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DETERIORATION OF STEEL PROPERTIES IN CORRODED SHEETS APPLIED TO SIDE SURFACE OF TANKS FOR LIQUID FUELS

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Abstract. Results of experimental investigations concerning a quantitative assessment of the influence of corrosion intensity in sheets applied to side surface of tanks for liquid fuels on values of mechanical properties of steel they have been made from, have been presented and analysed. Noticeable reduction of steel yield point as well as growth of its brittleness have been observed mainly in sheet zones with not uniform and pitting corrosion. The reason for such an occurrence is associated to impairment of cementite skeleton of steel, as well as to accumulation of micro-damages and micro-notches, both inside of material structure and on its surface, what resulted in local stress concentrations.

Keywords: corrosion, steel tanks, steel properties, tensile strength, impact resistance, brittleness, micro-notches.

1. Introduction

Destructive influence of corrosion on bearing capacity of steel member is most commonly associated only to a progressing in time diminution of its transverse section area which can carry the applied loads. Thus an assessment of technical condition of corroded structure in moment, when $\tau > \tau_0$ (τ_0 stands for commencement of its exploitation) requires collection of data that specifies actual, reduced comparing to initial, geometric measurements and their further statistical analysis. Diminished section area (or section modulus for bending elements) corrected in such a way is used to define an actual bearing capacity of a section. Moreover, it is assumed that a steel yield point f_y is constant in time, thus does not depend on type and advancement of corrosion. In case of ground tanks used for storage of liquid fuels, a reliable measure to apply for this purpose is a decrease of thickness of side surface steel sheets t. Correctly designed strip of such a side surface must ensure a safe exploitation for the whole structure during the time at least equal to foreseen service time τ_{req}, what means that $t_\tau = t\left(\tau \le \tau_{req}\right) > t_{\min}$. Therefore, to a minimal required thickness of side surface t_{min}, calculated on the base of bearing capacity condition without consideration of corrosion impact, an additional material allowance Δt is added in order to balance foreseen deterioration due to corrosion. Finally, the nominal sheet thickness is applied as $t_{nom} \ge t_{\min} + \Delta t$.

According to the authors, an approach that considers an impact of corrosion only by appropriate reduction of geometric measurements, should be regarded as insufficient, especially when structures with a particularly high risk and consequences of corrosive destruction are concerned. It regards especially steel chimneys and ground tanks for liquid fuels. It is so because this method totally ignores a different, yet not less important effect of corrosion – a deterioration of mechanical properties of corroded steel, especially the reduction of minimal yield point $R_{e,min}$ and ultimate tensile strength R_m, as well as the increase of its brittleness. Such a phenomenon is particularly dangerous in all cases when corrosion is not uniform and especially when it is accompanied by pitting corrosion.

The deterioration ratio of basic mechanical characteristics of corroded steel has been mainly studied in relation to reinforcing bars in concrete members (Almusallam 2001; Xu *et al.* 2003; Apostolopoulos *et al.* 2006; Apostolopoulos and Michalopoulos 2007). However, analogous experiments have been also carried out for different types of corroded constructional steel. One of the first of those was performed as early as in the late sixties (Suprunchuk *et al.* 1967). Let us notice the results obtained by Chen *et al.* (2005a) and Chen *et al.* (2005b). They have tested three kinds of steel: carbon steel (SS400), low-alloy steel (1604A, 1604B, 1605A, 1605B) and weathering steel (Acr-Ten A). Consequently, they have proved the monotonic diminution of steel properties related to increasing intensity of corrosive changes. However, they explain this phenomenon quite generally by an increased roughness of steel surface that makes local stress concentrations more probable to occur. Furthermore, the

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reliability-based algorithm for resistance evaluation of randomly corroded steel thin-walled structural members (as well as their life indices estimation), in which the reduction of initial material properties is taken into account, has been proposed by Gorokhov and Korolyov (2000).

It is necessary to pay attention that the corrosion process in refinery equipment, especially in tanks for oil or for the other liquid fuel storage, go through for specific corrosive agents (Garverick 1994; Harston and Ropital 2007), and therefore the results obtained by the authors cited above, for samples taken from typical steel structures, have not to be authoritative in the considered case. Some suggestions in the field of specific durability analysis for such type of steel tanks being in operation have been given by Yegorov (2002).

In Poland, an influence of corrosion on the reduction of steel resistance is considered practically only in design of steel chimneys. Standard *PN-93/B-03201* (1993) specifies a corrective coefficient $\alpha_{cor}(\tau) = \left[1 + 0.04\left(t_{nom} - t_\tau\right)\right]^{-1}$, which reduces design resistance $f_{d,red}(\tau) = \alpha_{cor}(\tau) f_d$. Włodarczyk (1998) proposes the value 0,04 used in the above equation to be exchanged for even more strict one of 0,05, basing on his own analysis and research. It is supposed that introducing a similar coefficient to design of steel tanks, referred to in the present paper, may constitute a significant completion to a detailed specification regarding anticorrosion protection and correct exploitation (for instance, due to *PN-B-03210:1997* (1997) standard). In order to define its value, it is necessary to undertake a representative experimental research. The results of research, carried out by the authors and presented in this paper, have been obtained during a technical assessment of only several fuel tanks, and therefore they are only preliminary and cannot be generalized.

2. Description of examined tanks

Material for analysis was taken from two tanks under renovation in a fuel base, each of volume $V = 2000\ \mathrm{m}^3$, with floating roof, constructed in 1975 according to typical technical documentation (tanks No. 3 and 4). Samples were cut from side surface steel on the level of wind bracing (Fig. 1), because in this area an intense pitting corrosion was observed. Tested sheets, as per archival documentation, had the initial thickness of $t_{nom} = 5\ mm$ and were made of balanced steel St3SY (an equivalent of the present S235JR). Tanks documentation did not include original metallurgical certificates and any other information about real chemical composition of an applied material. Control tests carried out with emission spectrometer *ARL 2460* confirmed that it fulfils requirements of standards for steel of this type. Initially outer and inner surfaces of inspected sheets were protected with varnish coat which endured mainly on the internal side of surface. Outer coating was locally completely destroyed (Fig. 2).

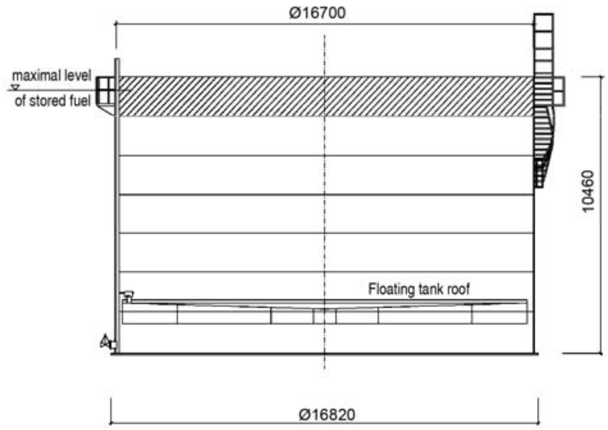

Fig. 1. Outline of tanks No. 3 and No. 4 with marked belt of side surface, from where corroded material was sampled

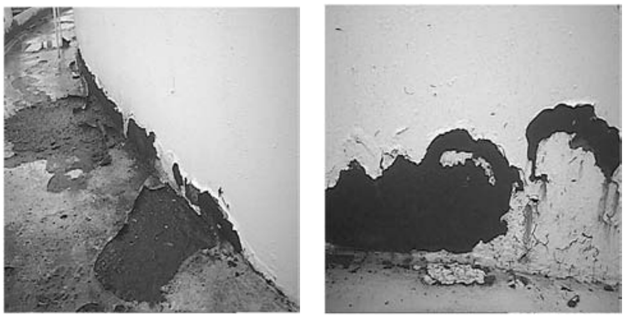

Fig. 2. Photographs of corrosive changes in belt of tank side surface on the level of wind bracing (visible areas of general not uniform corrosion)

All samples taken for testing from tanks No. 3 and 4 were oriented lengthwise to direction of rolling of steel sheets on side surface. Samples were taken adjacently to tanks circumference from the following characteristic areas:

- *area of general uniform corrosion* – noticed in places where protective coat layer was not destroyed; occurrence of oxygenated layers was stated of approximately 0.1÷0.3 mm thickness between varnish and clean steel surface as the result of diffusion of oxygen through varnish layer over many years,
- *area of general not uniform corrosion* – occurring locally in several places of the belt; it developed on surfaces initially covered by uniform corrosion, mainly in places where protective coating got damaged previously; areas were irregular, mostly of 20÷40 cm dimension (compare Fig. 2); therefore it can be considered as *a local corrosion*, following standard *PN-EN ISO 8044:2002* (2002),
- *area of average-width pitting corrosion* – according to *Champion's* classification; width of such a corrosive pit is approximately equal to its depth; noticed pits were developing in areas especially prone to corrosion (for example in all areas where accumulation of humidity and pollution was easier due to difficult access) and reached depth of average 1.5 mm, and maximally 2 mm, inside the material.

The research was completed with the analysis of material samples, taken in different time from tank with fixed roof, of volume $V = 320$ m^3, being renovated in the same fuel base, and used for storage of heavy combustible oil - mazout (tank No. 22 – Fig. 3). In this case areas of general uniform corrosion, as well as general not uniform and pitting corrosion, were noticeable, after removal of thermal insulation layer, mainly on outer side of tank (compare Fig. 3(a)). Corrosion was caused by humidity condensing between insulation and sheet surface. The only real protection was a painting coat, locally destroyed. Corrosion of internal surfaces of side surface sheets was partially limited by constantly present thin layer of stored mazout insulating from corrosive factors. Samples from tank No. 22 were cut out of sheets of the lowest and the most strained belt of thickness $t_{nom} = 4$ mm.

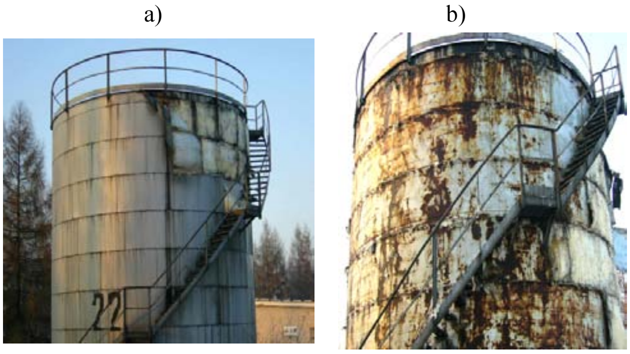

Fig. 3. Tank No. 22: a) during removal of insulation, b) corrosive changes on tank side surface after removal of protective layer

Tank No. 22, similarly to tanks No. 3 and 4, was made of balanced steel St3SY. According to actually binding regulations (*PN-B-03210:1997* 1997) steel of this kind is recommended for covering of tanks only up to thickness $t_{nom} \leq 10$ mm, provide it will be exploited mainly in mild temperatures. Because in real exploitation conditions such a limitation is difficult to fulfil, the authors paid much attention to impact resistance tests in negative temperatures.

In addition, the problem of coupling of an influence of particular corrosion types with the effect of anisotropy of mechanical characteristics of steel in this kind of sheets was taken into consideration. For this purpose two groups of samples were prepared, diverse only by direction of sampling from genuine material, especially:

- samples of direction A – with horizontal orientation, identical with direction of steel rolling,
- samples of direction B – with vertical orientation identical with transversal direction to steel rolling.

According to the authors, diversification of steel characteristics depending on direction of taking samples should be especially outlined in sheets made of balanced steel St3SY, being of lower quality than fully deoxidized steel St3S (S235JRG2).

3. Static tensile strength test

Some of the test results, obtained by the authors, were already published in our earlier papers (Maślak *et al.* 2004; Maślak *et al.* 2007). Strength testing was carried out at temperature of 23 °C for tanks No. 3 and 4, and 20 °C for tank No. 22, using machine *Instron 1273*, with flat quintuple samples, of orientation lengthwise to direction of steel rolling, as for requirements of standard (*PN-EN 10002-1:2004* 2004). Three samples were applied for one measurement point (except samples 3.5 and 4.5).

Samples from areas of uniform and not uniform corrosion were taken with preservation of original steel surface, after previous removal of loose oxygenated layer by brushing. For samples with pitting corrosion, due to necessity to precisely specify the initial section area A_0 on measurement length, machining was carried out in order to remove pits. The area of cross-section of such samples was specified each time taking into consideration a maximal random value of sheet thickness on measurement length. In this way minimal values of $R_{e,\min}$ and R_m, random on this length, were obtained in each measurement (in practice differences of thicknesses both for separate samples and between samples did not exceed hundredths of millimetre).

Results of testing the material from tanks No. 3 and 4 are specified in Table 1, while from tank No. 22 in Table 2. Such a method of preparing samples with pitting corrosion was determined by the authors' aspiration to obtain relatively reliable values of tested material constants, which required unequivocal determination of representative thickness of sample. Of course, due to unforeseeable place of rupture, obtained results must be considered only as a lower, safe estimation of real values of $R_{e,\min}$ and R_m.

The removal of external layer of deep corrosive pits meant as well the elimination of surface notches. In order to consider destructive influence of such type of notches on bearing capacity of corroded steel sheet, two additional samples were prepared – (3.5 and 4.5), from which pit corrosion layer was not removed. Significant differences in thicknesses of measurement lengths of so prepared samples did not allow a precise and unambiguous specification of initial section area A_0 values. Besides, it was not possible to specify the place of sample rupture beforehand. Thus, in evaluation of degree of sheet deterioration an equivalent section area A_{eq} was applied, considering only minimal on measurement length influence of general not uniform corrosion, and omitting any decreases due to corrosive pits. Thus values R_e, R_m and $A_{5,65}$ (Table 1), obtained by this method, are not strictly the material constants, as they consider not only change of mechanical characteristics of steel but also corrosive losses in the place of sample rupture. They are, nevertheless, a kind of indication of material condition, considering the combination of effect of mechanical steel properties degradation with reduction of its bearing capacity caused by surface notches.

Table 1. Results of static tensile strength test of material from tanks No. 3 and 4

Place of sampling	Sample number	R_e [MPa]	R_m [MPa]	$A_{5,65}$ [%]
Tank No. 3				
Areas of general uniform corrosion	3.1.1	299	417	34.4
	3.1.2	288	411	31.2
	3.1.3	299	416	32.7
	Mean	295	415	32.8
Areas of general not uniform corrosion	3.2.1	263	383	27.9
	3.2.2	255	378	32.3
	3.2.3	256	379	31.2
	Mean	258	380	30.5
Areas of pitting corrosion	3.4.1	276	390	30.0
	3.4.2	269	385	26.2
	3.4.3	270	389	35.0
	Mean	272	388	30.4
	3.5 *)	160	357	20.6
Tank No. 4				
Areas of general uniform corrosion	4.1.1	288	405	33.5
	4.1.2	293	408	32.9
	4.1.3	290	405	32.5
	Mean	290	406	33.0
Areas of general not uniform corrosion	4.2.1	268	388	37.9
	4.2.2	261	386	31.7
	4.2.3	268	385	36.2
	Mean	266	386	35.3
Areas of pitting corrosion	4.4.1	266	384	35.8
	4.4.2	268	391	31.1
	4.4.3	274	405	24.5
	Mean	269	393	30.5
	4.5 *)	188	311	11.7

*) sample in which pit corrosion layer on measurement length was not removed (results R_e, R_m and $A_{5,65}$ are defined for an equivalent section area A_{eq} instead of an initial section area A_0).

Table 2. Results of static tensile strength test of material from tank No. 22

Place of sampling	Sample number	R_e [MPa]	R_m [MPa]	$A_{5,65}$ [%]
Direction A				
Areas of general uniform corrosion	22.1.1	294	416	38,5
	22.1.2	299	421	40.2
	22.1.3	302	418	37.9
	Mean	298	418	38.9
Areas of general not uniform corrosion	22.2.1	272	402	34.6
	22.2.2	272	390	17.6
	22.2.3	238	354	16.9
	Mean	261	382	23.0
Areas of pitting corrosion	22.3.1	255	378	32.5
	22.3.2	254	384	25.8
	22.3.3	257	387	23.0
	Mean	255	383	27.1
Direction B				
Areas of general uniform corrosion	22.1.1	303	411	35.0
	22.1.2	312	414	34.8
	22.1.3	305	408	31.9
	Mean	307	411	33.9
Areas of general not uniform corrosion	22.2.1	270	400	27.5
	22.2.2	267	387	38.8
	22.2.3	264	379	25.2
	Mean	267	389	30.5
Areas of pitting corrosion	22.3.1	277	403	33.7
	22.3.2	261	377	23.3
	22.3.3	267	388	26.5
	Mean	268	389	27.8

4. Impact resistance test

To measure the impact resistance, *Charpy's* hammer type *PS30*, having potential energy of 300 J, was used as a testing device, according to regulations of standard (*PN-EN 10045-1:1994* 1994). Testing was carried out at 23 °C for tanks No. 3 and 4, and 20 °C for tank No. 22. Besides that, an additional impact resistance test was carried out at temperature of –20 °C on samples from area of not uniform corrosion of tanks No. 3 and No. 4, as well as on samples cut from area of pitting corrosion in tank No. 22. Samples tested in negative temperature were cooled in alcoholic cryostat for at least 15 min from the moment of obtaining the established testing temperature. Patterns with *Charpy V* notch were used (3 pieces for one measurement point), according to requirements specified by standard (*EN 10025-2:2002* 2002). All samples used for testing were undersized due to small thickness of tested sheets. Results of impact resistance tests are specified in Tables 3 and 4.

5. Examination of sheets microstructure and morphology of fractures

Examination of microstructure was carried out with optical microscope *Leica Q500MC* with digital picture registration, on lengthwise polished sections non etched, and etched with 5% solution of *Nital*, at 25 and 200-times magnification. Fig. 4 shows edges of sheets taken from external surface of tanks No. 3 and 4. They were located in tested belts of tank side surface on the level of wind bracing, thus in zones of dominating significance of general, not uniform corrosion. These areas are unprotected against corrosion due to degradation and varnish loss. Photographs illustrate occurrence of small pits on surface of sheets which are surface notches.

a) b)

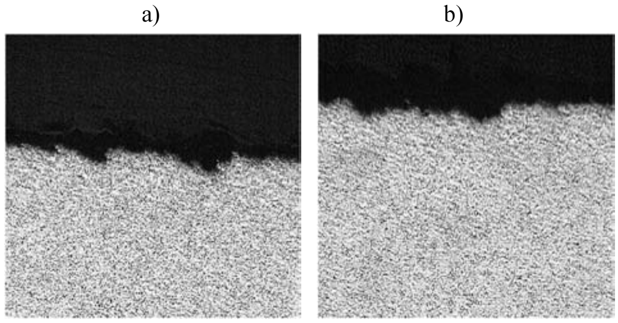

Fig. 4. Corroded edges of sheets in 25-times magnification: a) sheet from tank No. 3, b) sheet from tank No. 4. Etched with Nital solution. Dark areas in upper part of photography – resin with which samples were covered before executing polished sections

Table 3. Results of KCV impact resistance test for steel from tanks No. 3 and 4

Place of sampling	Sample number	*KCV* [J/cm²] 23°C	*KCV* [J/cm²] –20 °C
Tank No. 3			
Areas of general uniform corrosion	3.1.1	150.5	–
	3.1.2	135	–
	3.1.3	131.5	–
	Mean	139	–
Areas of general, not uniform corrosion	3.2.1	137	–
	3.2.2	134	–
	3.2.3	131	–
	Mean	134	–
	3.3.1	–	127
	3.3.2	–	110
	3.3.3	–	124
	Mean	–	120
Areas of pitting corrosion	3.4.1	56.5	–
	3.4.2	119.5	–
	3.4.3	139	–
	Mean	105	–
Tank No. 4			
Areas of general uniform corrosion	4.1.1	131	–
	4.1.2	131	–
	4.1.3	129	–
	Mean	130	–
Areas of general, not uniform corrosion	4.2.1	121	–
	4.2.2	123	–
	4.2.3	121	–
	Mean	122	–
	4.3.1	–	32.5
	4.3.2	–	50
	4.3.3	–	18.5
	Mean	–	33.5
Areas of pitting corrosion	4.4.1	53.5	–
	4.4.2	52.5	–
	4.4.3	44.5	–
	Mean	50	–

Table 4. Results of KCV impact resistance test for steel from tank No. 22

Place of sampling	Sample number	*KCV* [J/cm²] 20°C	*KCV* [J/cm²] –20 °C
Direction A			
Areas of general uniform corrosion	22.1.1	134.5	–
	22.1.2	123.5	–
	22.1.3	128	–
	Mean	129	–
Areas of general, not uniform corrosion	22.2.1	126.5	–
	22.2.2	128	–
	22.2.3	131	–
	Mean	128.5	–
Areas of pitting corrosion	22.3.1	128	–
	22.3.2	131	–
	22.3.3	123.5	–
	Mean	127.5	–
	22.4.1	–	114
	22.4.2	–	125
	22.4.3	–	137
	Mean	–	125
Direction B			
Areas of general uniform corrosion	22.1.1	69	–
	22.1.2	67	–
	22.1.3	67	–
	Mean	68	–
Areas of general, not uniform corrosion	22.2.1	62.5	–
	22.2.2	62.5	–
	22.2.3	68.5	–
	Mean	65.5	–
Areas of pitting corrosion	22.3.1	61	–
	22.3.2	58	–
	22.3.3	59.5	–
	Mean	59.5	–
	22.4.1	–	59.5
	22.4.2	–	62.5
	22.4.3	–	58
	Mean	–	60

Microstructure of sheets (Fig. 5) has a ferritic-pearlitic character, typical of St3SY steel, with a majority of ferrite grains. Fig. 6 shows a non etched polished section, where significant degree of non-metallic pollution can be noticed, being mainly cold shuts, probably of manganese sulphide MnS, which have an unfavourable form of long range of sharp edges aligned in parallel to steel rolling direction.

a) b)

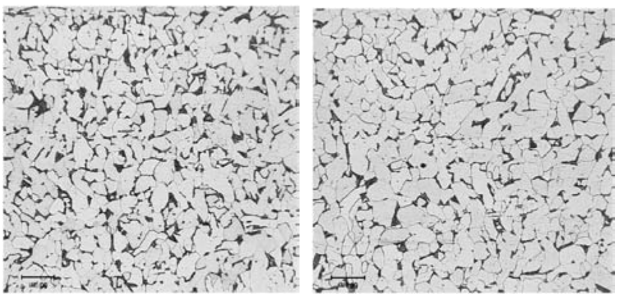

Fig. 5. Microstructure of examined sheets, magnified 200 times, etched with Nital solution: a) sheet from tank No. 3, b) sheet from tank No. 4

a) b)

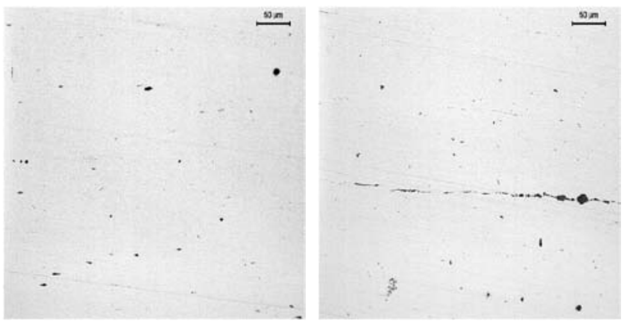

Fig. 6. Non-metallic inclusions in tested sheets, not etched polished sections, magnified 200 times: a) sheet from tank No. 3, b) sheet from tank No. 4, visible range of MnS cold shut

Fracture morphology was examined using *Joel* scanning microscope, on samples of fractures obtained after impact resistance tests of sheets from tank No. 4, at 100, 200 and 1000 times magnifications. In case of samples broken at 23 °C a typical plastic fracture was obtained (Fig. 7). Numerous delaminations and craters remaining after removal of non-metallic inclusions can be noticed, corresponding with the character of pollutions shown in Fig. 6. Morphology of fracture of samples broken in temperature of –20 °C (Fig. 8) shows a different, brittle trans-crystalline fracture characterised by a very low impact resistance, what corresponds well with the results of impact resistance tests (Table 3).

a) b)

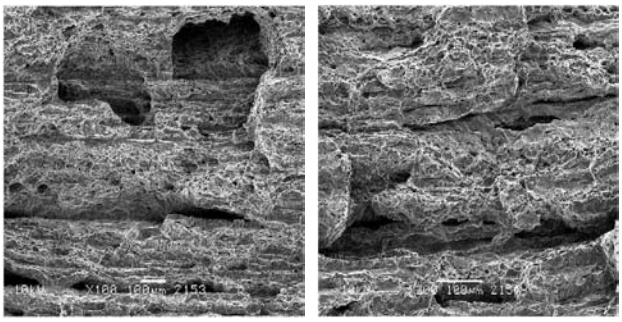

Fig. 7. Fracture morphology of impact resistance samples from tank No. 4 broken at 23 °C. Plastic fracture. Magnification: a) 100 times, b) 200 times

a) b)

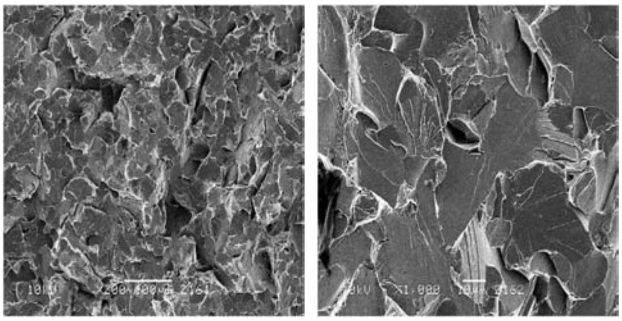

Fig. 8. Fracture morphology of impact resistance samples from tank No. 4 broken at –20 °C. Brittle trans-crystalline fracture. Magnification: a) 200 times, b) 1000 times

6. Analysis of results and conclusions

Tests carried out by the authors concerned only three rather small tanks. It should be underlined that these are not fully representative objects for all tanks for liquid fuels being exploited in Poland. There are already 4 structures with volume exceeding 100 000 m^3, and more than 60 with volume of 50 000 m^3 in our country. Obtained results cannot therefore be a base for generalisation, nevertheless, they draw attention to the issue.

Tests confirmed a significant degradation of basic mechanical properties of steel, caused by corrosion progressing in time. Reduction of R_e and R_m is particularly great at the moment, when material goes from phase of uniform corrosion, caused by diffusion of oxygen to atmosphere, over years through intact varnish coating, into a phase characterized by not uniform corrosion, usually developing around inevitable local damages in all kinds of anti-corrosive protections. This effect is strengthened by an unequal distribution of sheet resistance on the length of tank circumference, which results from random changeability of actual thickness of corroded belt of increasing intensity. The results for samples taken from not uniform corrosion area, both from tanks No. 3 and 4, as well as from those cut out from tank No. 22, revealed approximately 13% of relative decrease of steel yield point R_e, and approximately 5–9% reduction of ultimate tensile strength R_m, comparing to values for steel with uniform corrosion (Tables 1, 2). In this phase no significant loss of impact resistance of steel is observed (Tables 3, 4). According to the authors, the effect of material resistance decrease may be in this case connected with weakening the coherence and homogeneity of steel structure caused by corrosion. It regards especially a gradual degradation of integrity of internal cementite skeleton binding ferrite and pearlite grains. In case of no corrosion, a mechanical resistance of skeleton material is usually higher than grains resistance. However, the initiation of corrosion process causes the skeleton to become anodal in relation to the surface of grains, due to it is being attacked more intensely. Besides, a skeleton material is usually in scarcely organized state, therefore it has a relatively high stacking fault energy compared to the inside of grain.

Passage to sequent phase of material weakening due to corrosion is characterized by the appearance of increasing number of deep corrosion pits. Samples taken from areas of pitting corrosion (with removed pitted layer) did not prove a further decrease of resistance parameters comparing to those specified for not a uniform corrosion, but due to a noticeable diminution of active section area there is a significant reduction of limited internal loads: force F_e, initiating a permanent plastic deformation, and force F_m, corresponding to the ultimate tensile strength. In this phase of corrosion the superposition of previously observed effect of steel mechanical properties reduction, with a very unfavourable and relatively fast increasing influence of sheet bearing capacity deterioration, caused by corrosion pits, acting as surface notches, causing in local stress concentration, seems to be especially dangerous. Some evaluation of threat level, due to combined influence of both factors, was obtained from tests of samples 3.5 and 4.5, with remaining pitted layer, for which values R_e, R_m and $A_{5,65}$ were indicated, with regard to the area of substitutive section A_{eq}. Due to the fact that such section area is defined by corrosive losses caused by only general not uniform corrosion, a destructive influence of pits in this case is totally included in the apparent reduction of steel properties. It can be noticed that substitutive values of R_e and R_m corrected in such a way, are much below minimal design values required by standards for steel St3S (S235JR) ($R_{e,\min} = 235$ MPa, $R_{m,\min} = 375$ MPa). Nevertheless, the values from tests are not comparable with standard values due to a different method of determination. For the same reason they should not be identified with real material constants describing properties of corroded steel. It seems that an optimal solution in this case would be to introduce, analogically to standard *PN-93/B-03201* (1993), an additional coefficient α_{pit} (*pitting corrosion*) reducing the bearing capacity of sheets.

Values of elongations $A_{5,65}$ of samples 3.5 and 4.5 with pitting corrosion also do not fulfil minimum required by standard (26%). It proves a significant reduction of steel ductility and increase of its brittleness, what is confirmed by impact resistance tests (Tables 1 and 3). This is particularly dangerous, as may lead to brittle cracking of steel especially in winter conditions (see impact resistance test KCV at temperature –20 °C).

Results of impact resistance tests KCV at room temperature of samples of lengthwise orientation (along direction of steel rolling) practically do not reveal any significant changes of its real value in areas with increasing degree of damages of corroded surface. It seems justified to suppose that in the analysed case it reaches 120–130 J/cm^2. Yet it has to be underlined that the areas with advanced pitting corrosion are a significant exception. Results obtained from some of samples, especially cut out from tank No. 4, shown a sudden loss of impact resistance to approximately 50 J/cm^2. Admittedly, these results are still acceptable, but, accompanied by a relatively low steel ductility (small values of elongations $A_{5,65}$), clearly prove a significant increase of steel brittleness in this area.

The authors associate this effect with activation of considerable number of inner micro-notches in pitting corroded steel (apart from described previously surface notches). This hypothesis seems to find confirmation in results of material microstructure and fractures morphology tests presented in this paper. Examination of etched polished sections, especially on samples from tank No. 4, shown a high content of non-metallic inclusions, particularly manganese sulphide, shaped unfavourably in a range (Fig. 6(b)). These must be related to technological shortages of metallurgy 30 years ago. Such inclusions constitute internal notches present during all exploitation time of tank, thus seemingly not connected directly with a corrosion of steel. Nevertheless, it should be pointed out that they are not coherent with metallic matrix by what they get easily pulled out from genuine material leaving craters on borders of grains (Fig. 7). According to *Evans* theory, such micro-damages together with different defects of metal surface can be treated as probable seeds of corrosive pits. Each pit in sequence transforms into surface notch, causing stress concentration and by this weakening the material resistance. Thus, it may be concluded, that the more polluted material, the more micro-defects and micro-notches, and so the lower corrosion resistance. Another considerably important fact is that these notches noticeably rise a temperature of conversion from plastic state into brittle one, what is a negative occurrence. Sooner brittleness of steel, according to theory of *Dix*, further developed by *Keating* and *Evans*, facilitates propagation of corrosive stress cracks. It is particularly important for tank side surface sheets in which tensile stresses are dominating. Such a stress state induces opening and activation of micro-cracks created in the metal. Generalizing, an increase of temperature of conversion into a brittle state and, in consequence, an increase of steel brittleness at room temperature seems to satisfactorily explain an observed effect during tests of impact resistance of the described above sample taken from tank No. 4. Intensification of such process takes obviously place in winter conditions, when the impact resistance is much lower (Tables 3, 4).

Such conclusions seem to find the confirmation in the results of experiments performed by Ohashi *et al.* (2001). The bend tests were carried out on a roughened, corroded steel annular plate, prepared from an oil storage tank. It was found there that a marked decrease of load-carrying capacity, occurred in the high deflection region, depends on the degree of corrosion damage. The reason for extensive loss of such capacity was explained on the base of successive observation of crack growth behaviour on the corroded surface of the considered annular plate.

Much poorer impact resistance of steel with pitting corrosion from tank No. 4 comparing to analogical material cut out from tank No. 3, constructed at the same time and with the use of identical steel type is explained by significant differences in concentration and depth of observed corrosive pits. This conclusion corresponds well with an increased number of non-metallic inclusions in tank No. 4 (Fig. 6(b)) revealed by microscopic examination. It proves a very important role of melt quality and rolling method for further corrosion resistance and indirectly for bearing capacity of tank side surface, what is rarely considered in practice.

Although in side surface sheets of fuel tanks the most important are circumferential tension stresses, nevertheless, an outstanding anisotropy of impact resistance of steel cannot remain unnoticed. It seems that such a significant decrease of its value in samples of orientation perpendicular to direction of rolling (Table 4) cannot be explained only by application of balance steel type and lacks in metallurgic technology 30 years ago. This issue requires further research.

It has to be noticed as well that differences between results for samples cut out from tanks No. 3 and No. 4, and those taken for tank No. 22, may partially result from a different location of tested material in the tank. While it seems justified to assume that the corroded belt of tank side surface supporting wind bracing (analysed in case of tanks No. 3 and No. 4) is working in membrane condition, and even in uniaxial stress state, then in the case of sheets taken from tank No. 22, we encounter a complex stress state due to boundary disturbances near connection of side surface sheet with the bottom of tank.

With time passing local corrosive damages may turn into a strip of significant width, covering a big part of tank circumference. Then it is necessary to exchange the whole fragments of tank side surface. Therefore, it is essential to apply an anti-corrosive protection and to monitor it regularly. Yet it should be realized that even a suitable early execution of repair works consisted in applying such a protection, may not guarantee further trouble-free tank service, unless a reduction of resistance parameters due to not uniform and pitting corrosion is taken into account.

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SURŪDIJUSIŲ LAKŠTŲ, NAUDOTŲ SKYSTOJO KURO TALPYKLŲ IŠORINIAMS PAVIRŠIAMS, PLIENO SAVYBIŲ BLOGĖJIMAS

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S a n t r a u k a

Pateikti ir aptarti eksperimentinių tyrimų, susijusių su lakštų, naudotų skystojo kuro talpyklų išoriniams paviršiams, rūdijimo intensyvumo poveikio į plieno, iš kurio jie buvo pagaminti, mechaninių savybių skaitiniu įvertinimu, rezultatai. Vertas dėmesio plieno takumo ribos sumažėjimas, taip pat jo trapumo padidėjimas, buvo pastebėti lakštų srityse, pakenktose tolygiojo ir taškinio rūdijimo. Tokio atvejo priežastis siejama su plieno cementito griaučių gadinimu, taip pat su mikropažaidų ir mikrogriovelių sankaupa, abiems esant medžiagos sandaroje ir ant jos paviršiaus. Tai sukėlė vietinių įtempių santalką.

Reikšminiai žodžiai: rūdijimas, plieninės skysčių talpyklos, plieno savybės, tempiamasis stipris, smūginė laikomoji galia, trapumas, mikrogrioveliai.

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