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Materials resistant to extreme temperature and pressure for future hydrogen and steam turbines, modern 2- and 4-pole NPP turbogenerators

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Contents of presentation

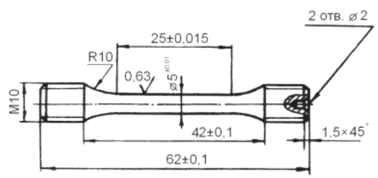
GIGATOR 4 is the most efficient 4–pole turbogenerator "Alstom" for the nuclear market, making it a solid long-term investment.

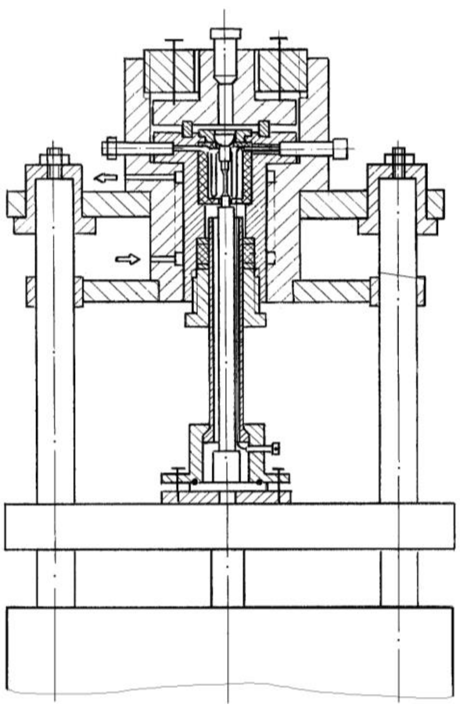
- GIGATOR 4-pole, the turbogenerator behind Alstom's proprietary ARABELLE™ steam turbine, sets the benchmark for reliability and efficiency. Covering an output range from 900 MW to 2,000 MW, in both 50 and 60 Hz markets, the world largest turbogenerators in operation today are GIGATOR 4-pole with a power output of 1,550 MW.
- Alstom is the world's most experienced turbogeneratoe supplier for nuclear application, with worldwide long operational experience. About one third of the world's nuclear fleet are today equipped with Alstom turbogenerators. Recent orders include Flamanville 3 in France, Ling and Hong Yan He in China as well as orders from UniStar in the USA.

Time in Hydrogen During Long Term Service

- The fiftieth percentile for the inspected population falls within the age group (11-15) years.
- That is, there is some point within this age group such that 50% of the inspected units were older and 50% of the inspected units were younger. Therefore, if age were a strong factor, it is expected that class 3 recommendations should fall below the norm for age groups **(0 – 5) years** and **(6 – 10) years**, fall on the norm in the age group (11 – 15) years, and rise above the norm in the age groups (16 – 20) years, (21 – 25) years and (**26 – 30) years**.
- Furthermore, the age group (0 – 5) years should be mostly class 1 and the age group (26 – 30) should be mostly class 3.

Tensile test in hydrogen of extreme temperature (1000 K) and pressure (100 MPa)

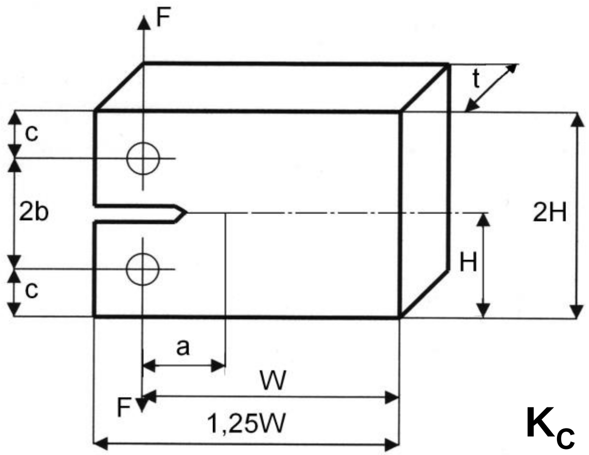




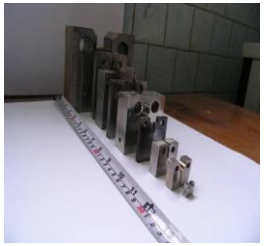
$$\beta_{\psi} = \frac{\psi_{H}}{\psi_{He}}$$

$$\beta_{\sigma_B} = \frac{\sigma_{B(H)}}{\sigma_{B(He)}}$$

Crack propagation test in hydrogen



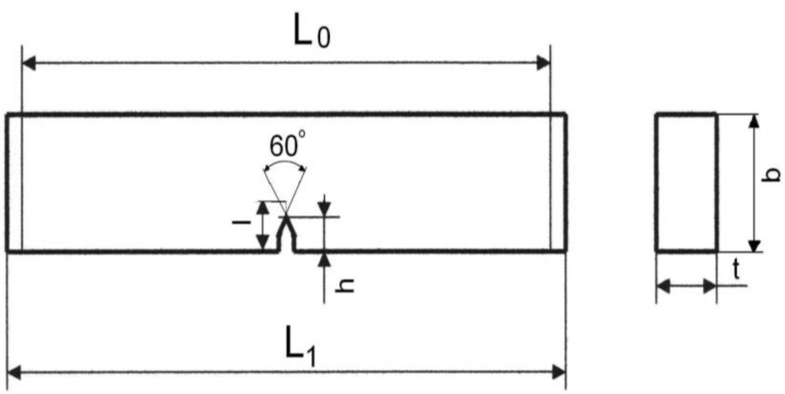
t, mm	4,5	10	13	20	25	25	50
c, mm	2,925	6,5	8,45	13	16,25	16,25	22,5
2b,mm	4,95	11	14,3	22	27,5	38,5	55
2H,mm	10,8	24	31,2	48	60	60	120
W,mm	9	20	26	40	50	70	100



$$K_C = P\times(2w + l)\times Y(H/w, C/H, l/w)/t\times(w - l)^{3/2} \quad (1)$$

$t, W\text{-}a, a \geq 2{,}5\,(K_C^H/\sigma_{0,2}^H)^2$ (2) $0{,}45W \leq a \leq 0{,}55W$ (3)

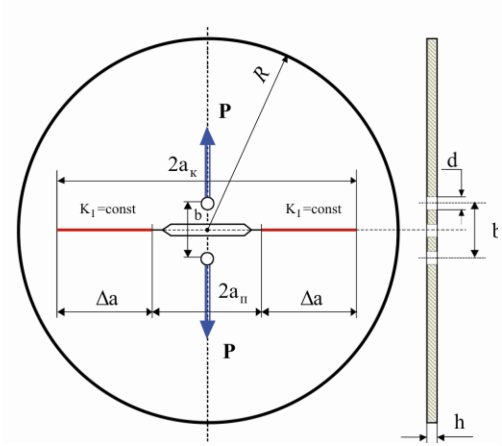
Bulk

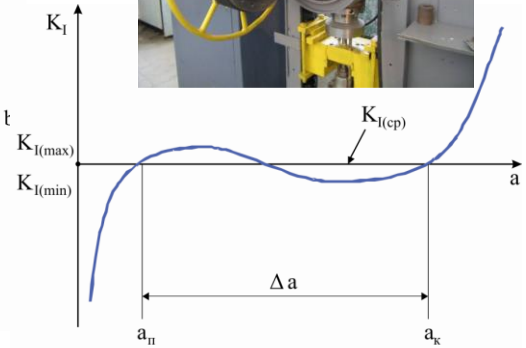


$L_0 \times b \times t = 160 \times 40 \times 20$ mm

$K_Q = P_Q L Y(\varepsilon)/(tb^{3/2})$
$Y(\varepsilon) = 3{,}494(1-3{,}396\varepsilon+5{,}839\varepsilon^2)$
$0{,}4b \leq l \leq 0{,}55b$ (4)

Disc

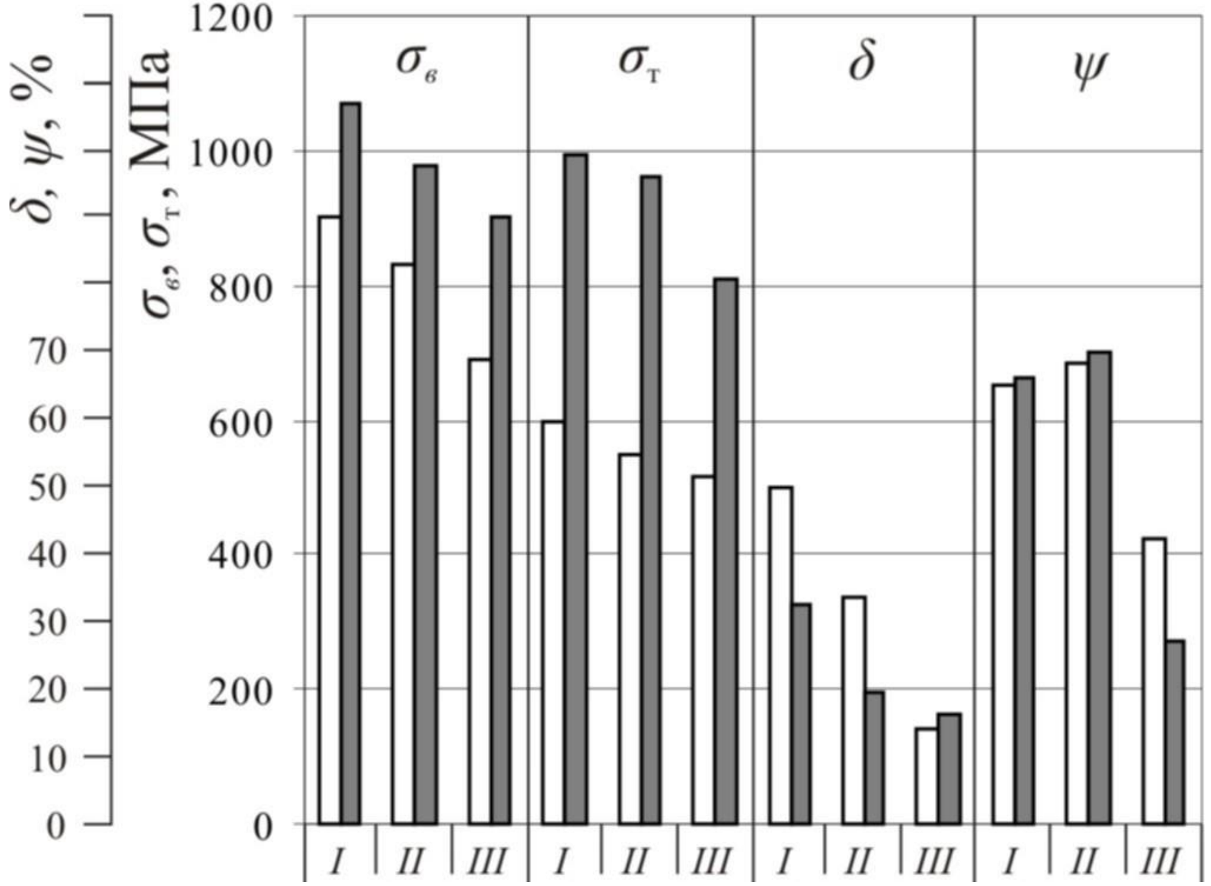




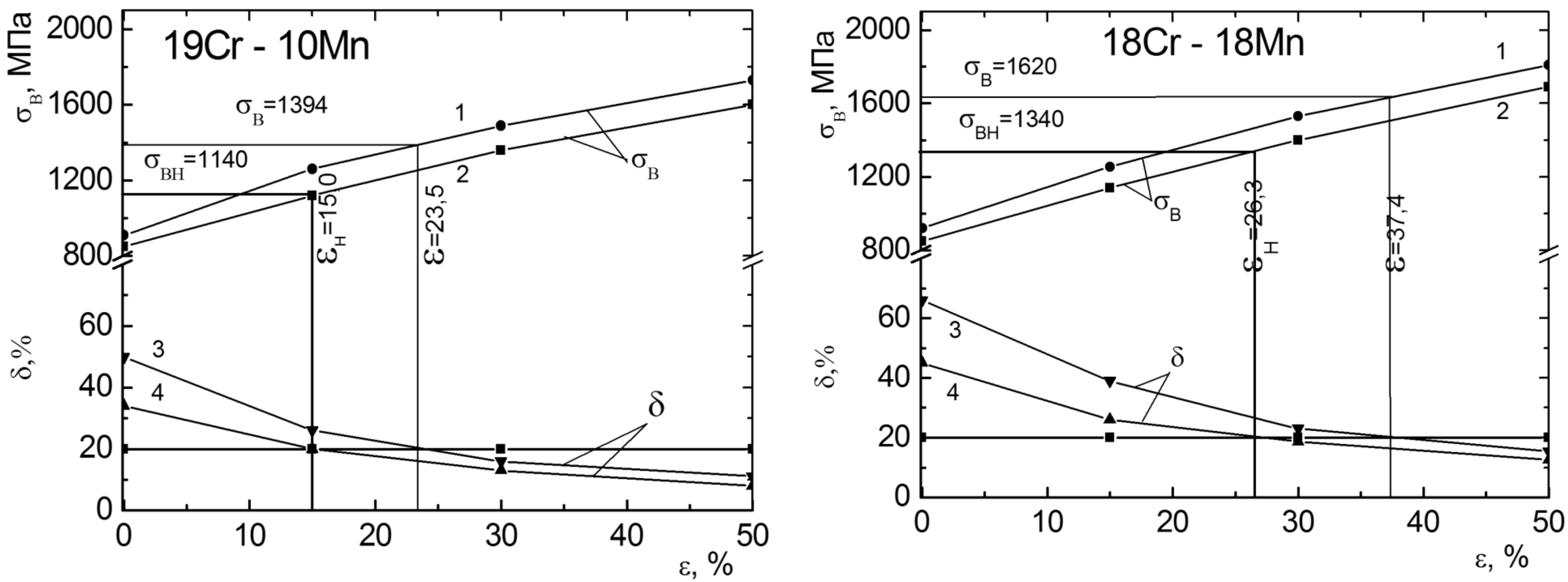
$$K_I = 0{,}417\cdot\frac{P}{h};\ МПа\cdot\sqrt{м},\ a_n \leq a \leq a_k \quad (5)$$

Physical and mechanical characteristics of steels for retaining rings units of turbogenerator in air (*A*) and in gaseous hydrogen (*H*)

Steel	*E* (Young modulus), GPa	σ_T , MPa	σ_B , MPa	δ ,%	Ψ ,%	K_{1c}, MPa√m
8Mn–8Ni–4Cr-0,1N	189 (*A*) 185 (*H*)	1157 (*A*) 1002 (*H*)	925 (*A*) 800 (*H*)	30 (*A*) 22 (*H*)	60 (*A*) 55 (*H*)	200 (*A*) 160 (*H*)
18Mn–18Cr-0,56 N	200 (*A*) 197 (*H*)	1197 (*A*) 1152 (*H*)	1136 (*A*) 1121 (*H*)	29 (A) 21(*H*)	64 (*A*) 60 (*H*)	268 (*A*) 224 (*H*)

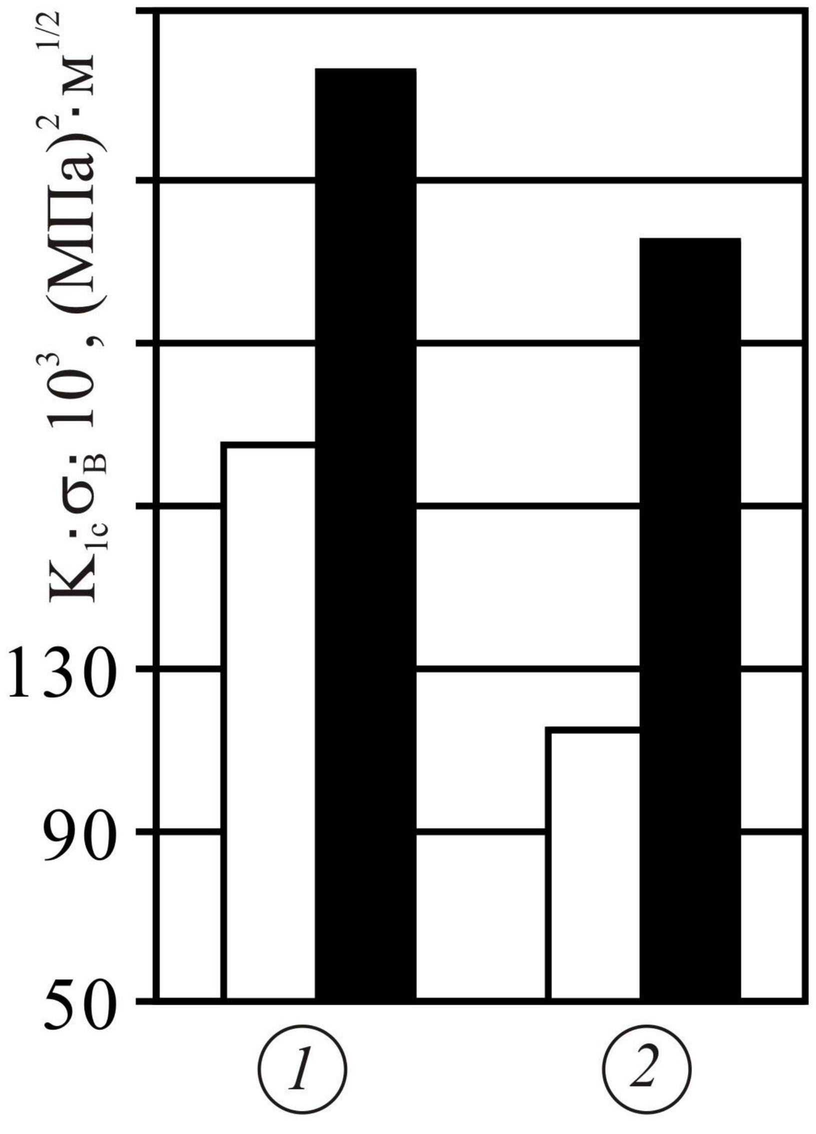


Changing of mechanical characteristics of 18Mn-18Cr-0,56N steel (dark column) and 19Cr-10Mn-0,5N steel (light column) during the (rapture test) on air (*I*), in gaseous hydrogen (*II*) after hydrogen saturation (*III*) has shown the better hydrogen resistance of steels with higher content of NITROGEN

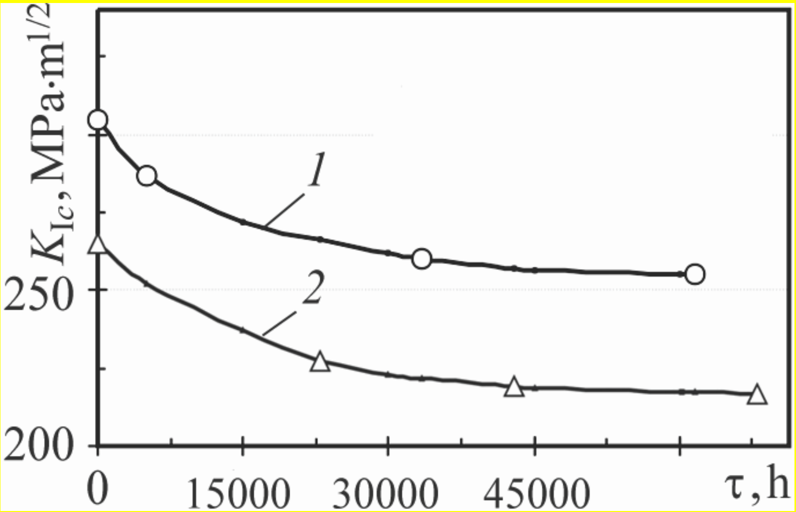


(*a*) (*b*)

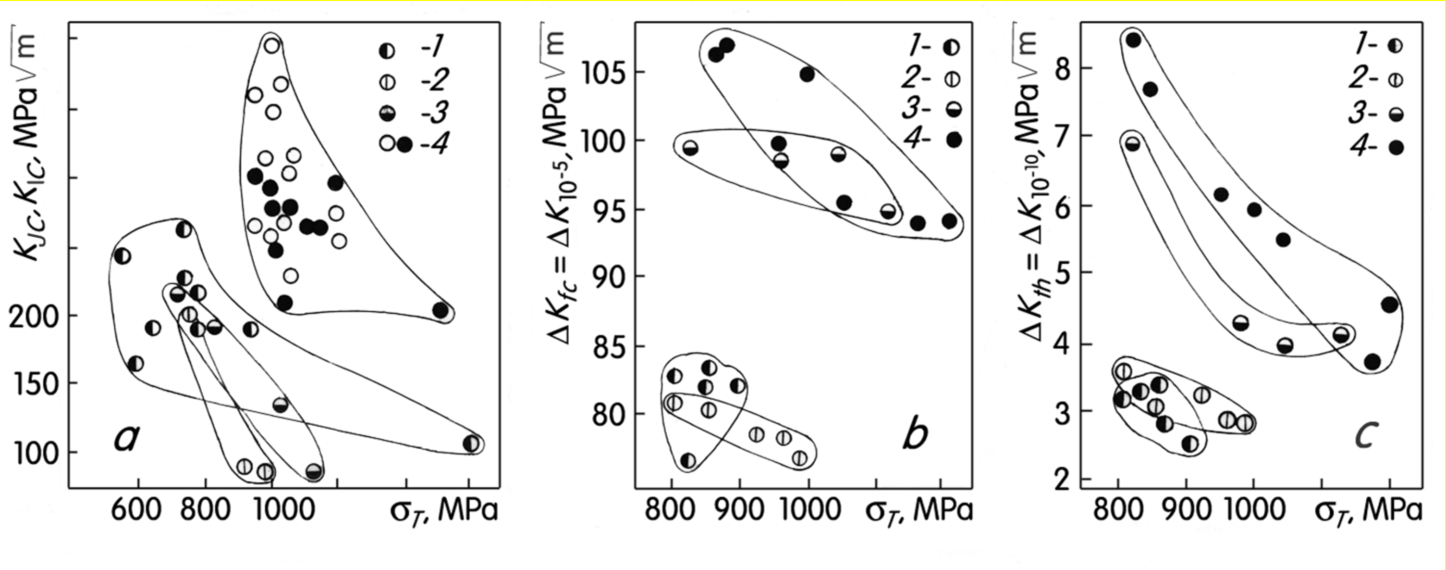
Influence of cold working level of 19Cr-10Mn (*a*) and 18Mn-18Cr (*b*) steel on strength and plasticity in gaseous hydrogen under pressure 0,5 MPa has shown the higher parameters of strengthening (for obtaining δ>20% level of strengthening is 37,4 % (26,3% - H) 23,5% (15,0% - H)



Influence of hydrogen with temperature up to 80 ºC during 68 thousand of hours on multiplication of strength on fracture toughness 18Mn-18Cr (dark column) and 19Cr-10Mn steels (light column):
1 – air; *2* – hydrogen



Fracture toughness K_{Ic} values for steel 12Х18АГ16Ш versus time of steel operation in gaseous hydrogen at 80°C: 1 – σ_U= 950 MPa: 2 – σ_U= 1150 MPa.



Diagrams for assessment of hydrogen effect on the fracture mechanics parameters of steels used for generators:

a – tests in air (○ – K_{JC}, ● – K_{IC});

b – tests under electrolytic charging of hydrogen at current density 100 A/m$^{2;}$;

c – tests under electrolytic charging of hydrogen at current density 100 A/m$^{2;}$;

1 – steel 38ХН3МФА);

2 – retaining ring steel 60Х3Г8Н8В (8Mn8Ni4Cr);

3 – steel 55Х4Г18;

4 – steel 12Х18АГ18.

There is a strong dependence of fracture mechanics parameters on the values of yield stress of steels used for generators. The assessment of hydrogen effect on these parameters with comparisson with air can be made from the following (presented upper) diagrams

Here: is a fracture toughness defined under static loading by standard method; is a static fracture toughness defined on a base of J-integral; is a cyclic fracture toughness defined from a diagram of fatigue crack growth; is a range of threshold stress intensity factor, which can be also defined from fatigue crack growth diagram.

Methods of workability assessment of materials with cracks

1. Very important are the data about changing fracture toughness and other characteristics of material in the conditions of hydrogen containing environments action. Experimental investigation, which has performed in Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine deals with the study of change of such physical-mechanical characteristics as E (Young modulus), δ, ψ (macro deformations) .

2. Take in to account, that in some cases materials embrittlement after long-term service (30–40 years) leads to the cracks appearance with size less, than predicted theoretically

CONCLUSIONS 1

1. It is shown, that using of nitrogen content filler material and nitrogen content protective atmosphere allows in 1.5 times to decrease the losses nitrogen's concentration in weld metal comparatively with welding of high nitrogen steels obtained by standard welding procedure (in the last case concentration of nitrogen in the weld metal decreases in 3 times comparable to base metal). It allows to save the sufficient level of his concentration in weld metal (0,32%) and provide the necessary level of strength.

2. High nitrogen steels of types 18Mn–18Cr and 19Cr–10Mn and their welded joints are sensitive to act both atmosphere of gaseous hydrogen and preliminary electrolytic hydrogenation. In such circumstances characteristics of strength (σ_B) decreases up to 20 per cent, characteristics of plastic (δ) up to 45 per cent.

3. At elevated temperatures hydrogen affects differently the mechanical characteristics of austenitic steels at 450...600 K by its durability, plasticity, critical values of static and fatigue crack growth resistance has an advantage over the austenitic hardened steel.

4. As a result of intensive temperature softening it is inferior to austenitic one by temporal resistance and yield strength. By the threshold parameter, ΔK_{th}, austenitic steel is more resistant. At room temperature low-cycle durability is the most sensitive to hydrogen effect, at 673 K parameter K_{fc} of maraging steel decreases.

5.The 18Mn–18Cr steel exceeds 19Cr–10Mn steel in 1.8 – 2.7 times after held in medium gaseous hydrogen with indication of $K_{1c} \cdot \sigma_u$.

6. The normative values of critical length of crack for retaining rings of turbogenerations ТГВ-200 with 18Mn–18Cr steel must be reduce on 25-30 per cent because it is necessary to take into consideration influence of technological hydrogen medium (for retaining rings of turbogeneration rotor's of series ТГВ-200, -500,- 1000 critical length of crack $a_{кр}$ must reduce with 25,0 mm up to 18,75 – 17,5 mm).

Last resaltshas issued from

- **Sandia National Laboratories**, Livermore, USA,
- Materials Testing Institute **University of Stuttgart**, Germany,
- Department of Materials Physics, **University of Science and Technology Beijing**, China,
- **Kyushu University**, Fukuoka, Japan

Permit us to conclude:

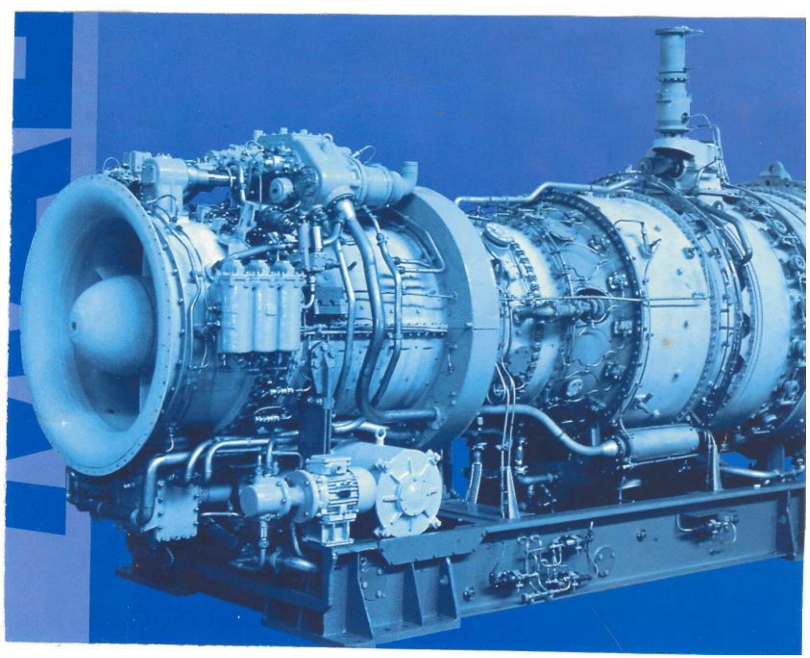
For structure and hydrogen concentration, which absorbed after long term service in hydrogen or hydrogen containing gas structural material has been alloyed by hydroged.

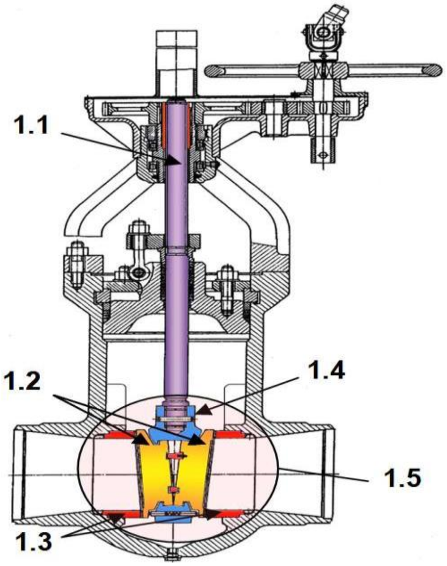
1. **ferritic, pearlitic, ferritic - pearlitic** steels: 2…5 ppm;
2. **ferritic - bainitic, bainitic – martensitic** steels: (5…7,5 ppm);
3. **martensitic** steels (1,5Ni;0,5Mo;2W), (2Ni;2Mo;1W), (9,5Ni;0,5W) with residual austenite after optimal heat treatment near 10%; (6…15 ppm);
4. **non stable austenitic steels type 12Cr18Ni**, cold working accompained by $\gamma \rightarrow \alpha$ transaction (for hydrogen pipes and tanks);
5. **stable high nitrogen steels P-900** (7…20 ppm) (for retaining rings); d
6. **dispersive hardened** steels (23Ni;1,5Mo;3Ti), (27Ni;1,5Mo;2W) (8…25 ppm);
7. **Ni-Cr-Fe alloys** (Ni55Cr19Fe12Mo9Nb2) (for distributive face of combustion chamber of gas turbine), (63Ni;6Mo;3Ti), (Ni56Mo6Nb4), (Ni42Fe36Cr14Nb3Mo2) (for inlet gas turbine nozzle),
8. **Ni-Co alloys** (Ni56Co15Cr9W6Al5Mo4, Ni64Cr14Co10Mo5Al3Ti3 (for gas turbine rotor disks and blades), which strengthenid by γ’ (Ni)3(Al,Ti) (stable up to 1100 ºC), γ”(Ni)3(Nb) (stable up to 1300 ºC) phases (8…30 ppm)

Distributive Face of Combustion Chamber of Gas Turbine

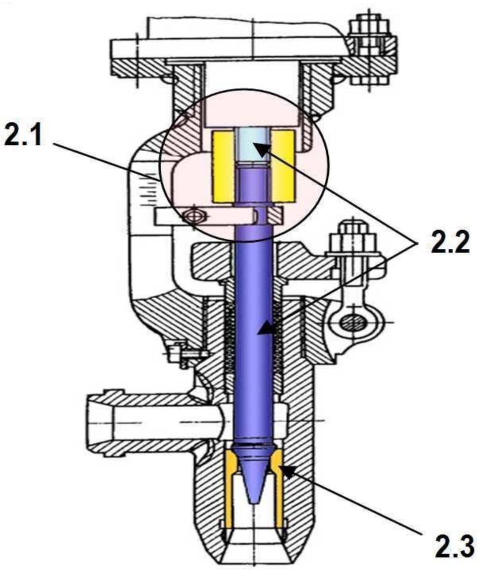
Inlet Gas Turbine Nozzle

Gas Turbine Rotor Disks and Blades

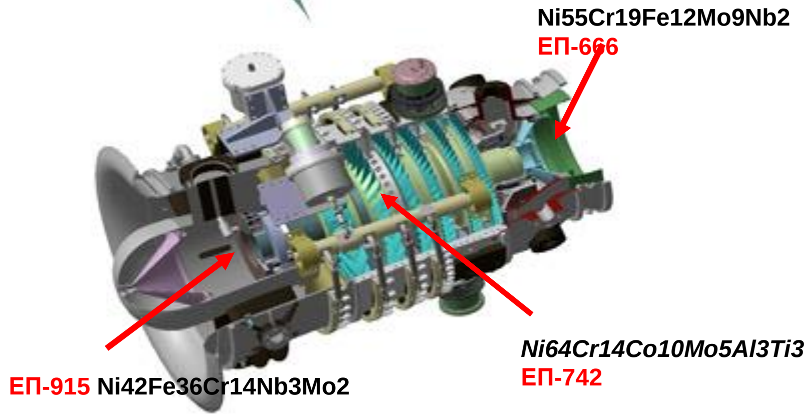




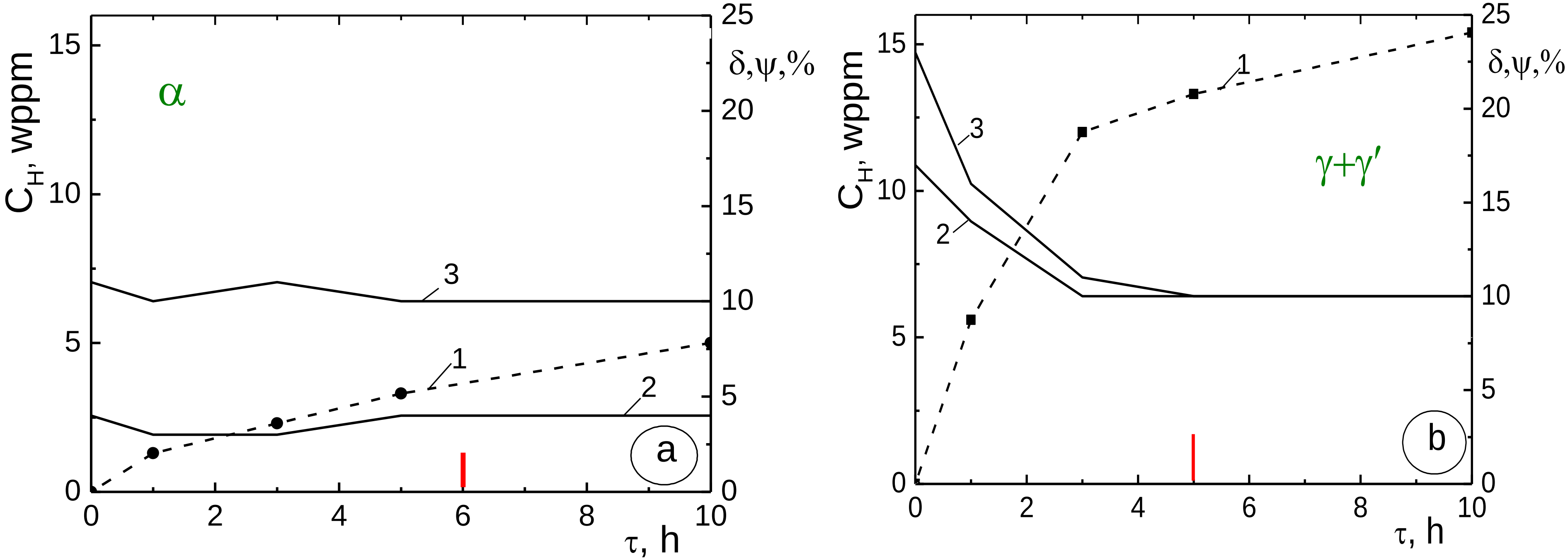
Flap: 1.1 – spindle;
1.2 – disks; 1.4 – cage



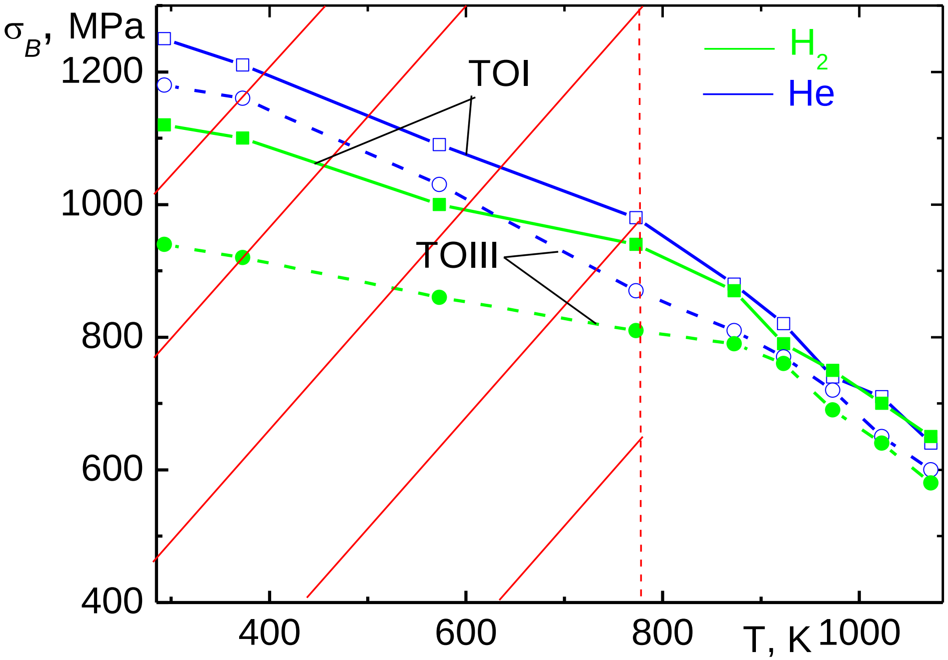
Injection valve:
2.1, 2.2 – stem, needle;
2.3 – seat


Ni55Cr19Fe12Mo9Nb2
ЕП-666
Ni64Cr14Co10Mo5Al3Ti3
ЕП-742
ЕП-915 Ni42Fe36Cr14Nb3Mo2

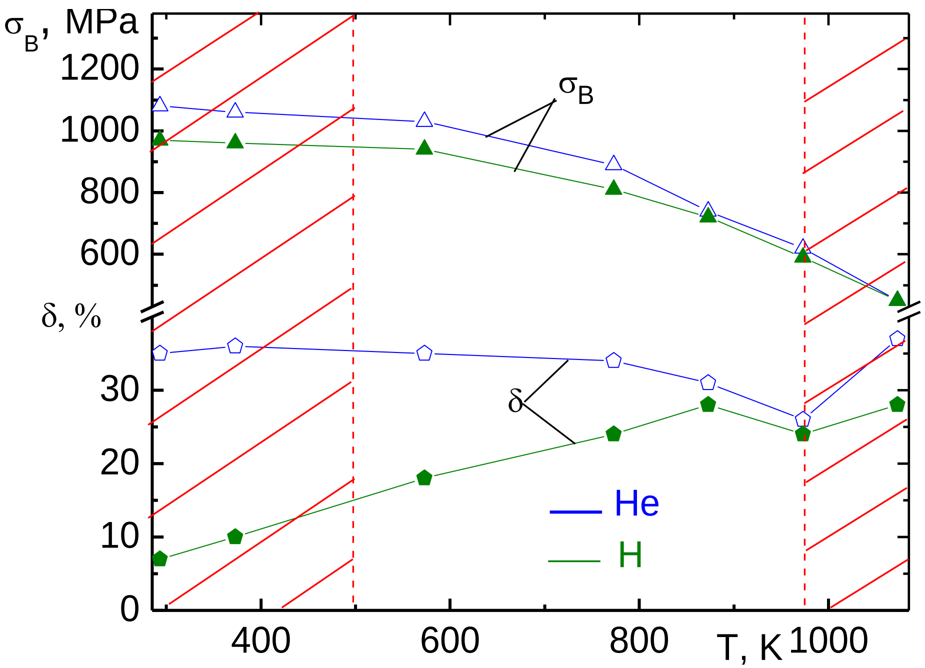
Сн (1), δ (2), ψ (3) ЕП-517 (a) ЕП-700 (b) 35 MPa Т = 293 К (Vdef. = 6,7×10-5 с-1) (623 К, 35 MPa H2).



ЕП-666(59 Ni,9Mo,2Nb) He (Δ, o) H_2 (●,▲)



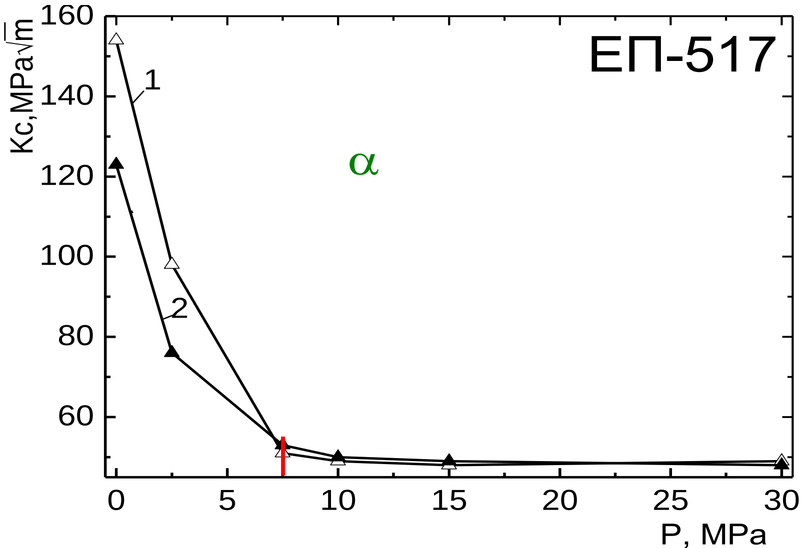
ЕП-915

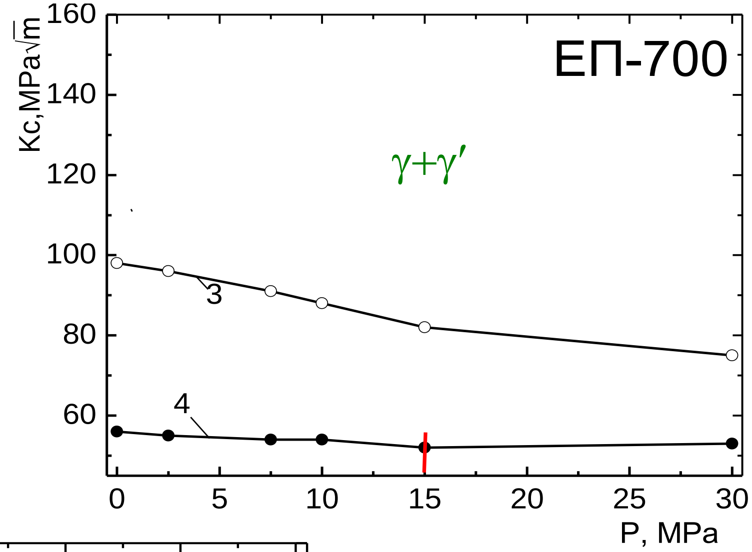


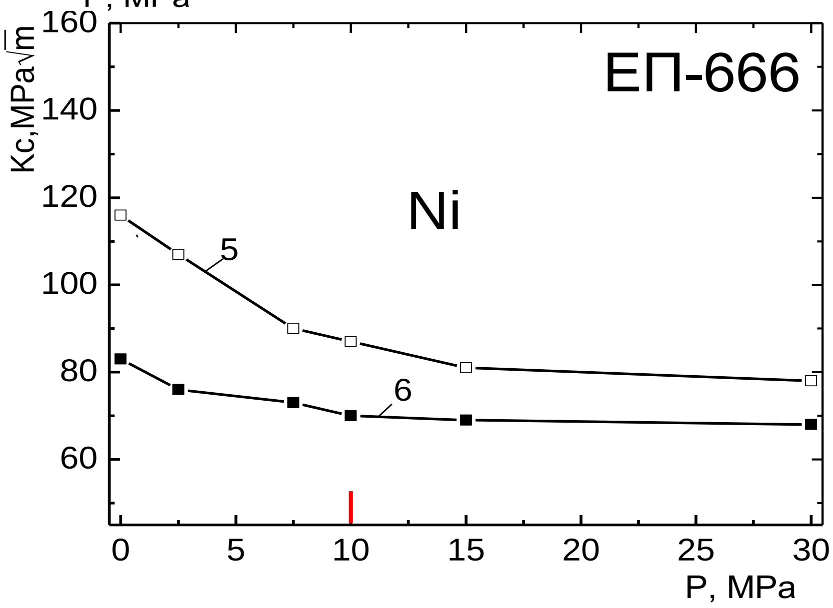
ЕП-666

ЕП-915 (42Ni,3Nb,2Mo) (623 К, 35 MPa,10 h.), (V = 0,1 mm/min).

Dependance of Kc ЕП-517 (1, 2) i ЕП-700 (3, 4), ЕП-666 (5, 6) of Hydrogen Pressure P at 293 K: 1, 3, 5 – initial state; 2, 4, 6 – after Hydrogenation.







CONCLUSIONS II

In the temperature interval 293…1073 K in vacuum and hydrogen under the pressure 35 MPa it has been investigated the mechanical properties of Ni63Cr18Fe9Mo6Ti3 alloy in cast and powder state. **It has been established that under the hydrogen influence more decreased the characteristics of plasticity and fracture toughness of cast materials, maximum decreasing of reduction in area in hydrogen at 773 K achieved 90% in comparison with value in vacuum.** Minimal sensitivity do hydrogen embrittlement of powder modification of alloy – due to more homogeneity of deformation properties characteristics distribution.

The parameters of loading and the modes of hydrogen action for which the mechanical characteristics of the investigated alloys are minimum at room temperature can be formulated as follows: strain rate Vdef ≤ 6.7·10-5 s-1 for tensile test and the strain amplitude ε = 1.6% under the conditions of low-cycle fatigue af hydrogen pressures above 10 MPa for the alloy 04Cr16Ni56 and hydrogen pressures above 15 MPa at concentration of preabsorbed hydrogen 19 wppm for the alloy 05Cr19Ni55; **for static crack propagation at hydrogen pressure above 10 MPa for the alloy 04Cr16Ni56 and hydrogen pressure above 15 MPa at concentration of absorbed hydrogen 19 wppm for the alloy 05Cr19Ni55.**

The plane-strain conditions required for the evaluation of KIc were fulfilled on compact tension specimens made of alloy 04Cr16Ni56 with thickness of 20 mm at hydrogen pressure above 10 MPa in the temperature range 293…473 K. **For all loading modes, the degree and temperature interval of hydrogen degradation for 04Cr16Ni56 alloy is much larger than for 05Cr19Ni55 alloy.**

Thank you very much for your attention