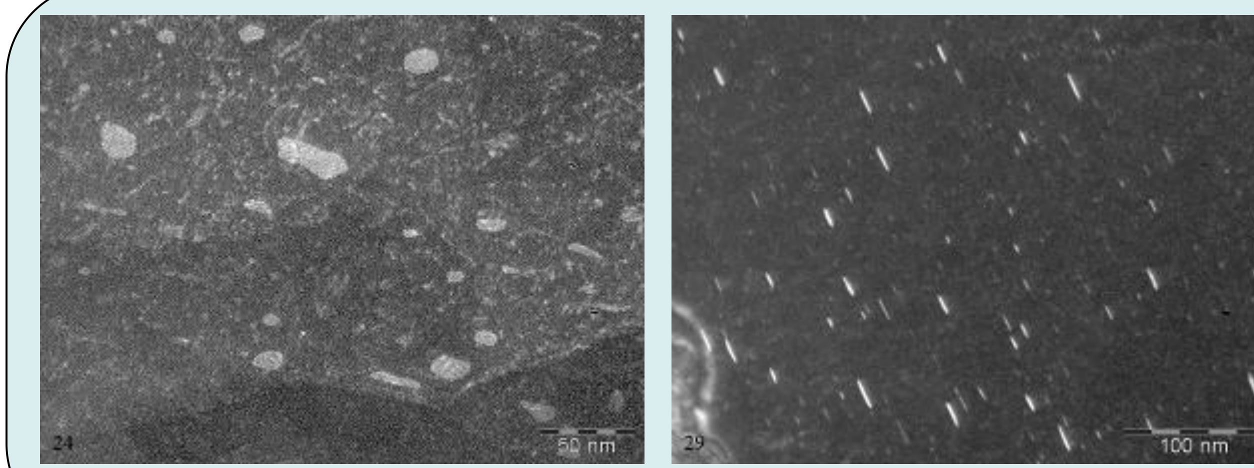
TEM

Table 2. Average diameter and concentration of Frank loops in irradiated samples.

Cross-section	Avg diameter, nm	Concentration, m^{-3}
As-received	10	$(3{,}3 \pm 0{,}8) \cdot 10^{22}$
ECAP long.	9	$(2{,}4 \pm 0{,}6) \cdot 10^{22}$
ECAP transv.	9	$(3{,}0 \pm 0{,}7) \cdot 10^{22}$



α-phase precipitates. Aphase particles are encircled in black.



Transv.

Frank loops UFG irradiated steel 08X18H10T
(T=350°C, ~12dpa)

Conclusions

1. **For the first time, an experiment was conducted on neutron irradiation of 08H18N10T steel samples in the UFG state (in comparison with steel in the coarse-grained state) in the BOR-60 reactor (350°C, 5, 12dpa and 450°C 15dpa) and SM-3 (up to 50dpa)**
2. **It is shown that a decrease in the grain size to 200-300 nm after ECAP leads to a significant increase in the strength characteristics and a decrease in the steel hardening at temperatures up to 600°C. At the same time, ductility (δo) remains at the level of 10–14%. At test temperatures starting from 600°C, the values of strength characteristics approach those of steels in a coarse-grained state.**
3. **Sensitivity of the UFG steel in the irradiated state vs. the strain rate is shown, which indicates an increase in the diffusion mechanism contribution to the strain process.**
4. **The effect of increased ductility was found in UFG steel compared to the coarse-grained state:**

- at 800°C and strain rate of 1 mm min in the unirradiated state;

- at 550°C and strain rate of 0.1 mm/min in the irradiated state.

Conclusions

5. Under all specified irradiation conditions, radiation hardening of the UFG steel is experimentally detected, the value of which depends on the temperature and test irradiation and remains at a test temperature of 650°C.

6. The concentration of dislocation loops in the UFG irradiated steel 08X18H10T (350°C, 12dpa) is from 2 to 3 times less than in the coarse-grained state. The formation of alpha-iron nanoparticles (no larger than 50 nm in size) is noted in the UFG steel at grains triple junctions.
7. The obtained results show the need to continue integrated PIEs of UFG materials to justify their use in reactor construction.

Thank you for attention!