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Corrosion-Hydrogen Degradation of the Shukhov Lattice Construction Steels

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Abstract

The technical state of the 100-year-old Shukhov lattice towers (in cities Mykolayiv and Cherkasy in Ukraine) and the Adziogol Lighthouse, located at the mouth of the Dnipro river, under the project of genius Russian engineer V. G. Shukhov with a use of widespread at that time rivet connection, is analysed. The peculiarity of such lattice hyperboloid designs consists in a minimisation of metal capacity. These unique constructions should be saved as the monuments of industrial architecture. The towers were partially broken-down in 1944 and later restored with a use of the weld technologies, therefore the problem of the workability evaluation of the weld joints is added. The results of the expertise of the structures from the point of materials science and corrosion-mechanical aspects of this problem are presented. The chemical content, corrosion and mechanical properties of authentic and repair metal are studied and the reasons of fracture of welds are analysed. It was established that the in-bulk angle metal of Adziogol Lighthouse is characterised by the lowest corrosion resistance what can be connected with the steel hydrogenation in the conditions of the near Black Sea environment. This factor intensifies in-bulk material degradation and therefore causes a sensitivity of the weld metal to stress corrosion cracking.

Keywords: tower; steel; fracture; corrosion; hydrogen

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1. Introduction

An investigation of long-term exploited steel constructions is of great importance. Special attention of scientific society is aimed recently for a saving the old metal constructions what predicts diagnostics of its structural strength. In particular, studies of the steel bridges, built in XVIII-XIX centuries, are carried out by Granat et al. (2010), Lesiuk and Szata (2011), De Jesus et al. (2011).

To such designs it is possible to add hyperboloid lattice towers, built at the beginning of XX century by the projects of the Russian engineer V. G. Shukhov, is reported by Kutnyi and Becker (2011). In comparison with other constructions of that time, their metal capacity is three times lower for the same ability to maintain loading. These constructions are not only monuments of the genius engineering decision for minimization of metal capacity but also serve as a basis for modern high buildings design. For example, the Canton Tower in China, built in 2010, also known as Guangzhou TV Astronomical and Sightseeing Tower, is 610 m high.

There are some monuments like this in Ukraine. Mainly, these are still operating lighthouses in the mouth of the Dnipro river and water-towers. Although they are not used in water-supply systems any more, it is important to save them as heritage sights of industrial architecture. Therefore they need research taking into account their technical state.

The main structural elements of Shukhov towers are triangles (the size of its shelf is of 10-15 mm) from low-carbon steel, connected by riveting. Structurally towers are made of distorted lines of triangles (Fig. 1), which are fixed with a help of series of horizontally located bent ring-like rims, from steel strips or triangles. Repair works were carried out by using more modern metal and welding technologies for constructions renovation and maintenance of their proper technical state (the towers were undermined during the military operations of the Second World War). Therefore at the modern stage it is important to investigate both the aged and later, the post-war manufactured steels of the lattice Shukhov towers, including the riveted and weld joints.

Fig. 1. General view of the Shukhov water-tower in Mykolayiv (a) and Cherkasy (b) cities, and Adziogol lighthouse (c).

2. Objects, materials and methods

The study objects are the water-towers in the cities Mykolayiv and Cherkasy, and the Adziogol lighthouse (photo by Kutnyi (2013)), located at the mouth of the Dnipro river with a peculiarity of service under the effect of sea atmosphere. A chemical content of the metal was determined on the atomic-emission spectrometer SPECTROMAX LMF 0.5, Brinell hardness HB – by the portable universal hardness meter NOVOTEST as an average value of 50 intentions, and metallographic observations were carried out as well.
The corrosion resistance of the steels was analysed on the basis of electrochemical research, construction of the potentiodynamic polarization curves (potential scan rate was of 1 mV/s, the reference electrode – Ag/AgCl). The aqueous NaCl solutions were used as corrosion environments: 0.3% (wt), the mineralization level of which corresponds to the atmospheric precipitation, and 3% (wt), which imitates sea water. All the tests were performed at ambient temperature and in open to air. The basic electrochemical characteristics of material (stationary potential $E_{st}$, corrosion current density $i_{corr}$, Tafel constants of anodic and cathode reactions $b_a$, $b_c$) were determined by the graph-analytic method. Polarization resistance was calculated using the Stern-Geary equation: $\Delta E/\Delta i = R_p = K/i_{corr}$, where constant $K = b_a \cdot b_c / [2.3 \cdot (b_a + b_c)]$.

3. Test results and discussion.

The main reason of a loss of the constructions integrity is atmospheric corrosion of metal. The characteristic corrosion damages of the basic elements of the Mykolayiv tower are presented in Fig. 2. The low part of the construction is the most damaged, including the riveted joints (Fig. 2a). Crevice corrosion in the places of the weld joints was revealed (Fig. 2b). The damage depth exceeded half of the weld thickness, and this indicates a substantial local loss of the ability to hold mechanical loading.

Fig. 2. The typical corrosion damages of structural elements: a – general corrosion of the riveted joint; b – crevice corrosion of the weld joint; c – stratification of metal from the triangle butt-end; d – stress corrosion cracking along weld metal.

The characteristic peculiarity of triangle degradation consists in its stratification from the butt-end which could spread practically throughout width of a triangle shelf (Fig. 2c). Such stratification of sheet or shaped rolling product can be connected with littering of metal by the detrimental nonmetallic inclusions, stretched under rolling by chainlets along the rolling direction. Obviously, the metallurgical technologies of the end of XIX – beginning of XX
centuries did not provide manufacturing of steel rolling clear enough for nonmetallic inclusions and attention to this problem was as high as it is in the present time, when harmfulness of such admixtures is evident. And metal with a plenty of nonmetallic inclusions is more sensitive to corrosion due a large electrochemical heterogeneity of its microstructure. All nonmetallic inclusions under the electrochemical interaction of metal with an aqueous environment play a role as effective cathodes which cause depolarization of anodic process of metal dissolution, and the more high its specific area on the steel triangles surface causes their more intensive corrosion. At the same time it is reported by Tsuru et al. (2005) that hydrogenation of metal is possible just near boundaries between inclusions and matrix as a result of the cathode process localization on nonmetallic inclusions. Hydrogen reduces substantially corrosion resistance of steel that was shown by Zakharuchuk et al. (2005). Hydrogen concentration along inclusion-matrix boundary can cause intergranular corrosion and its localization exactly on inclusion-matrix boundary. Besides – absorbed by metal hydrogen diffuses in the atomic state to inclusion boundary, where it recombines to the molecular state. As volume of hydrogen molecule is substantially more than volume of two atoms of hydrogen, its recombination is accompanied by creation of hydrogen gas pressure to the level, comparative with material local strength.

The other typical type of fracture was cracking of welded joints (Fig. 2d). An overload, fatigue or stress corrosion cracking can be assumed in relation to the mechanisms of formation of such cracks. A rectilinear character of crack propagation is peculiar for the first two types, since direction of crack growth is determined by the direction of applied tensile stresses. In our case the curvilinear trajectory of crack propagation and its branching were observed, that is peculiar for the process of stress corrosion cracking of metals. It is necessary to note that the corrosion process in places of limited access of environment can be accompanied by its acidifying, and that is why hydrogenation of metal can occur. This rises a risk of uncontrolled fracture due to the mechanisms of hydrogen embrittlement. Fracture of weld joints may occur also due to galvanic corrosion (Tsyrul'nyk et al., 2011).

The steel used in the different triangles of the Mykolayiv tower were substantially different concerning the chemical composition, in particular, the content of carbon (Table 1). So, the content of carbon of 0.40 mass. % in post-war steel makes the welding of triangles problematic. It is not excluded, that exactly it can explain a sensitivity of weld joint to stress corrosion cracking.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cu</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>authentic</td>
<td>0.28</td>
<td>0.48</td>
<td>0.006</td>
<td>0.013</td>
<td>0.043</td>
<td>0.019</td>
</tr>
<tr>
<td>repair metal</td>
<td>0.16</td>
<td>0.40</td>
<td>0.005</td>
<td>0.020</td>
<td>0.062</td>
<td>0.057</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>0.62</td>
<td>0.230</td>
<td>0.108</td>
<td>0.030</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Table 1. Chemical composition of steels of Shukhov water tower in Mykolayiv, mass. %.

Authentic and repair metals are also different concerning their hardness. Hardness of the metal of repaired triangles proved to be more stable, their values were in the range of 112 – 123 HB, the average value was 117 HB. Hardness of the authentic metal is substantially less - that it is possibly explained by the lower content of carbon. It changed in a wide range from 64 to 92. Possibly, it is the reason of 100-years degradation of metal, which can cause dissipated damaging and reduce hardness as revealed by Nykyforchyn et al. (2007), and Kryzhanivs'kyi and Nykyforchyn (2011).

Metallographic investigations gave some information on structural specific features. The ferrite-pearlite microstructure of authentic steel is characterised by a negligible quantity of long, but narrow pearlite grains (Fig. 3a). Grains of ferrite are globular in form, and their diameter changed in a wide range, from 35 to 90 µm. The substantial amount of large globular inclusions was identified within the ferrite matrix boundaries (Fig. 3b). In addition, the long formations of cementite were revealed along the ferrite grain boundaries (Fig. 3c, d), which as a brittle phase can reduce the resistance of metal to brittle fracture.

It should be mentioned that the similar microstructural features were found also by Lesiuk and Szata (2011) for the steels of the bridges, built 150 years ago, which were exploited under an influence of cyclic loading and atmospheric corrosion. It is not excluded, that just the simultaneous action of hydrogen and cyclic stresses is a driving force of diffusive processes in steel with formation of grain boundary cementite. Possibly, just such
microstructural features cause the stratifications in metal under corrosion environment action. It is clear that the effect of embrittlement is especially evident under the action of corrosion-hydrogen environment (water, staying too long in corrosion pits) which reduces the resistance of metal to stress corrosion cracking and corrosion fatigue.

It should be noted that the repair metal is characterized by the ferrite-pearlite structure typical for modern middle-carbon steels with substantially less density and size of inclusions than the age-old metal. The area of corrosion damages on its surface was also considerably less, and tracks of stratification in metal were not noticed.

The steels from the elements of the Cherkasy water-tower and Adziogol lighthouse are characterized by the different corrosion resistance (Table 2). In particular, it is established on the basis of potentiodynamic polarization studies that the water-tower steel is characterized by the higher corrosive resistance in 0.3% and 3% NaCl solutions (Table 2, Fig. 4) in comparison with the lighthouse steel. The water-tower steel is characterized by higher polarization resistance $R_p$, more positive level of stationary potential $E_{st}$, lower level of corrosion current density $i_{corr}$ and higher values of Tafel constants $b_a$, $b_c$ in comparison with the lighthouse steel.

The lower corrosion resistance of the lighthouse steel in comparison with the steel of water-tower is caused, obviously, by its long-term corrosion during service in a high-aggressive chloride-containing environment (in a marine atmosphere which contains moisture and salts, including chlorides). Tsuru et al. (2005) and Omura et al. (2006) showed that hydrogenation of steel in the conditions of atmospheric corrosion is possible – hydrogen penetrates into the steel during the process of moisture film drying on the steel surface. The obtained results proved that the lighthouse steel, probably, was hydrogenated in the process of service during long-term corrosion. At the same time Tsyrulnyk et al. (2007) revealed that hydrogen intensified redistribution of elements, which promoted
structural degradation of steels as it is reported by Nykyforchyn at al. (2010). Consequently, the obtained deterioration of some corrosion-electrochemical characteristics of the exploited lighthouse steel is, obviously, the display of its corrosion-hydrogen degradation.

4. Summary

The main danger of the Shukhov towers integrity is related to the intensive corrosion damage of metal, especially in the lower parts of constructions. It concerns the riveted and weld joints as well.

Some phenomena of corrosion-hydrogen degradation of the triangle lattice constructions are revealed: stress corrosion cracking of the weld metal; stratification of the triangle shelves from the side of their butt-ends in the direction of rolling.

Hardness of the authentic metal is essentially low, ranging from 64 to 92 HB. It can be caused by not only the low carbon content but also by a development of dissipated damaging during service.

The investigated materials are characterized by ferrite-pearlite microstructure with nonmetallic inclusions in the all steels, but the number of nonmetallic inclusions is greater as well as their size in the authentic steels.

Carbon steels of the Shukhov lattice constructions (the water-tower in Cherkasy and the Adziogol lighthouse) are characterized by the low corrosion resistance in 0.3% and 3% NaCl aqueous solutions. Lower corrosion resistance of the lighthouse steel in comparison with the water-tower steel is caused, evidently, by the long-term influence of more aggressive corrosion-hydrogenated environment in the conditions of the near Black Sea environment. This factor intensifies the in-bulk material degradation and therefore causes the weld metal sensitivity to stress corrosion cracking.

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