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MODERN DESTRUCTIVE AND NON-DESTRUCTIVE METHODS FOR EVALUATION OF IN-SERVICE DEGRADATION OF STRUCTURAL STEELS OPERATED IN AGGRESSIVE ENVIRONMENTS

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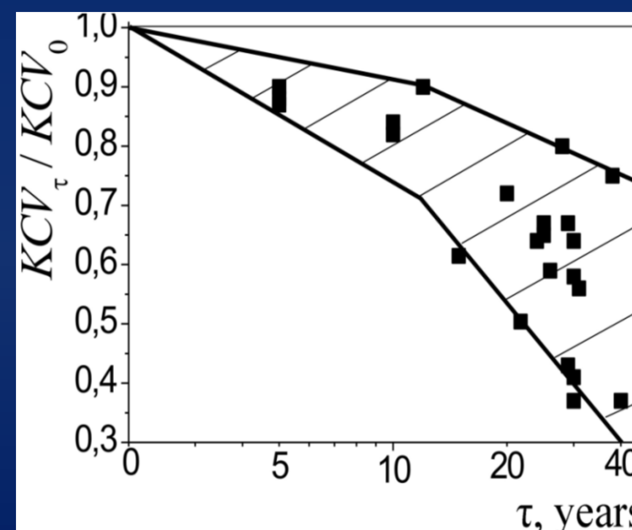
Overview

1. Introduction
2. The role of hydrogen in “in-bulk” steel degradation
3. Principal stages of in-bulk material degradation
4. Destructive methods for evaluation of in-service degradation of structural steels
5. Non-destructive electrochemical method for evaluation of in-service degradation of structural steels
6. Concluding remarks

1. Introduction

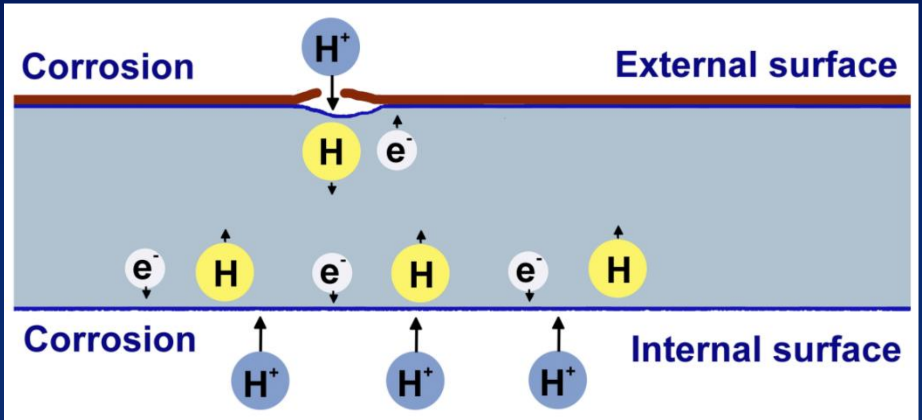
Gas transmission pipeline “Urengoy–Pomary–Uzhgorod” accident

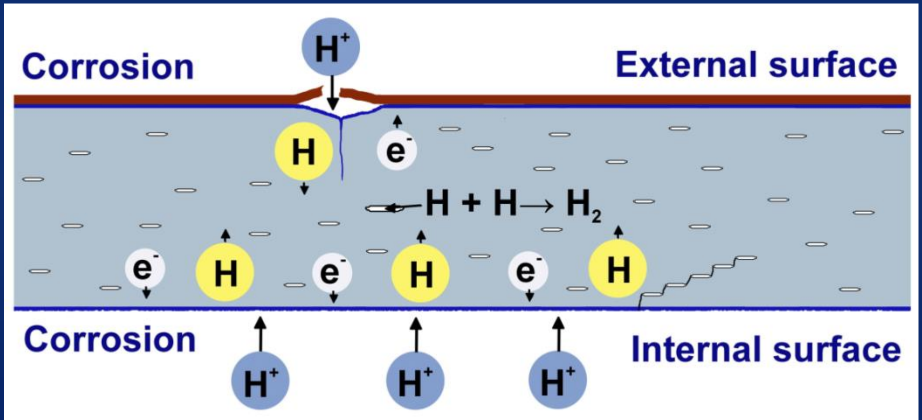


Mechanical properties degradation of gas pipeline steels under operation

2. The role of hydrogen in in-bulk steel degradation

Hydrogenation and damage accumulation of pipeline steels during their long-term service



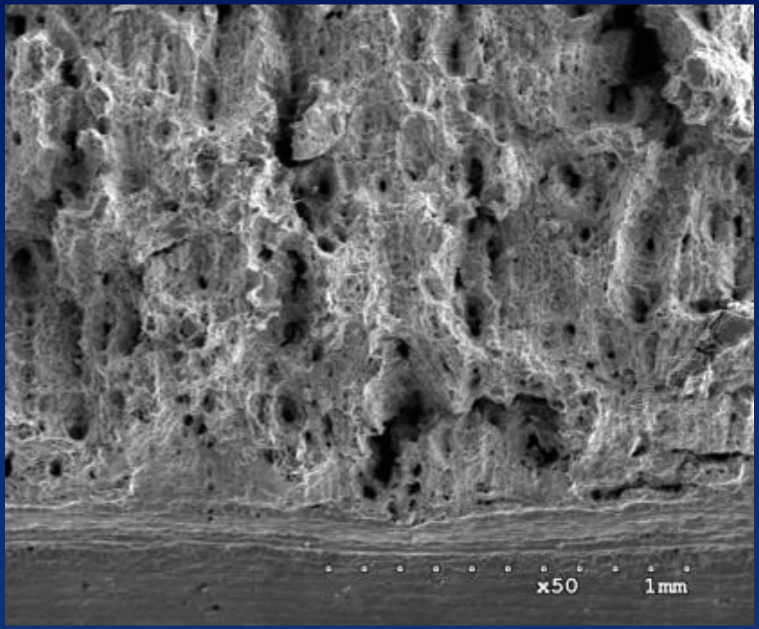


Damage accumulation

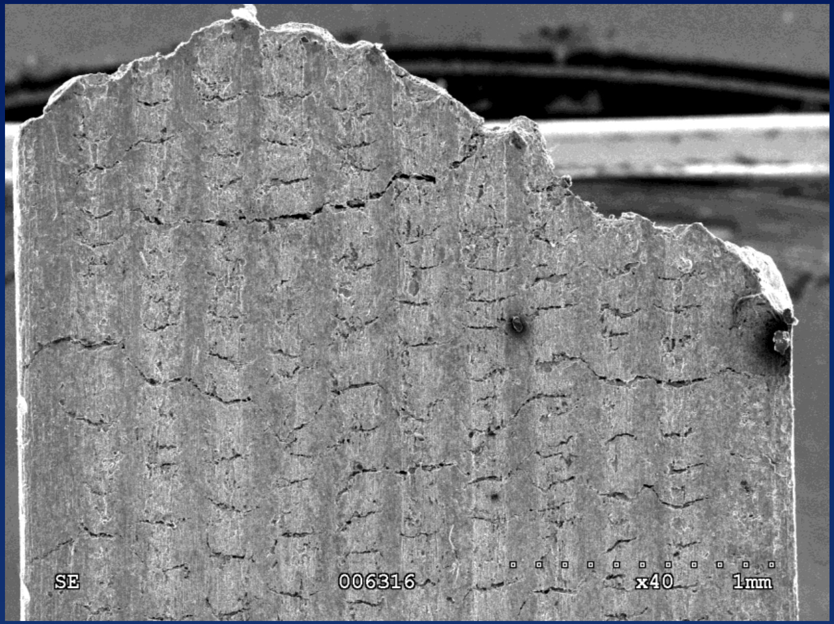
In-bulk material degradation is caused by mutual effect of stresses and hydrogen

2. The role of hydrogen in in-bulk steel degradation

Revealing of damage accumulation by mechanical loading

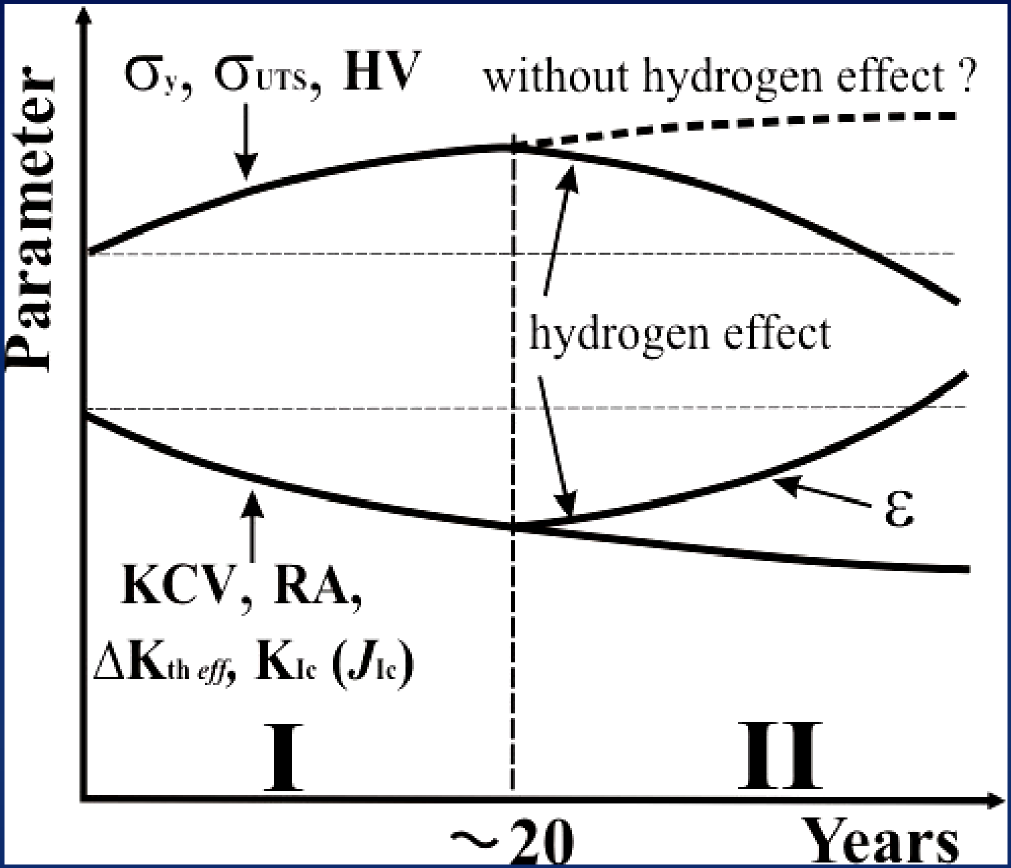


After Charpy impact test



After tension test

3. Principal stages of in-bulk material degradation



Deformation aging

Damage accumulation

4. Destructive methods for evaluation of in-service degradation of structural steels

Objects and materials:

Low-alloyed pipeline steels in the as-received state and after operation:

A) X52 low-alloyed steel in the as-received state (code X52) and after 30 years of operation from different pipes (t = 10 mm – X52-10; t = 12 mm – X52-12);
B) 17H1S low-alloyed steel (equivalent to X52) after 29-40 years of service;
C) Low carbon 0.20 C steel of pipe elbows of gas transportation system after 40 years of operation;
D) 10HS low-alloyed steel of oil pipeline after 28 years of service
E) Low carbon 0.10 C steel of oil storage tank after 30 years of service.

Methods:

1. Mechanical tests
2. SCC tests

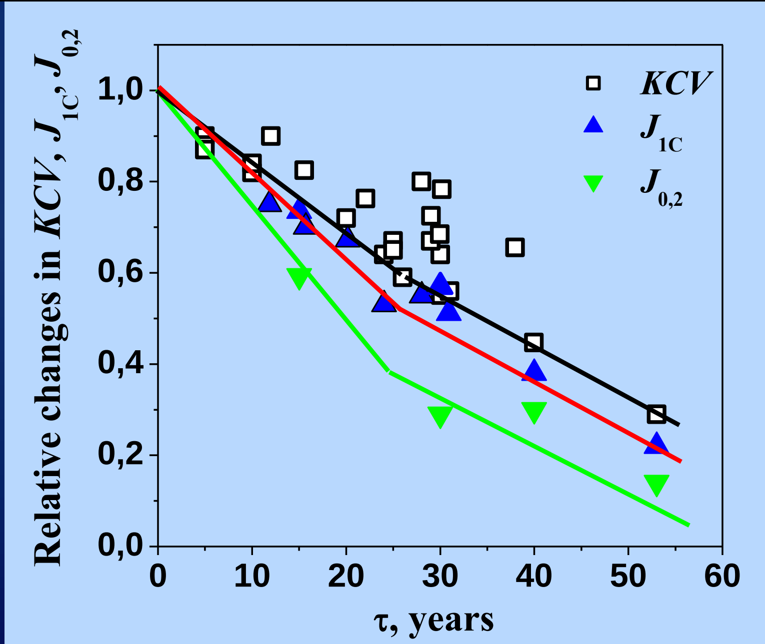
Oil and gas pipelines

Pipe elbows of gas transportation system

4. Destructive methods for evaluation of in-service degradation of structural steels

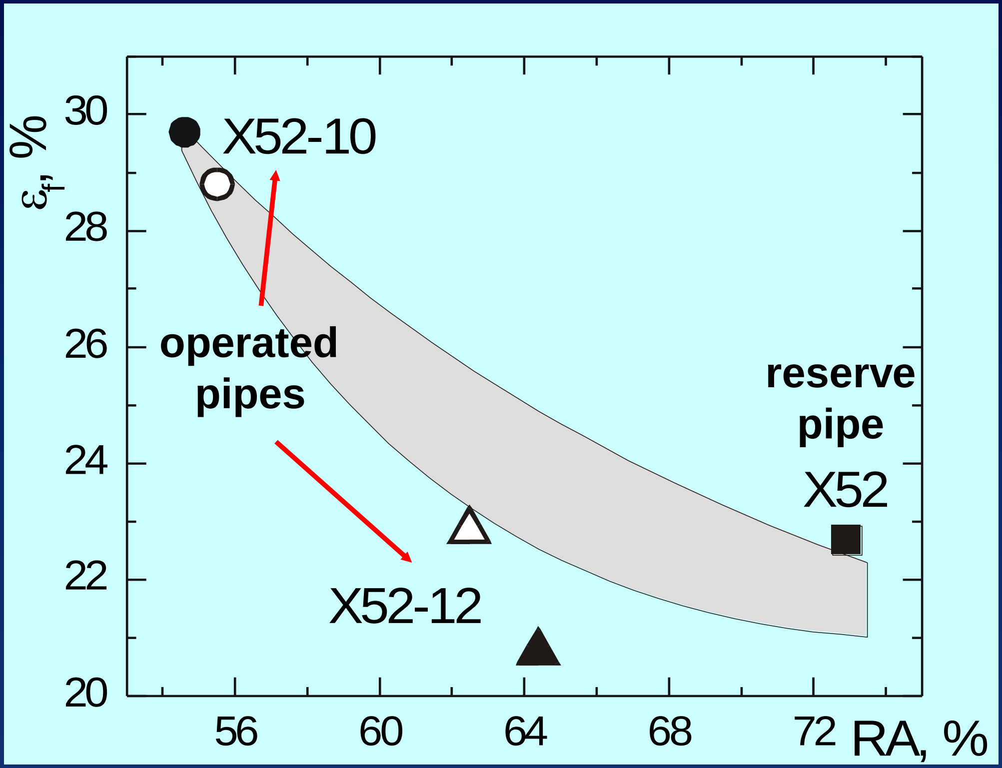
In-service degradation of gas transmission pipelines steels

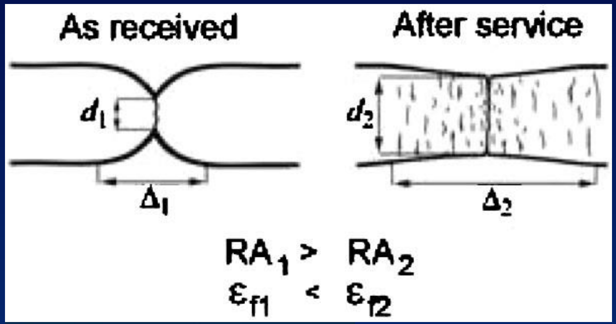
Steel	State	σ_y, MPa	σ_{UTS}, MPa	RA, %	ε, %	KCV, J/cm²	J_{IC}, MPa·√m
17H1S	As-received	378	595	79.0	20.2	200	322
17H1S	Operated 29 years	345	547	71.0	19.6	138	175
17H1S	Operated 40 years	302	515	69.0	26.3	125	-
X52	As-received	355	475	72,9	22.7	350	412
X52-12	Operated 30 years	261	455	63.4	21.9	186	127
X52-10	Operated 30 years	349	537	54.8	29.3	142	79

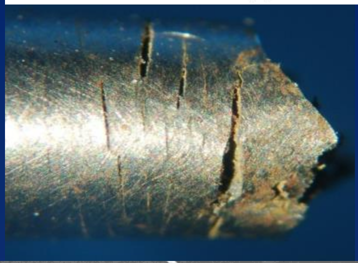


Relative changes in mechanical characteristics of 17HS, 17H1S, X52 and X60 low-alloyed pipeline steels, caused by in-service degradation

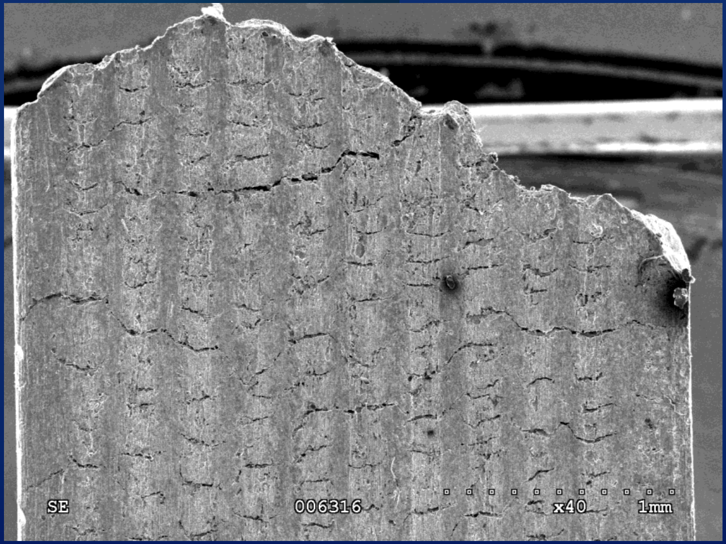
4. Destructive methods for evaluation of in-service degradation of structural steels







Dissipated damaging

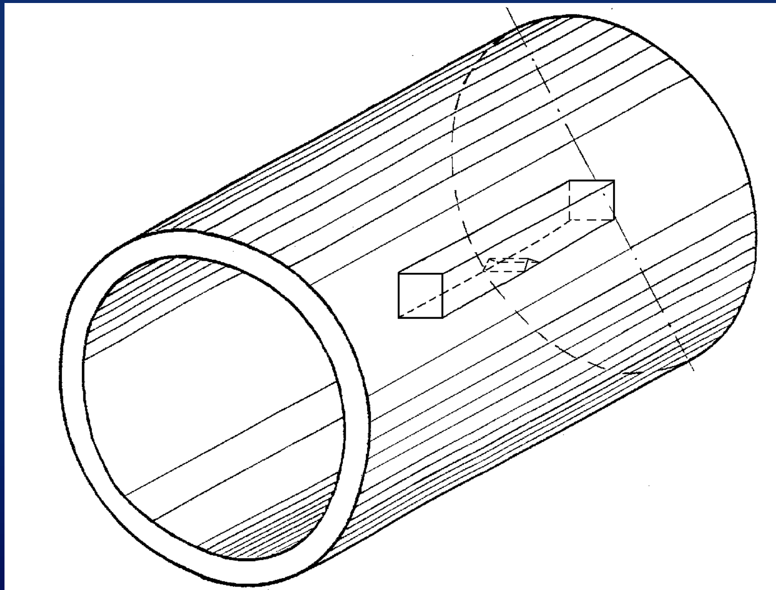


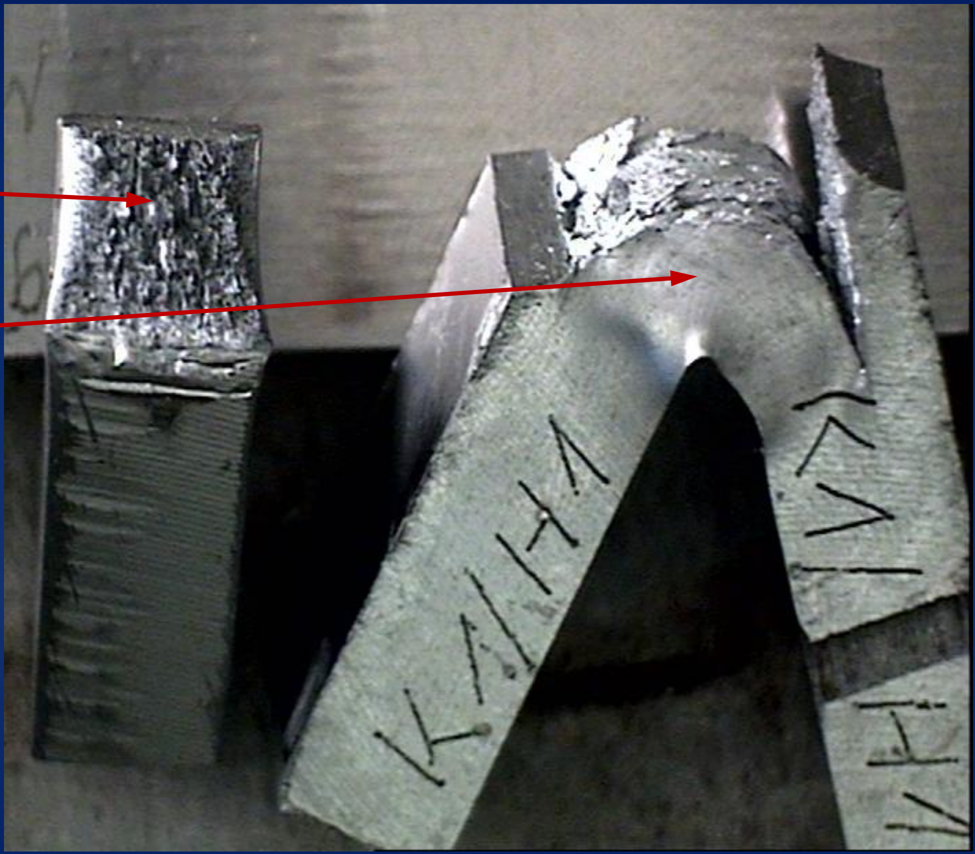
Opening of in-bulk multiple microcracks in the operated steel

4. Destructive methods for evaluation of in-service degradation of structural steels

10HS steel of oil transit pipeline after 28 years of service

State	*KCV*, J/cm^2
As-received	180
Operated, top section	95
Operated, bottom section	??

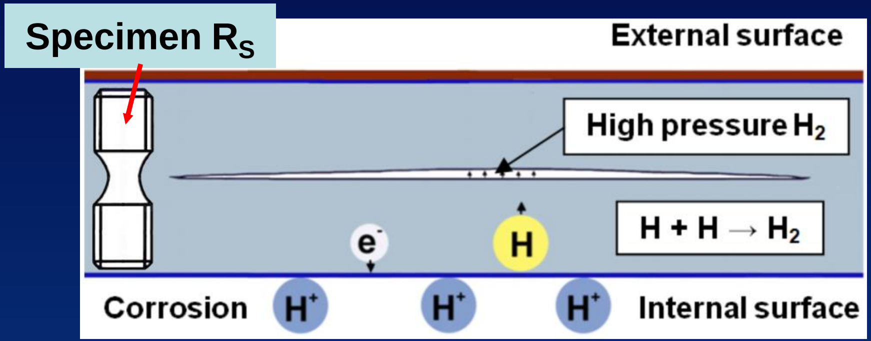




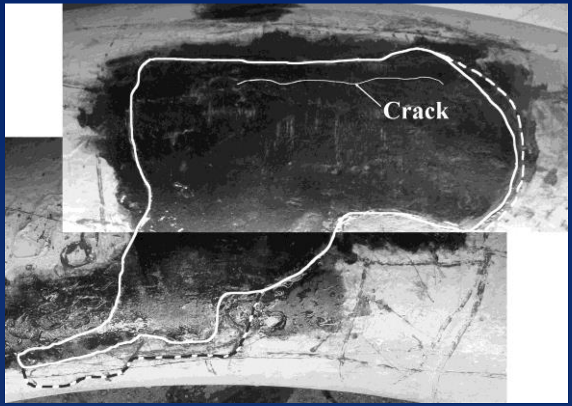
Delaminating

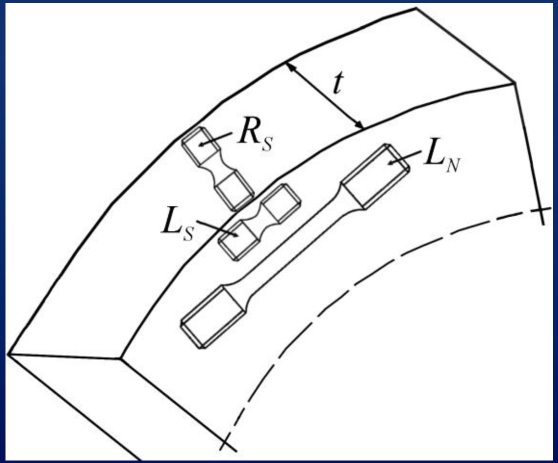
4. Destructive methods for evaluation of in-service degradation of structural steels

Large-scale delamination of the pipe elbow of gas transmission system



The low carbon 0.20 C steel (equivalent to AISI 1020)
40 years of operation
P_{max} - 5.5 MPa
T - up to 80°C

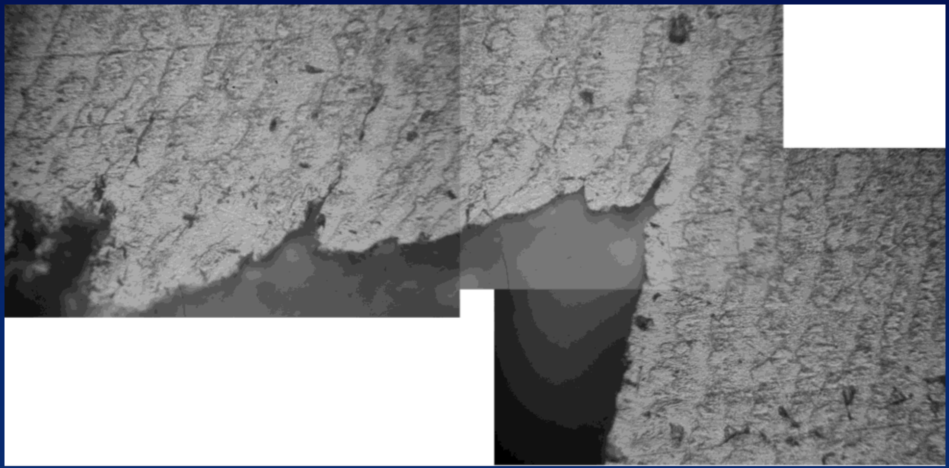




Pipe section	Speci-men type	σ_{UTS}, [MPa]	σ_Y, [MPa]	RA, [%]	Ratio $\frac{RA_R}{RA_L}$	Elongation, [%] / Relative displacement Δ, mm
Straight	L_N	482	293	64.0	-	17.6 / –
	L_S	562	451	67.5	-	– / 1.56
	R_S	604	427	38.7	0.57	– / 0.66
Tensioned	L_N	507	324	68.5	-	20.2 / –
	L_S	590	434	59.7	-	– / 1.20
	R_S	587	393	30.0	0.50	– / 0.40
Compressed	L_N	468	283	62.2	-	18.8 / –
	L_S	568	416	63.5	-	– / 1.31
	R_S	557	386	34.8	0.55	– / 0.58

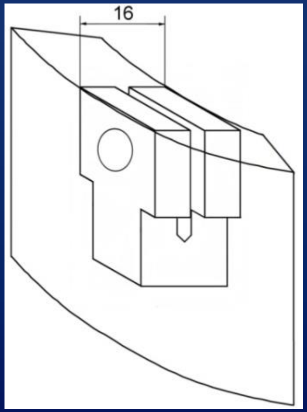
4. Destructive methods for evaluation of in-service degradation of structural steels

Pipe elbow section	Specimen cutting orientation	*KCV*, [J/cm²]
Straight	Longitudinal	131
	Short transverse	28
Tensioned	Longitudinal	188
	Short transverse	20
Compressed	Longitudinal	202
	Short transverse	-

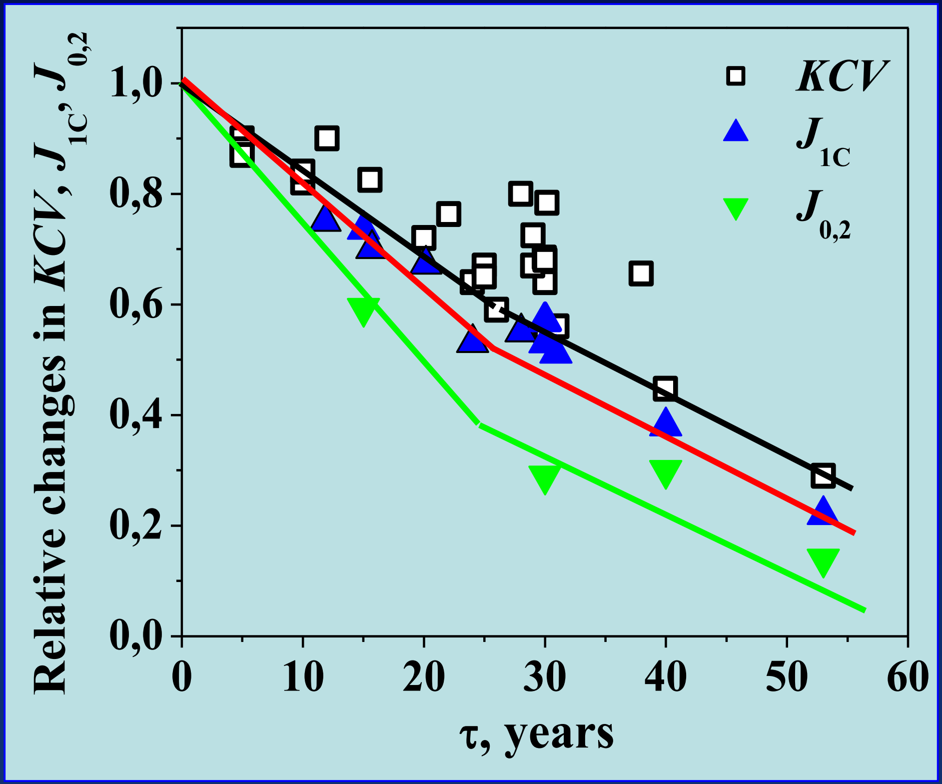


Cross section of the longitudinal V-notch specimen fractured after impact testing, showing crack branching due to delamination of the steel of the pipe elbow tensioned section

Designed short transverse V-notch specimen for impact testing



4. Destructive methods for evaluation of in-service degradation of structural steels



The most sensitive characteristics for an evaluation of in-service degradation by destructive methods are impact strength, fracture toughness and resistance to stress corrosion cracking.

Material	Test environment	Elongation, %	RA, %	K_ε, %	K_{RA}, %
As-received	Air	36	77	39	55
	Water, hydrogenation	14	42		
Operated	Air	28	56	25	5
	Water	7	3		

SCC tests by slow strain rate loading with 10^{-7} s^{-1}
Cathodic charging at i = 0.5 A/m^2

$K_\varepsilon = \varepsilon_{env}/\varepsilon \cdot 100\%$
$K_{RA} = RA_{env}/RA \cdot 100\%$

5. Non-destructive electrochemical method for evaluation of in-service degradation of structural steels

Objects and materials:

1. Low-alloyed pipeline steels in the as-received state and after operation:
A) X52 steel in the as-received state (code X52) and after 30 years of operation from different pipes (t = 10 mm – X52-10; t = 12 mm – X52-12);
B) 17H1S steels (equivalent to X52) after 29-40 years of service;
C) 10HS low-alloyed steel of oil pipeline after 28 years of service.

2. Low-carbon and low-alloyed steels of different structures in the as-received state and after operation:
A) St3 low-carbon steel of Shukhov's towers after above 100 years of service;
B) St 38b-2 low-carbon steel of portal cranes after 36-45 years of service;
C) 25Kh1M1Ph low-alloyed steel of roller of continuous casting machine.

3. 20Kh13 martensitic stainless steel of turbine blade in the as-received state and after operation ~$3\cdot10^5$ h.

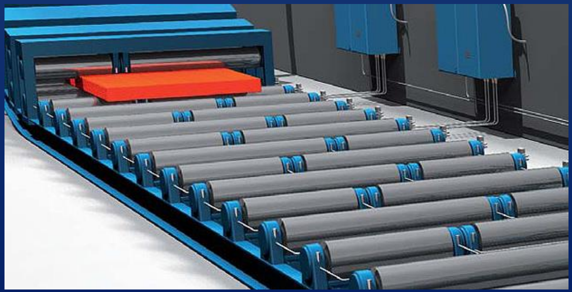
Shukhov's towers

Portal crane

Methods:

1. Mechanical tests
2. Electrochemical investigations

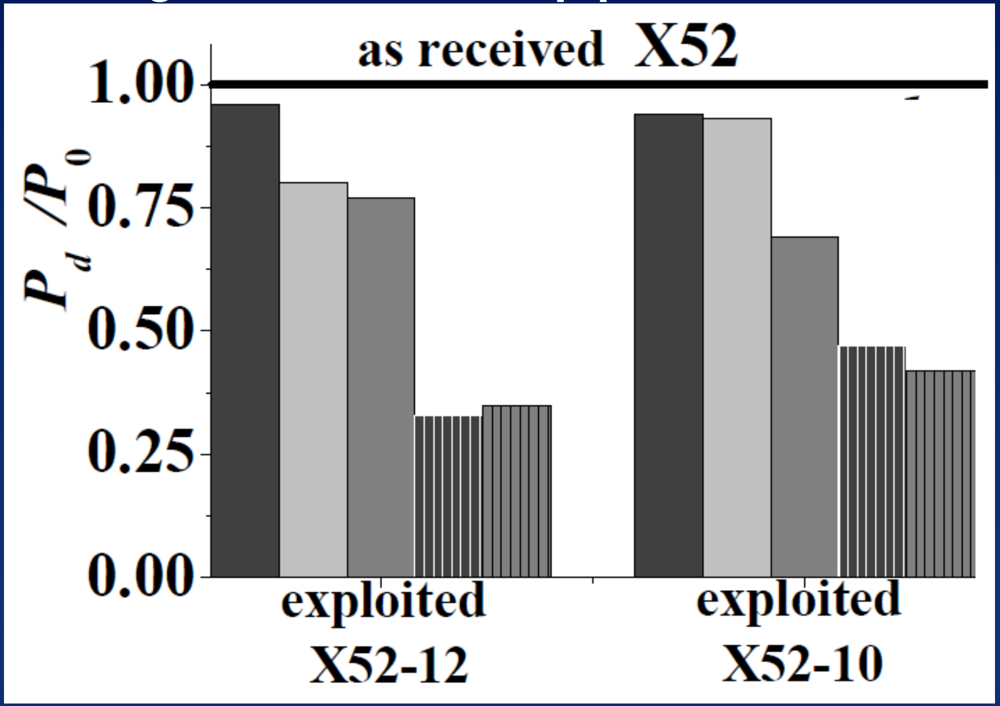
Oil and gas pipelines



Rollers of continuous casting machine

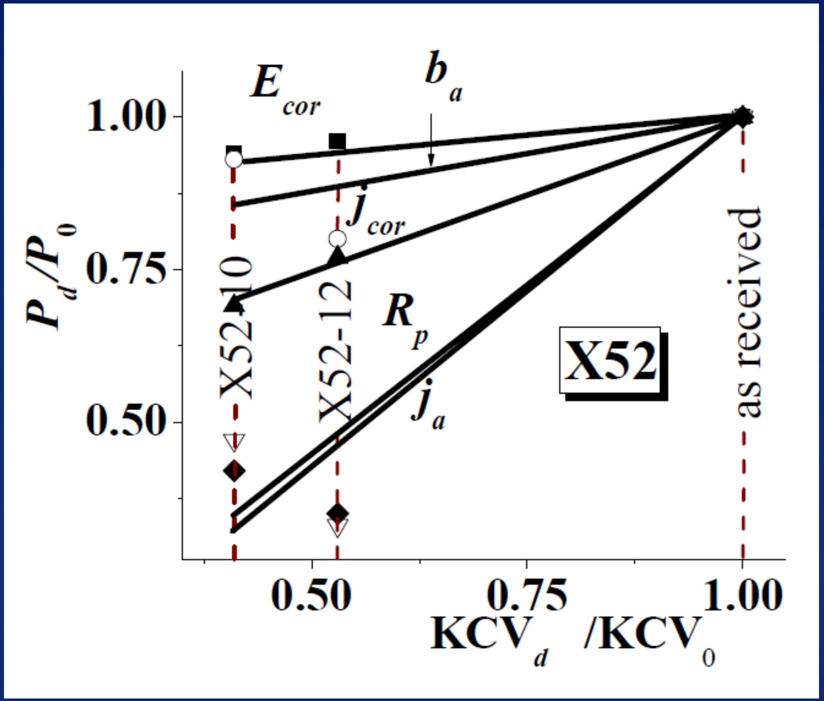
5. Non-destructive electrochemical method for evaluation of in-service degradation of structural steels

Degradation of electrochemical properties of gas transmission pipelines steels



Relative changes in electrochemical characteristics of X52 steels caused by in-service degradation:
1 – corrosion potential E_{corr}, 2 - Tafel constant b_a,
3 - corrosion current density i_{corr},
4 - current density at a certain anode potential i_a,
5 – polarization resistance R_p

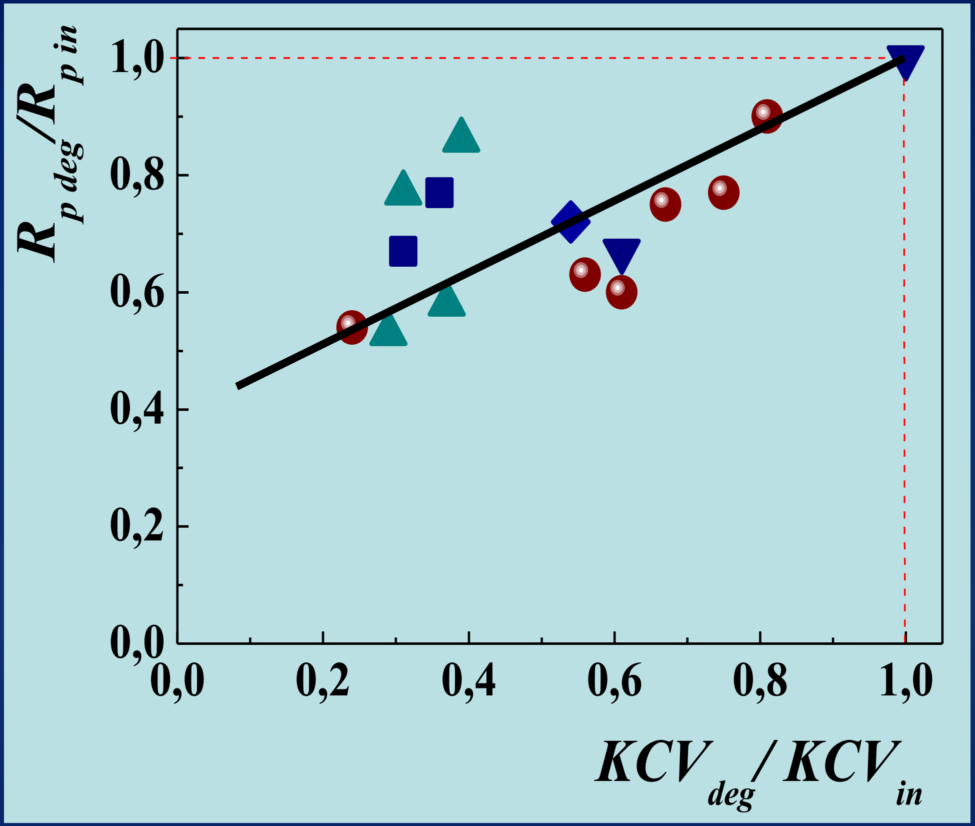
Sensitivity of the electrochemical characteristics to in-service degradation



Correlation between relative changes in electrochemical and mechanical characteristics of pipeline steels caused by in-service degradation

5. Non-destructive electrochemical method for evaluation of in-service degradation of structural steels

Using of electrochemical approach for an evaluation of mechanical properties degradation



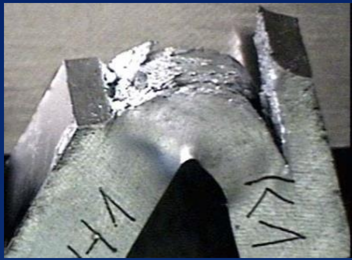
Correlation between relative decrease of mechanical (impact strength) and electrochemical (polarisation resistance) characteristics of 17H1S and X52 steels of operated gas transit pipelines

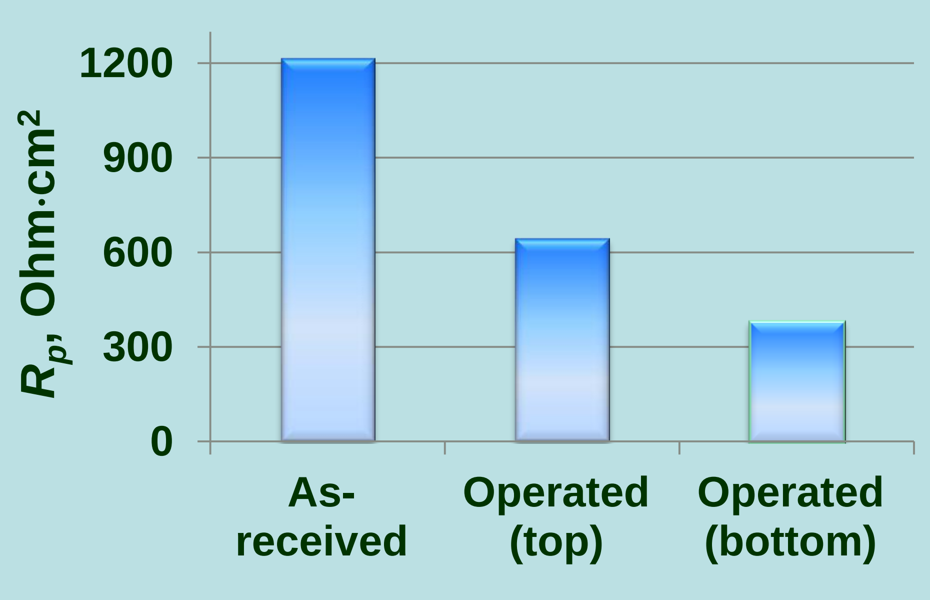
5. Non-destructive electrochemical method for evaluation of in-service degradation of structural steels

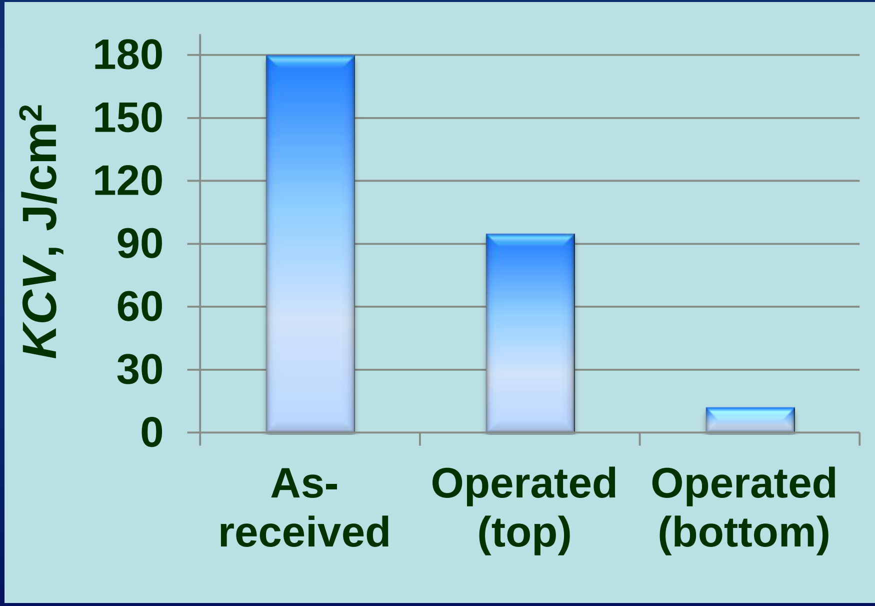
10HS low-alloyed steel of oil transit pipeline

Steel	E_{corr}, V	i_{corr}, μA/cm²	R_p, Ohm·cm²	*KCV*, J/cm²	$R_{p\ deg}$ / $R_{p\ in}$	KCV_{deg} / KCV_{in}
	Simulated residual water					
As-received	-0.51	22	1217	180	-	-
Operated 28 years (top)	-0.56	30	644	95	0.53	0.53
Operated 28 years (bottom)	-0.58	39	381	12*	0.31	0.07*

* – predicted data using electrochemical method

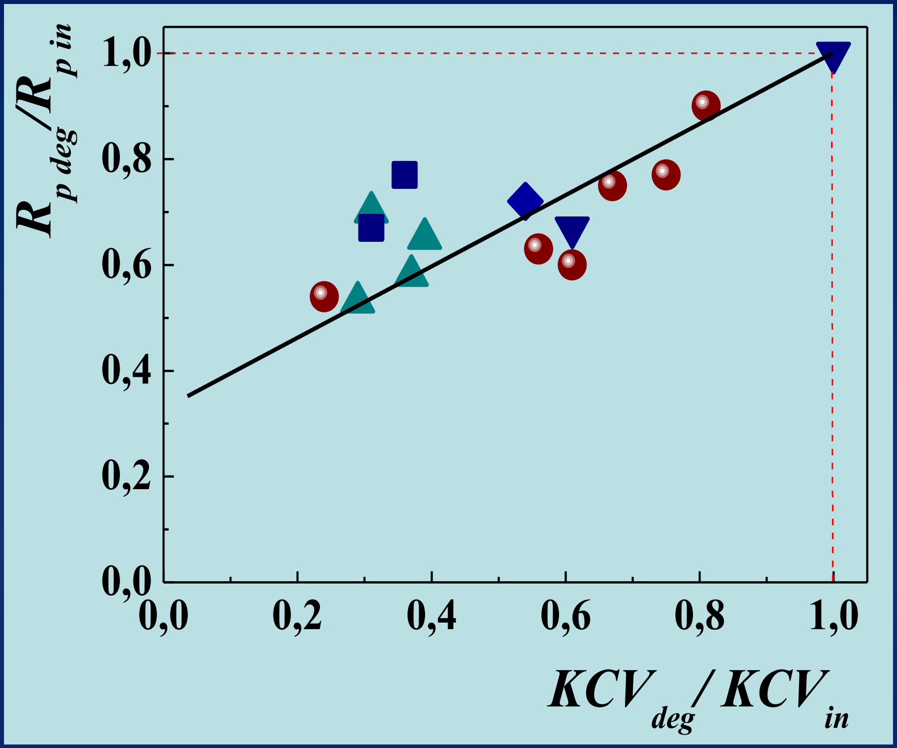




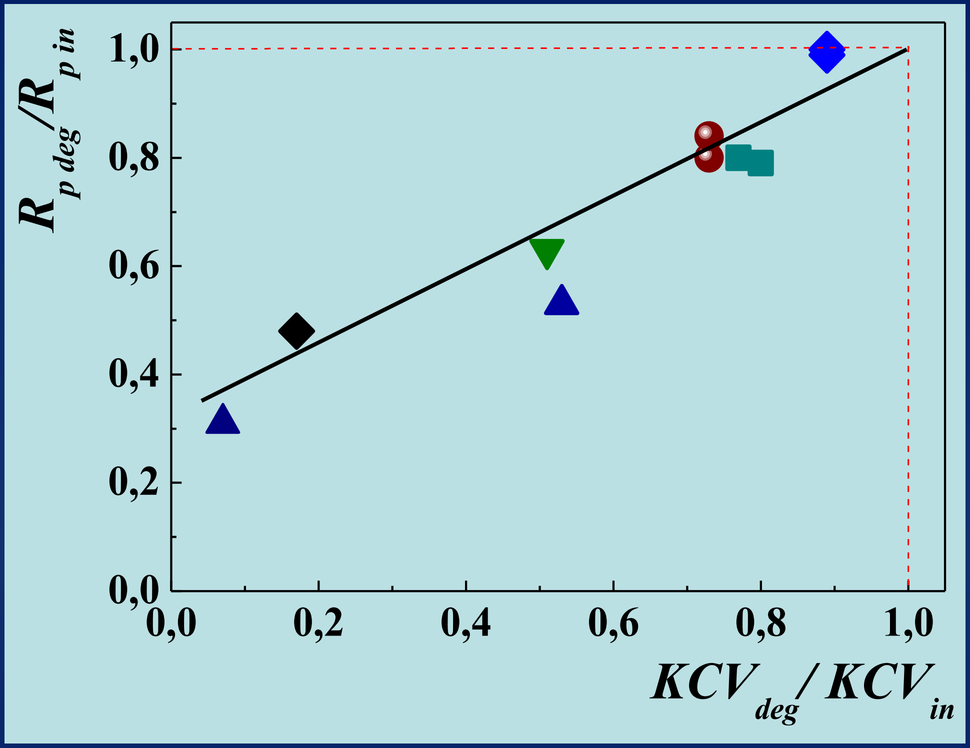


5. Non-destructive electrochemical method for evaluation of in-service degradation of structural steels

Using of electrochemical approach for an evaluation of mechanical properties degradation of low-carbon and low-alloyed steels



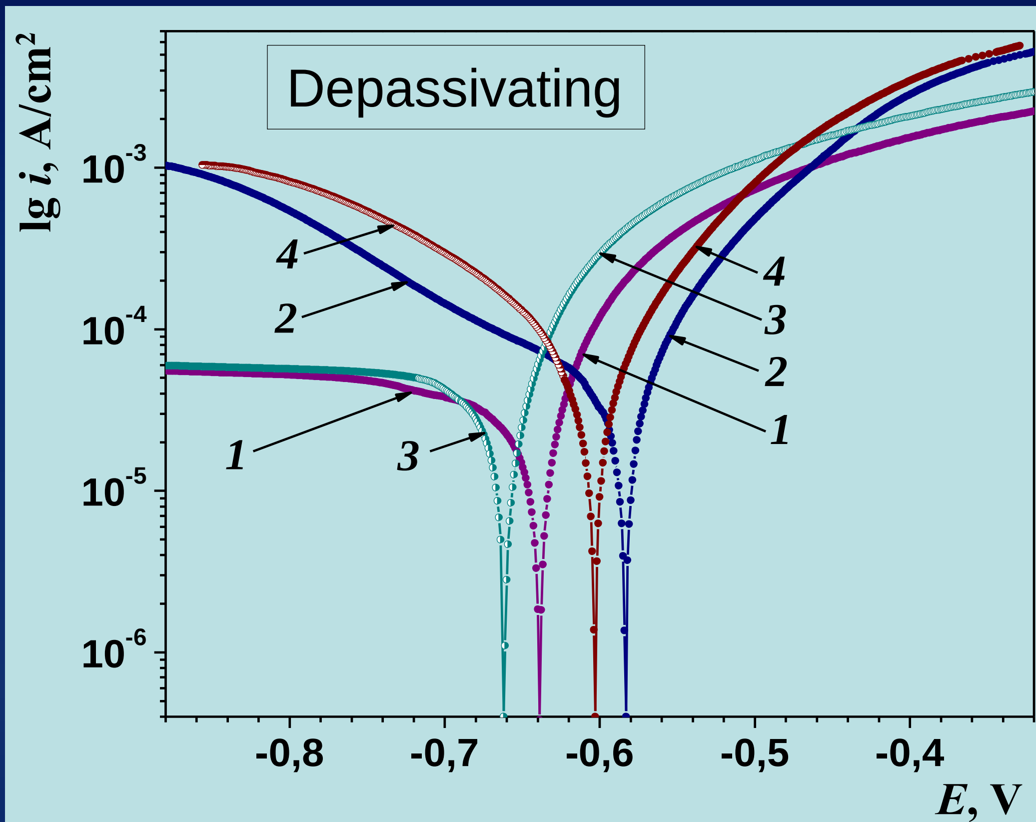
17H1S and X52 steels
of operated gas mains



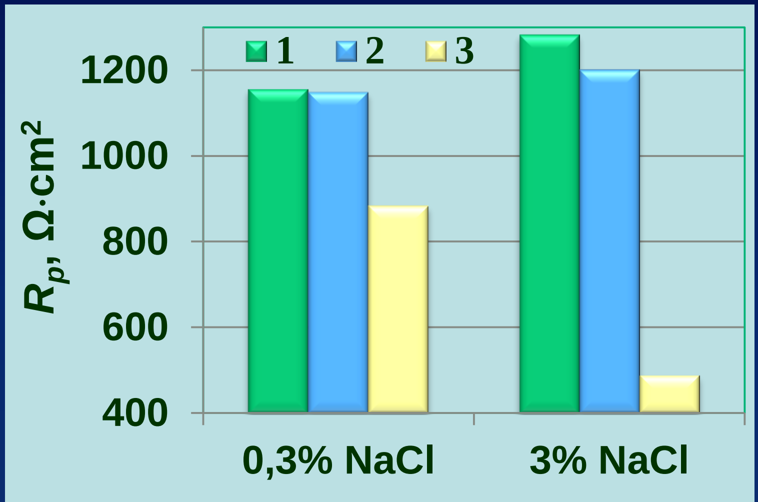
10HS, St3, St 38b-2, and 25Kh1M1Ph
steels of different operated structures

5. Non-destructive electrochemical method for evaluation of in-service degradation of structural steels

Sensitivity increase of electrochemical characteristics to in-service degradation

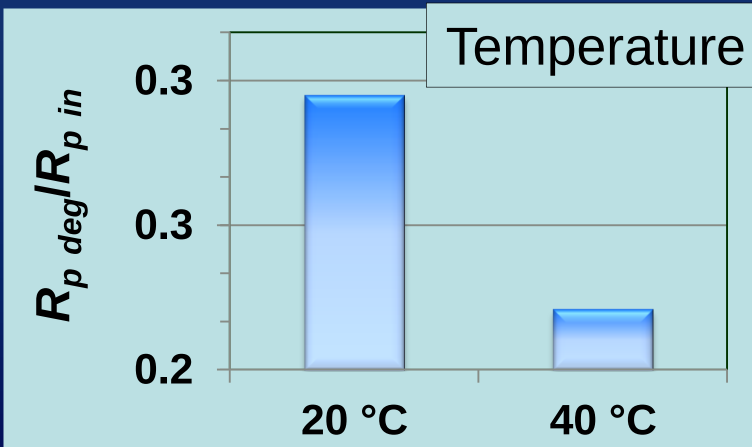


As-received (1, 2) and operated (3, 4) St3 steel in 0.3% NaCl pH 6.5 (1, 3) and 0.3% NaCl pH 2 (2, 4)



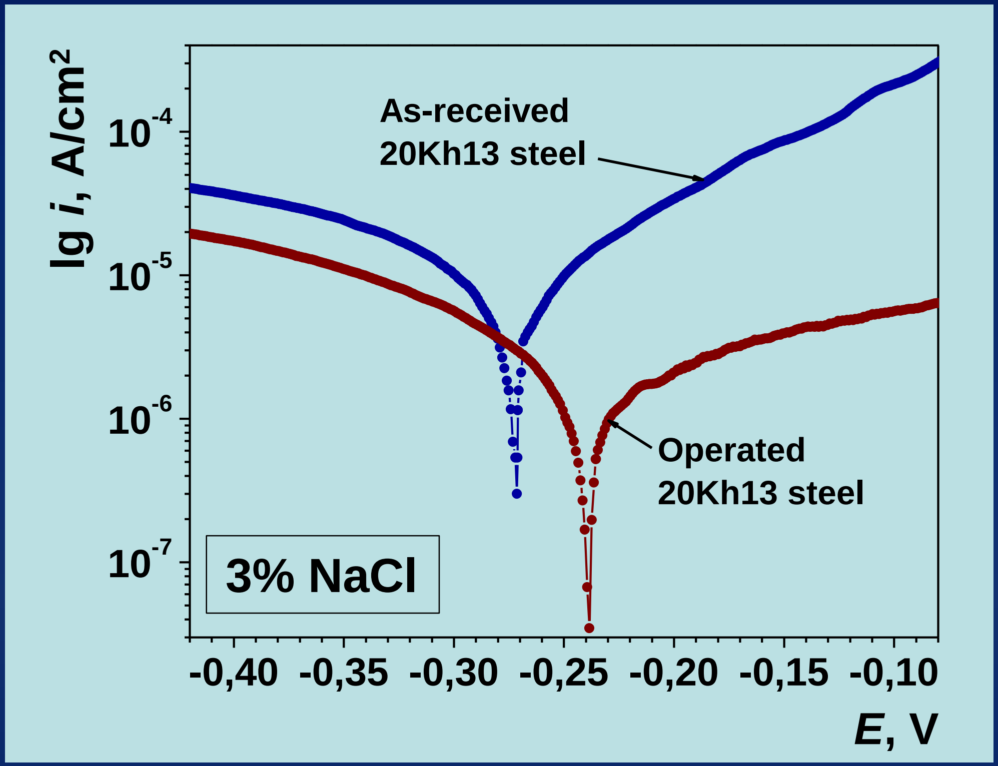
1 - modern St3 steel in the initial state;
2 – operated steel of the water tower;
3 – operated steel of the lighthouse

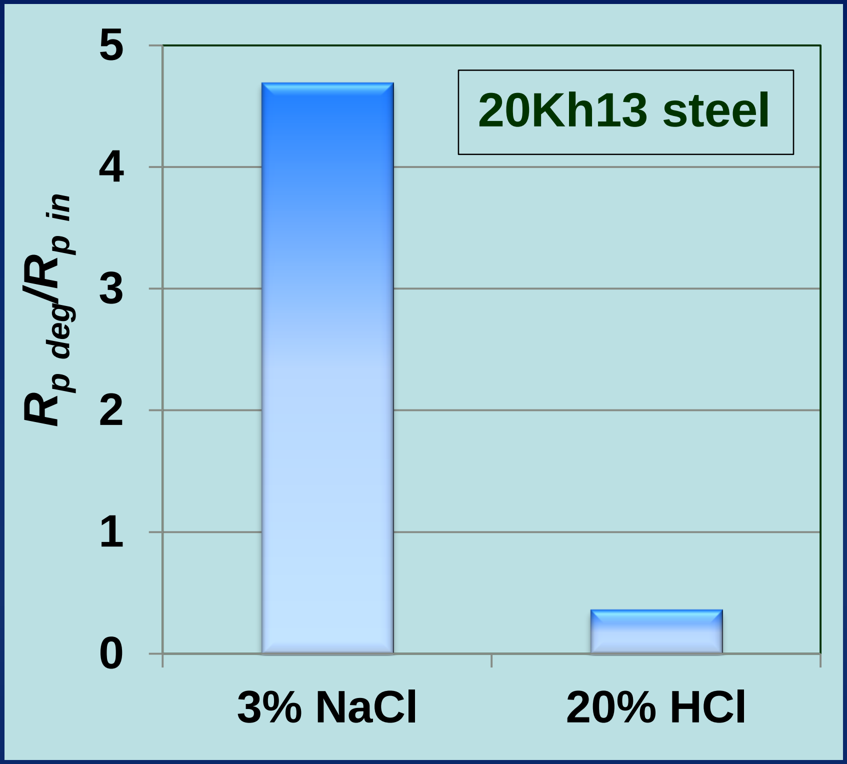
Relative change in polarization resistance of 10HS steel in simulated residual water



5. Non-destructive electrochemical method for evaluation of in-service degradation of structural steels

The peculiarities of using of electrochemical method for degradation evaluation of stainless steels





3% NaCl solution:
As-received 20Kh13 steel: R_p = 3.36 kΩ·cm^2
Operated 20Kh13 steel: R_p = 15.78 kΩ·cm^2

20% HCl solution:
As-received 20Kh13 steel: R_p = 230 Ω·cm^2
Operated 20Kh13 steel: R_p = 83 Ω·cm^2

6. Concluding remarks

- In-bulk degradation of structural steels operated in hydrogenating environments is caused by mutual effect of stresses and hydrogen, which accelerates in-service steel degradation.
- In-service degradation of structural steels resulted in their embrittlement and deterioration of mechanical and corrosion properties.
- The most sensitive characteristics for an evaluation of in-service degradation by destructive methods are impact strength, fracture toughness and resistance to stress corrosion cracking. Sensitivity of these parameters to in-service degradation assessment can be increased by preliminary hydrogen charging of tested specimens.
- Elongation cannot be served as characteristic of materials plasticity for degraded steels, if it detects an opening of in-bulk multiple microcracks: in such case elongation is increasing, however brittle fracture resistance is decreasing.
- Special short transverse specimens at testing should be used for correct characterisation of mechanical properties of steel sensitive to delamination.
- Non-destructive electrochemical method revealed to be reliable for estimation of mechanical properties of operated metal both in the laboratory and in the field, even if it is impossible to determine them in laboratory.

Thank you for

your attention!