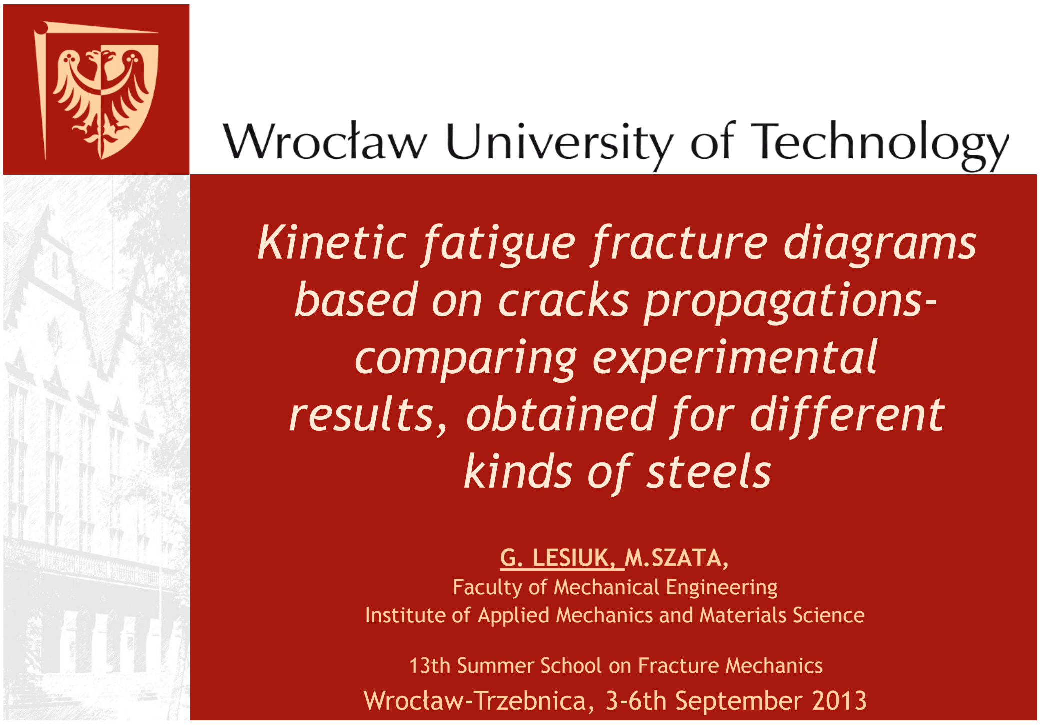
Kinetic fatigue fracture diagrams based on cracks propagations – comparing experimental results, obtained for different kinds of steels

Grzegorz Lesiuk* Mieczysław Szata

Trzebnica, 3–6 th September 2013



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Index of contest

1. Motivation for the investigation of fatigue crack growth rate in an old 19th century puddled steel,
2. Experimental results for puddled steel and fatigue crack growth model,
3. Energy concept for description of fatigue crack growth rate and new energy model,
4. Experimental validation for ΔH (energy parameter),
5. Summary and conclusions.

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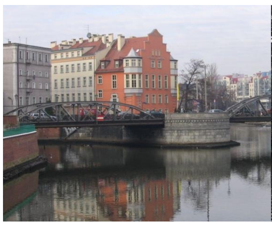
WROCŁAW „THE SECOND VENICE OF THE NORTH”


(1861)


(1875)


(1876)


(1885)


(1888-1889)


(1895-1897)

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WROCŁAW „THE SECOND VENICE OF THE NORTH”

(1908-1910)

(1915-1916)

(1885-1930)

(1904-1905)

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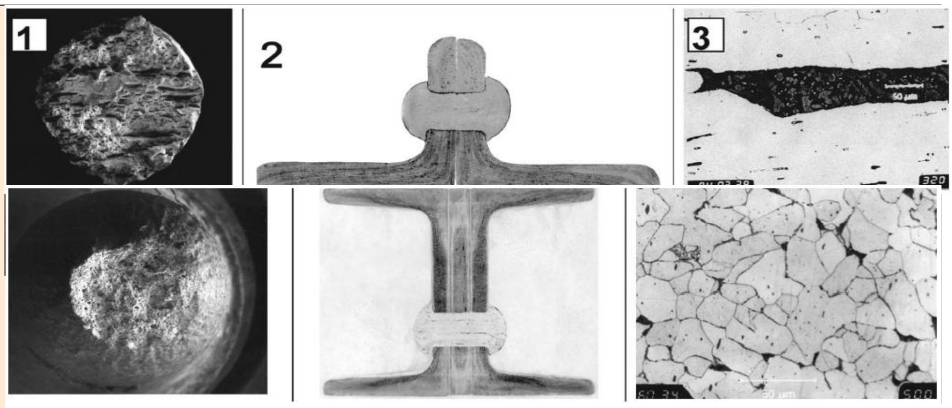
THE OLD METALLIC MATERIALS



* **R. Helmerich, B. Kühn, A. Nussbaumer**, *„Assessment of existing steel structures. A guideline for estimation of the remaining fatigue life*”, Structure and Infrastucture Engineering, 3(3):245-255, September 2007

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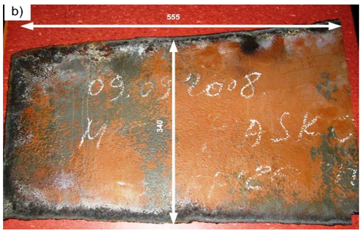
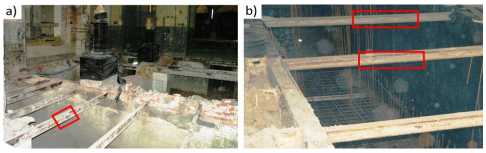
INVESTIGATED OBJECTS





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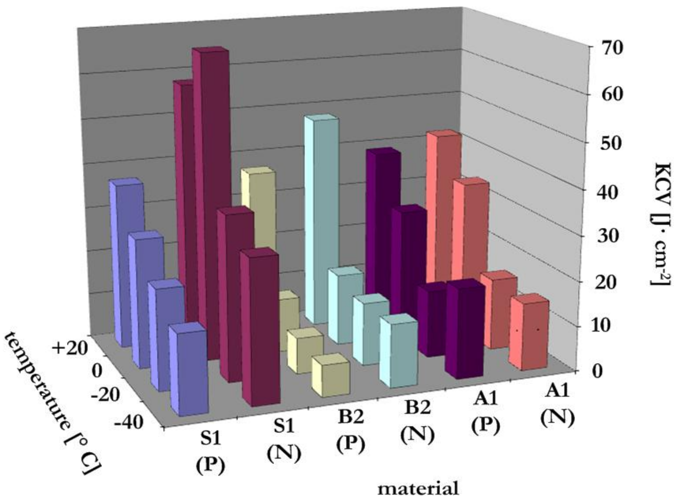
The chemical composition and results of static tensile test

Material
S1 (P)
S1 (N)
B2 (P)
B2 (N)
Piaskowy (P)
Piaskowy (N)



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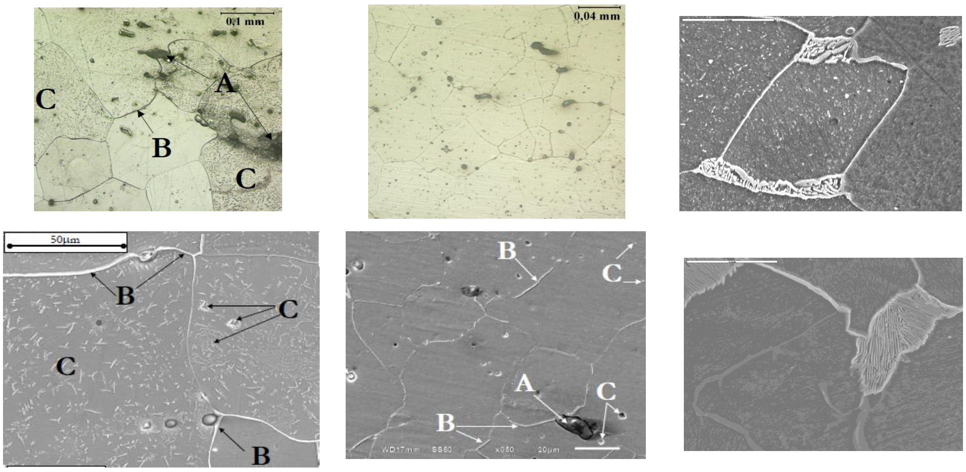
LIGHT MICROSCOPY
SCANNING ELECTRON MICROSCOPY



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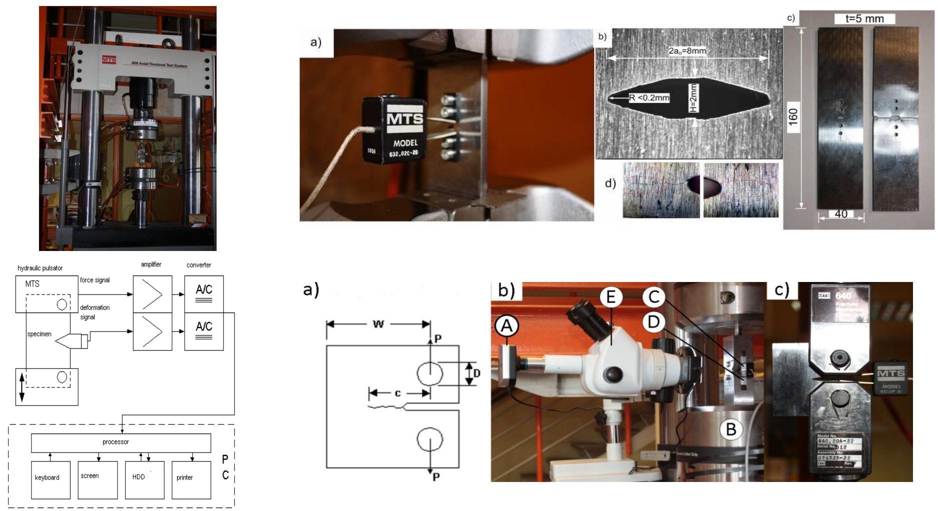
FATIGUE CRACK GROWTH DATA
MEASUREMENT STAND



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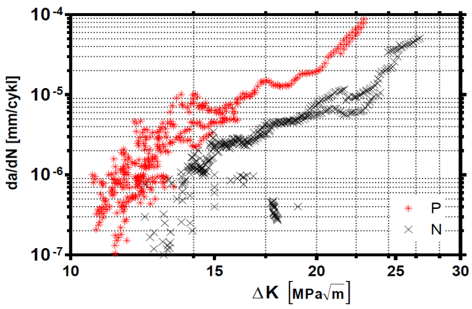
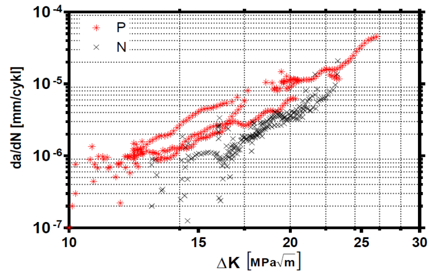
FCG diagrams: a) S1, b) B2

a)



b)



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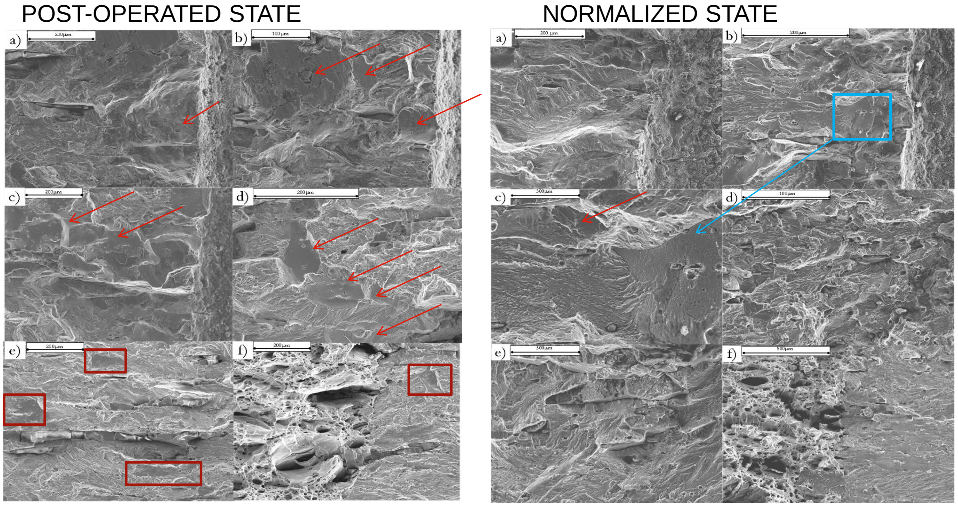
FRACTOGRAPHY OF CRACK PATHS FOR STEEL FROM MAIN RAILWAY STATION

POST-OPERATED STATE NORMALIZED STATE



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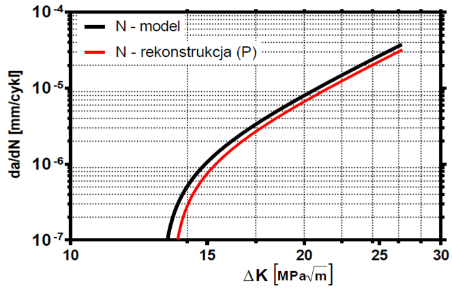
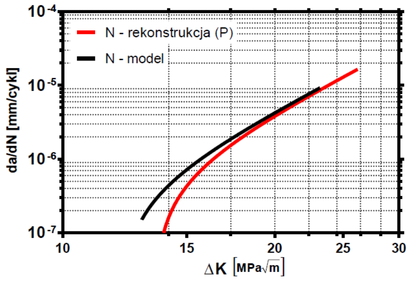
FATIGUE CRACK GROWTH MODEL FOR NORMALIZED AND POST-OPERATED STATE (S1 and B2)





	C	m	R^2	A	R^2
S1 P	2.44×10^{-13}	5.8	0.93	1.2×10^{4}	0.93
S1 N	7.73×10^{-15}	6.7	0.78	1.18×10^{4}	0.85
B1 P	1.83×10^{-13}	6	0.94	4.37×10^{3}	0.92
B1 N	5.48×10^{-14}	5.6	0.78	4.9×10^{3}	0.75

$$\frac{da}{dN} = \frac{A}{KCV^3 \sigma_{pl}^2} \sqrt{\left(\frac{KCV_{35}}{E}\right)^3} \left(\Delta K^5 - \Delta K_{th}^5\right)$$

MATERIAL	ΔK_{th} [$MPam^{0.5}$]	V[%]
S1P	9.9	7.7
S1N	13.47	16.3
B1P	9.87	14.9
B1N	14.41	8.3

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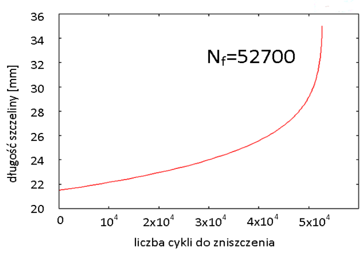
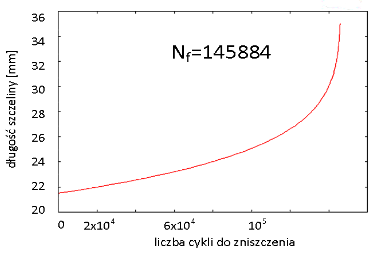
LOSS OF DURABILITY - SIMULATION

$$k_v = \frac{\frac{da}{dN} P}{\frac{da}{dN} N} = \frac{\frac{E_P^{1-0.5\alpha} KCV_P^{1+\gamma-0.5\alpha}}{\sigma_{pl(P)}^2 KCV_{35}^{\gamma}} \Phi_{1(P)} \left(\Pi_2, \Pi_3, \Pi_4\right) \Delta K^{\alpha}}{\frac{E_N^{1-0.5\alpha} KCV_N^{1+\gamma-0.5\alpha}}{\sigma_{pl(N)}^2 KCV_{35}^{\gamma}} \Phi_{1(N)} \left(\Pi_2, \Pi_3, \Pi_4\right) \Delta K^{\alpha}}$$

$$k_v = \left(\frac{\sigma_{pl(N)}}{\sigma_{pl(P)}}\right)^2 \left(\frac{E_p}{E_N}\right)^{1-0.5\alpha} \left(\frac{KCV_P}{KCV_N}\right)^{1+\gamma-0.5\alpha} \approx \left(\frac{\sigma_{pl(N)}}{\sigma_{pl(P)}}\right)^2 \left(\frac{KCV_P}{KCV_N}\right)^{1+\gamma-0.5\alpha}$$





- **64%** loss of durability (based on empirical data),
- **56%** loss of durability (based on proposed model)

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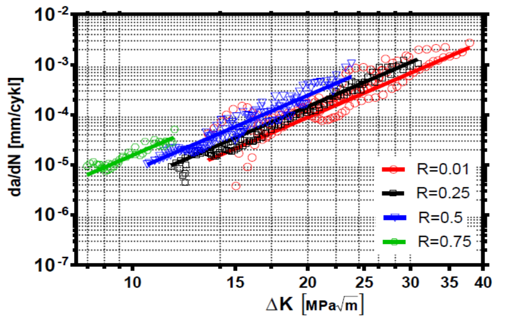
FAO BRIDGE (1892) - PORTUGAL (external data*)

R	C	m	R^2	A	R^2
0.01	1.2×10^{-10}	4.6	0.96	1.17×10^{4}	0.95
0.25	5.8×10^{-11}	4.9	0.94	1.36×10^{4}	0.94
0.5	2.6×10^{-11}	5.4	0.91	1.41×10^{4}	0.90
0.75	1.3×10^{-9}	4.1	0.84	1.3×10^{4}	0.81



Chemical composition:
0.09%C, 0.13%Mn, 0.06%Si, 0.14%P, 0.007%S
R_e=220 MPa, R_m=359 MPa, E=198.7GPa, A=23%, Z=13%, KCV=58.6 J/cm^2

$$\frac{da}{dN} = \frac{A}{KCV^3\sigma_{pl}^2}\sqrt{\left(\frac{KCV_{35}}{E}\right)^3}\left(\Delta K^5 - \Delta K_{th}^5\right)(1-R)^{-1.15}$$

*) **A.M. P. de Jesus, A. L.L. da Silva, M.V. Figueiredo, J.A.F.O. Correira, A.S. Ribierio, A.A. Fernandes**, „*Strain-life and crack propagation fatigue data from several portuguese old metallic riveted bridges*", Engineering Failure Analysis, 18(1):148-163, 2011

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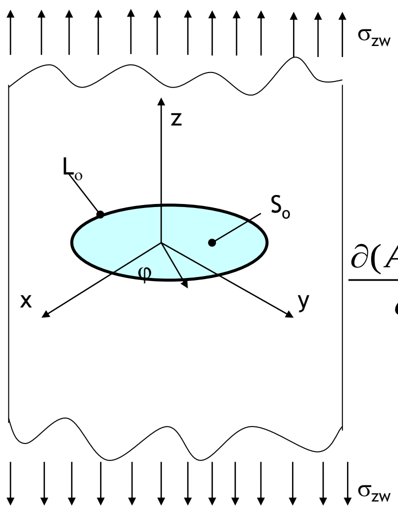
PART II DERIVATION OF THE KINETIC CRACK GROWTH FORMULA



$$A + Q = W + K_e + \Gamma$$

$$\frac{\partial A}{\partial N} = \frac{\partial W}{\partial N} + \frac{\partial \Gamma}{\partial N}$$

$$\frac{\partial (A-W)}{\partial N} = \frac{\partial W_p^o}{\partial N} \longrightarrow W_p^o = W_c^o + W_s^o$$

$$\frac{\partial S}{\partial N} = \frac{\dfrac{\partial W_c}{\partial N}}{\dfrac{\partial(\Gamma - W)}{\partial S}} \qquad Wc = \frac{\partial Wc}{\partial N}\Delta N$$

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MAIN FUNDAMENTALS

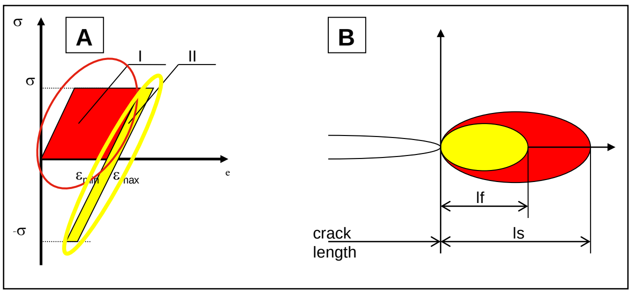

Fig. 5. Simple scheme of: a) external loading, b) plastic area ahead of a crack tip

$$\frac{\partial Ws}{\partial S}$$

$$\frac{\partial^2 Wc}{\partial S \partial N}$$

We can write this quantity $\frac{\partial Wc}{\partial N}$ as:

$$\frac{\partial Wc}{\partial N} = \int_L \int_0^{lf} \frac{\partial^2 Wc}{\partial S \partial N} dF$$

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SIMPLIFICATION IN ANALITICAL DESCRIPTION OF FINAL CRACK PROPAGATION EQUATION

If we assume the constant value of COD (δ) we can write the following quantities as:

$$\frac{\partial S}{\partial N} = \frac{\partial W_c}{\partial N} / \frac{\partial(\Gamma - W_s)}{\partial S} \qquad \frac{\partial \Gamma}{\partial S} \cong \sigma_{plf} \varepsilon_{fc} \qquad \frac{\partial W_s}{\partial S} \cong \sigma_{plf} \varepsilon_{\max}$$

$$\frac{\partial(\Gamma - W_s)}{\partial S} \cong \sigma_{plf} \varepsilon_{fc} - \sigma_{plf} \varepsilon_{\max} = \sigma_{plf} \varepsilon_{fc} \left(1 - \frac{K_{I\max}^2}{K_{fc}^2}\right)$$

$$\frac{dS}{dN} = \frac{W_c^{(1)}}{\sigma_{plf} \varepsilon_{fc} (1 - K_{I\max}^2 / K_{fc}^2)}$$

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FINAL FORM (AFTER SIMPLIFICATIONS), NEW ENERGY PARAMETER - ΔH

$$\frac{dl}{dN} = \frac{\alpha W_c^{(1)}}{B\sigma_{plf}\varepsilon_{fc}(1 - K_{\mathrm{I}\,max}^2 / K_{fc}^2)}$$

$$\Delta H = \frac{W_c^{(1)}}{B(1 - K_{\mathrm{I}max}^2 / K_{fc}^2)}$$

B - thickness of specimen,
Wc - dissipated energy value in each cycle of loading,
σ_{plf} - cyclic yield stress,
ε_{fc} - cyclic strain critical value,
K_{fc} - critical (cyclic) SIF
K_{Imax} - maximum value of SIF for loading cycle,
α - constant dimensionless factor.

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EXPERIMENTAL VALIDATION

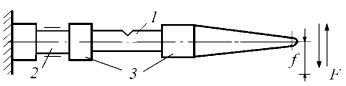

Fig. 6. Beam specimen (12x18x8)

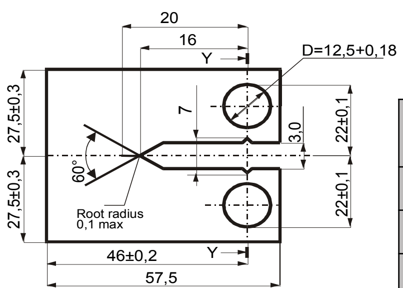

Fig. 7. CC(T) specimen (compatible with ASTM E 399-81)

- **12HMF (14MoV63)** (0,1%C; 1,1%Cr; 0,26%Mo; 0,17%V; 0,54Mn; 0,019%S; 0,015%P),
- **18G2A (S355J0)** (0,2%C; 0,26%Mo; 0,2%Cu; 1,3%Mn; 0,03%S, 0,02%P),
- **40H (41Cr4)** (0,4%C; 0,7%Mn; 1,1%Cr; 0,3%Si; 0,3%Ni; 0,03%S; 0,02%P).

MATERIAL	R_m [MPa]	R_e/ $R_{0,2}$[MPa]	A_5[%]	K_{fc}[MPa*$m^{0,5}$]
12HMF	470	208	29	80
18G2A	600	350	22	105
40H (41Cr4)	980	780	10	45, 80, 100*

Tab. 4. Mechanical properties of investigated steels

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KINETIC FATIGUE FRACTURE DIAGRAMS
40H (41Cr4) steel

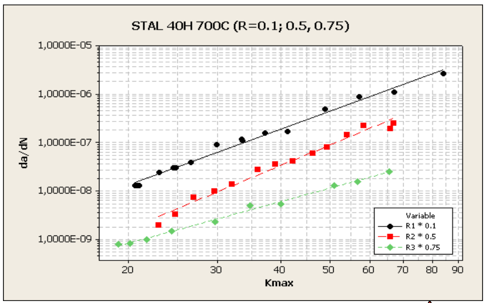
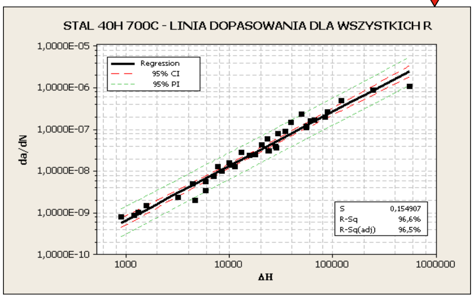


Fig. 8.
Classical KFFD da/dN-K_{max} (R 0.1 0.5 0.75) for 40H (41Cr4)steel.

Fig. 9.
New energy KFFD da/dN-ΔH (R 0.1 0.5 0.75) for 40H (41Cr4) steel.



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KINETIC FATIGUE FRACTURE DIAGRAMS
18G2A (S355J0) steel

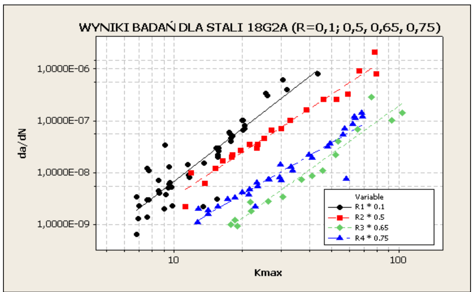
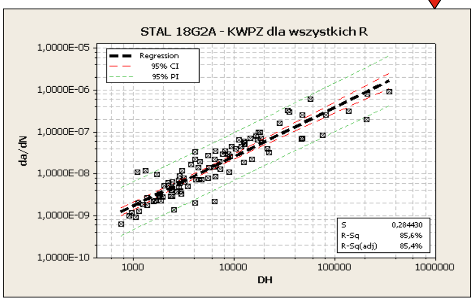


Fig. 10.
Classical KFFD da/dN-K_{max} (R 0.1 0.5 0.75) for 18G2A steel.

Fig. 11.
New energy KFFD da/dN-ΔH (R 0.1 0.5 0.75) for 18G2A steel.



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KINETIC FATIGUE FRACTURE DIAGRAMS
12HMF (14MoV63) steel

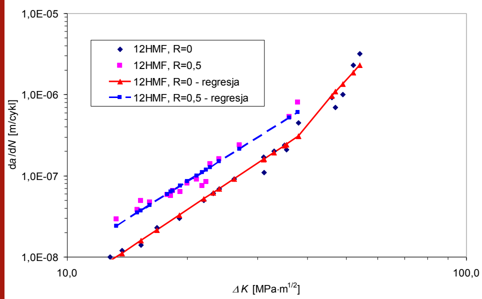
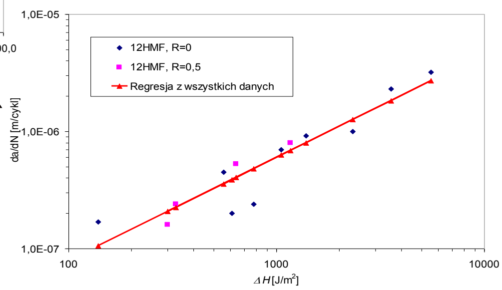


Fig. 12.
Classical KFFD da/dN-K_{max} (R 0.1 0.5 0.75) for 12HMF steel.

Fig. 13.
New energy KFFD da/dN-ΔH (R 0.1 0.5 0.75) for 12HMF steel.



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CONCLUSIONS

- The processes of structural degradation have been identified. In each case it has been shown that there are degradation changes at the microstructure level,
- These processes participate in brittleness (it is particularly visible in impact loading resistance) fracture surface seems to confirm the brittle tendency of crack propagation,
- The differences in fatigue crack growth are observed,
- In the Paris regime, exponent *m* on the level „5" value is noticeable. It is relatively high in comparison with modern construction steel (i.e. for S355J0 m=3) subjected to the bridges building,
- Newe energy model of fatigue crack growth (energy parameter ΔH) describes the kinetics of fatigue fracture independently of the stress ratio R. There features can be useful in application for the description of fatigue crack growth rate in an old steel,
- New measurement method (based on magneto-mechanical Villari effect) opens new possibilities in energy modeling of fatigue crack growth rate.

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THE END

THANK YOU FOR YOUR ATTENTION!