ASPECTS OF STRUCTURAL DEGRADATION IN OLD BRIDGE STEELS BY MEANS OF FATIGUE CRACK PROPAGATION

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The paper presents conclusions drawn from studies related to old steel structures, especially those erected on the turn of the 19th century. The objects of interest of the authors were Wroclaw Pomorskie Bridges: the Central Pomorski Bridge and the North Pomorski Bridge (1885, 1930 respectively), as well as the Sand Bridge (1861). The material used for their construction was puddled steel or cast steel. In the course of long operation the steels (especially the puddled one) show susceptibility to degradation processes. In this paper the results of metallographic tests (light microscopy, SEM) and mechanical properties tests (hardness measurement, static tensile test) presenting the state of structural degradation have been presented. Also, the initial study results for the puddled steel coming from the Sand Bridge and concerning development of a fatigue crack have been presented. Basic quantities describing the kinetics of fatigue crack growth have been determined.

Keywords: *fatigue crack growth rate; puddled steel; microstructural degradation.*

Using published data [1–7] and own research of the old steel structures the problem of worsening the usefulness of such structures is appearing. The Degradation Theory initiated at the Wrocław University of Technology in the nineties of the last century [1] was dealing initially with problems related to surface mining machines. Its development has led to systematic analysis of the machine (structure) – environment system. In the course of works several problems involved in steel structural degradation have been documented [2, 3]. The problem is becoming more serious when referred to bridge structures from the turn of the 19th century. In particular, it concerns the puddled steel which, as the studies show, is more susceptible to structural degradation processes than the cast steel. Material aspects of the Degradation Theory have been expressed in [2, 6]. The essential issue in the old structure studies is evaluation of a steel part wear degree. Lack of comparison material – the modern steel production technologies are far different from those in the centuries past – makes the evaluation of a structural part wear difficult. The only solution elaborated within the Degradation Theory and its material aspects [2, 7] is assuming the normalised state as the level for comparison.

The steel from Wroclaw Pomorskie Bridges: puddle steels of the Sand Pomorski Bridge (year 1861), the Central Pomorski Bridge (1885) and cast steel of the North Pomorski Bridge (1930), all after-operation state, were the objects of the study. The goal of this work is investigation of the influence the structural degradation processes on the kinetics of fatigue cracking. According to the above the basic mechanical properties; yield stress $\sigma_{0.2}$, ultimate tensile stress σ_B, Young Modulus E, uniform elongation δ_u, reduction in area ψ (for Sand Bridge) have been obtained from static tensile test. The threshold stress intensity factor values ΔK_{th} were obtained from the fatigue crack growth for experimental data. All investigations were performed in two states; P – after operating state and the normalised (N) one.

Examples of structural degradation. In order to understand the further part of this work the puddled steels and their basic mechanical properties will be described. The

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Corresponding author: G. LESIUK, e-mail*:* Grzegorz.Lesiuk@pwr.wroc.pl issue is focused on this kind of the old metallic material because many old riveted structures (still operating) are erected from puddled steel. So firstly, it was the wrought iron (later called a puddled steel – as at that time the concept of steel was not clearly defined yet) was produced with the puddle method. It was produced in small batches (of some 200…500 kg in weight) in the puddling furnace, in which the pig iron in a solid state was partially melted with hot gas created in the process of burning hard coal or coke. Due to the oxidizing influence of combustion gases, a carbon was burned out from the pig iron in the first place. That way the process was rising the alloy solidification temperature. The slag at the alloy surface required permanent mixing, in order to provide access of the oxidizing gases to melted metal. The steel production process was called puddling (*Eng. puddled steel*). At a relatively low temperature obtained at a puddling furnace (about 1400°C), a solidification of decarbonised pig iron took place, where it created a lump in the doughy state with low carbon contents but plenty of slag contaminations [8, 9]. The essential property of structures created from puddled steel was high heterogeneity of their chemical composition and its laminar structure (Fig. 1).

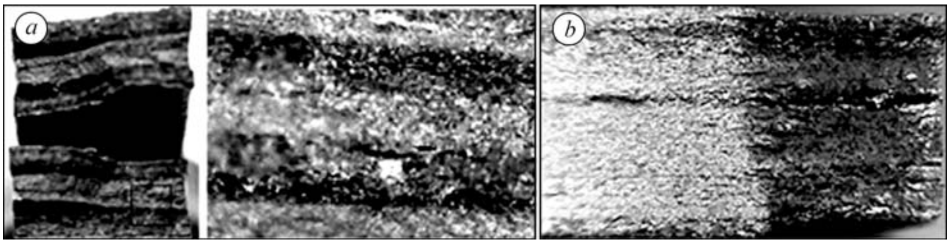

Fig. 1. Puddled steel – characteristic fracture of this steel after static tensile test, a flat sample fracture view to the left, a magnified fragment of the area marked with the frame to the right – visible numerous de-laminations and characteristic lamellar fracture structure (*a*); fracture after fatigue crack growth tests – on the left the fatigue crack growth area, on the right the static fracture (*b*).

Most probably, it resulted from small batches placed in a puddling furnace. In addition, the technology itself caused high contamination of the steel. All that influenced creation of local material flaws and extremely wide distribution of statistic results. Such situation was not neutral to the macroscopic properties of the steel – the puddled steel was characterised with diversification of elongation and yield and ultimate tensile strength both in the rolling direction, as well as in the direction perpendicular to it.

The level of $\sigma_{0.2}$ of puddled steel is about 280…310 MPa, total elongation δ is between 7…25%. Papers [9] indicate the significant fluctuations related to $E \sim 170\ldots200$ GPa, though results such as $E = 132.8$ GPa were also recorded.

From [8] it results that puddled iron (the puddled steels) produced in the second half of 19th century had the following parameters: density $g = (7.6\ldots7.8)$ Mg/m^3; carbon contents C = (0.05…0.1)%; phosphorus contents P ~ 0.4%; $\sigma_{0.2} = 210\ldots290$ MPa, elastic limit $\sigma_H = 150\ldots160$ MPa, $\sigma_B = 300\ldots400$ MPa, elongation $\delta_5 = 8\ldots25\%$, all values for the rolling direction; $E = 200\ldots215$ GPa. In the rolling direction the values are significantly higher than in the direction perpendicular to it. Degradation processes taking place in old steels consist, among others, on decomposition of pearlite to ferrite and carbides, nitrides and carbides separations inside grains and at grain boundaries (in this case we talk of tertiary cementite).

In order to illustrate the structure types and features indicating the degradation progress, the following figures present exemplary microscopic observation results (light microscopy and SEM) for parts coming from Wroclaw bridges. A banded structure typical of puddled steel (ferritic-pearlitic) in the rolling direction and non- homogeneous grain size are shown in Fig. 2.

The frame marks plastically strained chain of non-metallic inclusions. An example of structure with extreme intensity of contamination with non-metallic inclusions is shown in Fig. 3*a*, coming from tests of the Central Pomorski Bridge. Fig. 3*b* presents also the mentioned structures changed by degradation. Also in case of the cast steel, degradation separations could be observed – such as in Fig. 4*b*.

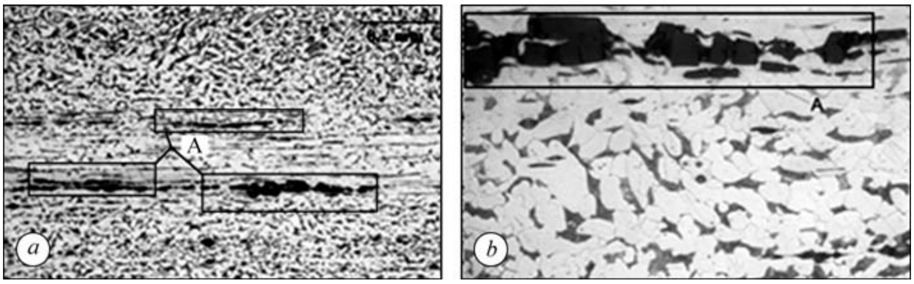

Fig. 2. Microphotographs (light microscopy) of the structure of steel from the North Sand Bridge: *a* – ferritic-pearlitic structure of steel with chains of non-metallic inclusions (A), and the banded structure in the rolling direction, marked with frames; *b* – magnified area A [10].

The views of Figs. 2*a* and 4*a* have to be compared in order to find difference in contamination of puddled steels with non-metallic inclusions (Fig. 2*a*), with that of the cast steels (Fig. 4*a*).

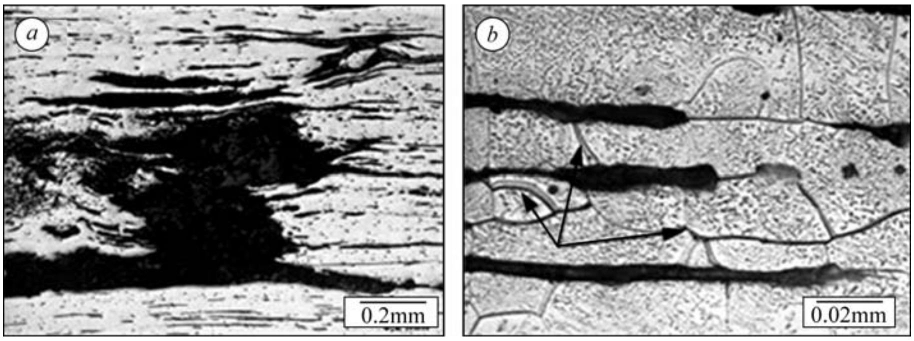

Fig. 3. Microphotographs (light microscopy) of the structure of steel from the Central Pomorski Bridge: *a* – an area with extreme intensity of non-metallic inclusions visible; *b* – area with degradation symptoms (A) – nitrides and carbides separations inside grains, separations of Fe_3C_{III} at grain boundaries marked with arrows [10].

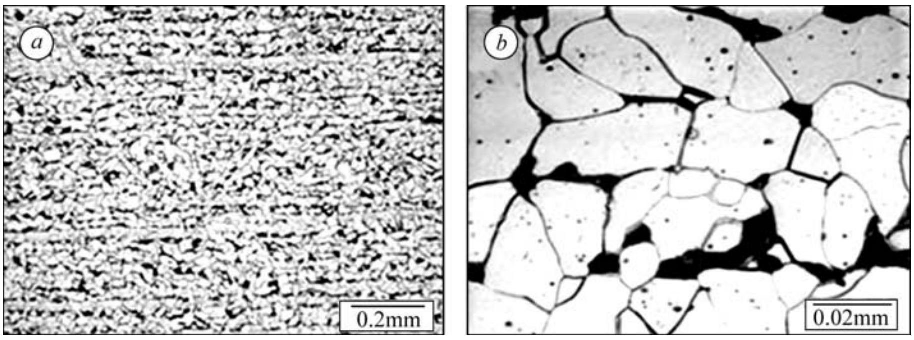

Fig. 4. Microphotographs (light microscopy) of the steel structures from the North Pomorski: *a* – fine-grained ferritic-pearlitic steel structure; *b* – ferrite-pearlite grain structure of the fine-lamellar structure and seldom separations (nitrides) inside ferrite grains. Local Fe_3C envelope at grain boundaries [3].

Basic mechanical properties of puddled steel (the Sand Bridge). Processes of structural degradation presented in the previous subsection considerably influence basic mechanical characteristics i.e. hardness and impact resistance. Based on the literature studies and own research of the authors it could be stated that, in general, the development and intensification of degradation processes cause distinct increase in hardness (it drops after normalising), which took place in all the tested steel grades. In case of impact resistance the effect of structural degradation changes is even more distinct and is observed in the form of its fall in the after-operation state and subsequent rise in the normalized state. Physical explanation of such behavior is related to the presence of numerous separations (especially of those at the grain boundaries) of a brittle phase such as cementite, which causes a drop in ductility and, in consequence, favors the cleavage fracture. In relation to that the impact resistance (*KCV*) drops drastically at low temperature. Moreover, as a result of many-year studies it could be stated that in a significant number of case the brittle-ductile transition temperature stabilizes in the post-operation state within the range of positive temperatures. We can observe the mentioned effect in Fig. 5. The black horizontal line means the value of impact resistance – 35 J/cm^2 as a minimal value for the contemporary bridge steel. The *KCV* values are higher in each case in the post operating state – it is caused by degrading processes.

In the static tensile test the ratio $\sigma_{0.2}/\sigma_B$ is frequently adapted as a useful indicator for a wear degree (structural degradation). However, as the other study results show [2] it is not always the case. Development of degradation processes is also reflected in elongation (δ), as well as reduction in area (ψ) of the specimen which is naturally the measure of material ductility. In the presented study results for the Sand Bridge collected in Table 1, the distinct growth effect in both mentioned characteristics in the normalized state may be observed. A hypothesis could be made that this becomes a rule, but as known from [8, 9] the puddled steel shows a significant scatter in static tensile test results, which sometimes upsets observation of the effect (see [3], and test results for puddled steel from segment I) and may lead to rejecting the mentioned hypothesis. The yield point and tensile strength behavior generally show the tendency to assume higher values in the post-operation state than in the normalized state, but sometimes they could be different (see Table 1).

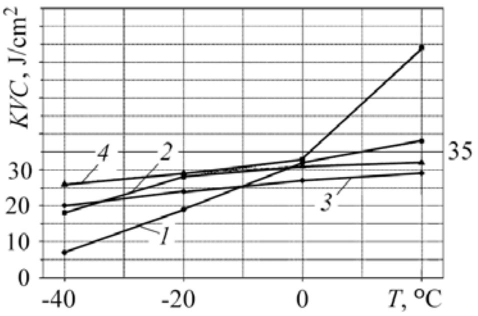

Fig. 5. Impact resistance of puddled and cast steels from the Sand Bridge in the after-operation (*P*) and normalised (*N*) states [11]: *1* – puddled steel (*P* state); *2* – puddled steel (*N* state); *3* – cast steel (*P* state); *4* – cast steel (*N* state).

Table 1. Results of the static tensile tests for puddled steel (the Sand Bridge)

	$\sigma_{0.2}$, MPa	σ_B, MPa	*E*, GPa	ψ, %	δ_u, %
State *P*	263.3 ± 5.8	410 ± 21.1	197 ± 4.9	18.26 ± 2.9	12.87 ± 2.3
State *N*	294 ± 20.9	442 ± 18.5	202 ± 10.7	23 ± 0.45	16.7 ± 0.1

The ductility indicators (ψ and δ_u) have shown the significant difference between the two states: post operating (*P*) and normalised (*N*). A small comment should be required in the case of quantity δ_u (see Table 1). The effect of degradation processes should be stronger visible in hardness than in the results of tensile test. In structural degraded materials the hardness values are always higher [2, 3, 6] than in the normalised state *N*. In our case, the hardness was measured using Vickers Method (in agreement with normative document PN-EN ISO 6507-1:1999 load: $F = 10$ kG (98.070 N)). The results of hardness test are the following: in post operating state $\mathrm{HV}_{10} = 145 \pm 9$; in normalized state $\mathrm{HV}_{10} = 115 \pm 15$.

Fatigue crack growth study in the puddled steel after 149-year operation period. In face of the degradation processes influence pattern on structure part behavior in the structural degradation conditions as presented in the above subsection the cyclic tests seem to be justified. In particular, it concerns the fatigue cracking propogation tests. Fatigue and fatigue crack development is the most dangerous pair of hazards for that structure types. Therefore, the knowledge of that subject, both the direction and character of the fatigue crack development, enables either the evaluation of the existing cracks development stability or determination of time between subsequent inspections, or finally, to make the decision on a bridge load capacity. This subsection presents fatigue crack growth test results for puddled steel samples coming from the Sand Bridge.

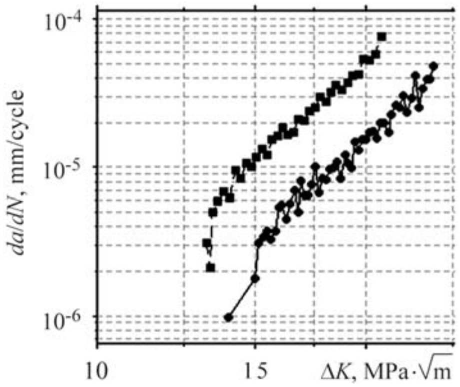

Fig. 6. Fatigue crack growth diagrams for bridge steel after-operation (*P*, ■) and normalised (*N*, ●) states, stress ratio $R = 0.1$.

Considering the limited thickness of samples and technical capabilities of the dynamics laboratory in the Institute of Materials Science and Applied Mechanics WUT, it has been decided to use the M(*T*) samples according to the ASTM E647 Standard (Middle Cracked Tension Specimen type, where $t = 5$ mm, $W = 40$ mm, $L = 4$ W), fixed in the testing machine by hydraulic clamps. The samples were collected from steel parts of the Sand Bridge. The tests were made on the MTS 810 testing machine using the constant amplitude method, and ΔK decreasing test. A sample was being loaded while maintaining the constant stress ratio of $R = 0.1$ with sinusoidal load in the 1.8…18 kN range applied with 10 Hz frequency. The mechanical crack was made using electric discharging machine. Before the proper test the notch was "sharpened" according to the ASTM E647 Standard, while strictly keeping up to all the test validity rigors (Fig. 6).

The crack length was measured using compliance method and was also checked and compared with the length obtained from manual, optical method using traveling microscope. Test results are presented in Table 2, where ΔK_{th} – threshold value of the stress intensity factor, *C*, *m* are Paris model constants (characteristic for a given steel group). Similar values of the *C* and *m* constants in the after-operation and normalized state indicate a similarity in the way of crack propagation in this range.

Table 2. Summary of characteristics related to fatigue crack growth

	after-operation state	normalized state
ΔK_{th}, MPa·$\sqrt{\text{m}}$	10.8	14.4
Exponent *m*	5.34	5.11
Constant *C*	$10^{-11.52}$	$10^{-11.74}$

A difference in the threshold quantities of ΔK_{th} has been observed instead, which could be related to the presence of ageing processes in the tested steel. It has to be noticed that the exponent m in the Paris formula directly responsible for the rate of fatigue crack development in the tested steel (low-carbon grade) is high, i.e. much higher than for the modern low-carbon steels (where $m = 3$). Also the expected ΔK_{fc} quantity will be relatively low in comparison with the modern low-carbon steels.

CONCLUSIONS

The problems related to operating old steel structures from the end of 19th and beginning of 20th century are cobsidered. The contemporary construction materials have been discussed [8, 9]. The processes of structural degradation have also been presented on the example of samples taken from Wroclaw bridges, such as the Central Pomorski Bridge, North Pomorski Bridge and Sand Bridge. In each case it has been shown that there are degradation changes on the microstructure level. Such situation is not neutral for the basic strength characteristics. A drop in steel ductility and increase in its hardness favour brittle cracking. In such circumstances the cracking mechanics is a very valuable tool. The research results for fatigue cracking gap development in the puddled steel coming from the Sand Bridge operated for 149 years are presented. The results obtained for the post-operating state are comparable with those achieved by independent research teams [1, 8]. What differs the results of the authors' study from those presented in the papers mentioned here is the performance of the tests in two states: the after-operation and the normalized. The differences in fatigue cracking kinetics observed in areas I and III (Fig. 6), may result from the development of degradation processes (threshold range of ΔK_{th} and fatigue fracture toughness ΔK_{fc}). However, since a small number of samples in the tests were used the statistical verification is not reliable. That is why, while making a hypothesis that such kinetics changes are a rule, one have to be cautious. In the rectilinear part instead, the relatively high m exponent value in the Paris law is noticeable, while the lack of differences in the fatigue cracking kinetics in that area may indicate the insensitivity of the crack propagation way to structure. That seems to be supported by the experimental facts known in the cracking mechanics. Independently of the results obtained (here, the notice related to difference in the fatigue cracking kinetics) the cracking mechanics enables rational planning of the cracking inspection periods in the structural components.

РЕЗЮМЕ. Досліджено сталі мостів біля Вроцлава (Польща): дві пудлингові, експлуатовані з 1861 і 1885 рр., а також ливарну (1930 р.). Сталі, особливо пудлингові, чутливі до деградаційних процесів, що проявилось у зміні структури і механічних властивостей, найвідчутніше – у зниженні опору втомному росту тріщини.

РЕЗЮМЕ. Исследованы стали мостов в районе Вроцлава (Польша): две пудлинговые, эксплуатируемые с 1861 и 1885 гг., а также литейную (1930 г.). Стали, особенно пудлинговые, чувствительны к деградационным процессам, что проявилось как в изменении структуры, так и механических свойств, наиболее значительно – в понижении сопротивления усталостному росту трещин.

1. *Dudek D., Oziemski S., and Sobczykiewicz W.* Elements of the machine degradation theory // Problematics of the Working Machines. – 1994. – № 4. – P. 5–35 (in Polish).
2. *Pękalski G.* Material aspects of the surface mining machines degradation and theories of relevant processes // Report of the SPR series. – 1999. – № 14. – P. 105–131 (in Polish).
3. *Rabiega J. and Pękalski G.* Material tests of the Pomorskie Bridges: South, Central and North over the Odra River in Wrocław // Report of the SPR series. – 2007. – № 9. – P. 47–84.
4. *Hydrogen* degradation of steels in gas mains after long period of operation / O. T. Tsyrulnyk, H. M. Nykyforchyn, Yu. D. Petryna et al. // Materials Science. – 2007. – № 5. – P. 708–717.
5. *In-service* degradation of trunk gas pipeline X52 steel / G. Gabetta, H. M. Nykyforchyn, E. Lunarska et al. // Materials Science. – 2008. – № 1. – P. 104–119.
6. *Pękalski G.* Material aspects of the degradation theory – conception of a multi-criterion system of estimation of the state of material // Systems. – 1998. – № 3. – P. 108–129 (in Polish).
7. *Dudziński W. and Haimann K.* Evaluation of the degradation degree in materials applied in surface mining machines using the method of electron microscopy // III Scientific Conf.: Experimental Methods in machine building and operation, Wrocław–Szklarska Poręba, 1997. – P. 243–253 (in Polish).
8. *Bodarski Z. and Czapliński K.* Former iron construction materials in the light of historical development // Conf. Proc.: Repair and reinforcement of metal structures, lightweight lining and industrial floors, Ustroń, 2000. – P. 87–133 (in Polish).
9. *Czapliński K.* Former products from iron alloys // Lower Silesia Education Publishing, Wrocław, 2009 (in Polish).
10. *Lesiuk G. and Szata M.* Microstructural degradation processes in elements of bridges erected at the turn of the 19th and 20th centuries // Zeszyty Naukowe Wyższej Szkoły Oficerskiej we Wrocławiu. – 2010. – № 1. – P. 96–109.
11. *Wiecha L.* Evaluation of the degrading state of the Sand Bridge // MSc. Thesis, supervisor Pekalski Grzegorz, Wroclaw University of Technology. – Wroclaw, 2009. – P. 47–53 (in Polish).

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