CASE STUDIES OF WELDED STEEL STRUCTURE FAILURES

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Abstract
The contribution summarized several case studies of welded steel structures, which happened in Slovakian water works (dam), transmission gas pipelines, petrochemical industry and at the cement work in last years. The microfractographical analysis gave us a very useful tool to reveal mechanism and causes of the failures. The main features of cracks predominately in weld joints are illustrated on real cases of breakdowns. Cases of liquid metal embrittlement, sulphide stress corrosion cracking and hot temperature corrosion are concerned. The present paper dealt with some metallurgical and fractographical features of cracks in the welded joints, which where illustrated on selected real cases of the breakdowns. To distinguish the crack types and to know their causes is very important for adoption of proper measures at repair welding.

Keywords: welded joints, steel structures, cold cracking, liquid metal embrittlement, sulphide stress corrosion cracking, hot temperature corrosion

1 Breakdown in lower gate of Danube lock chamber
A serious breakdown occurred in the left gate lock of Gabčíkovo dam lock chamber resulted in shut down of ship transport through the lower section of Danube river for more than five weeks [1, 2]. Steel structure of the gate was of all-welded box design of considerable size (18.5 m width, 21.95 m height and 2 mm thickness). It was evident on first sight that the gate breakdown took place in brittle mode (Fig. 1). The employed steel was a high strength (S530Q) low–alloy Cr-Mo-B type with unfavorably high carbon equivalent of Ce = 0.79 to 0.82. The breakdown fractures initiated from the cracks in welded joints (Figs. 2, 3). In this case the cold, hydrogen induced cracks are concerned which were formed due to insufficient preheat temperature applied in welding. This is proved also by the presence of martensitic structure in the HAZ (Fig. 4 bottom). These cold cracks with intercrystalline surface appearance (Fig. 5) at repeating cyclic loading of the gate propagated by the mechanism of low-cycle (high-strain) fatigue with typical rest lines (Fig. 6) till they attained the critical size, when they followed in a sudden brittle fracture with the characteristic river morphology (Fig. 7).

2 Gas pipeline failures
Slovakia belongs to the countries with the densest network of high pressure transmission gas pipelines. Four large diameter lines are already passing through its territory, whereas the 5th line is being completed at present. The oldest gas pipelines are in service for almost four decades and though they are inspected periodically, from time to time some failures of pipelines occur.
2.1 1st international gas pipeline

First case occurred on the 1st international gas pipeline which was built in 1965. This line, made of an old Russian steel 15 G2S (type L380N) low alloyed with Si (see Table 1) is the most problematic one at present. In this line low ductility and toughness of steel have met together which poor workmanship and defective corrosion protection of pipeline [3].

In this case (spirally welded pipe OD 720 x 8 mm) 1.8 m long crack was running along the spiral weld (Fig. 8). The initiation point was in the place where the spiral weld meets the tie strip weld. The spiral weld which exhibits very high misalignment of both linear and opposite runs is shown...
in Fig. 9a. The crack was initiated by LME (liquid metal embrittlement) of remelted copper (Fig. 9b). Cu came from abrading of Cu electric contact rods which were applied at manufacturing of spiral welds at that time.

Table 1 Chemical composition [wt %] and mechanical properties of the 15 G2S steel

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14 - 0.15</td>
<td>1.37 - 1.45</td>
<td>1.07 - 1.08</td>
<td>0.014</td>
<td>0.029</td>
<td>0.06</td>
<td>0.05</td>
<td>0.08</td>
<td>0.032</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Re [MPa]</th>
<th>Rm [MPa]</th>
<th>A5 [%]</th>
<th>ChV FATT (50 J.cm$^{-2}$)</th>
<th>Upper shelf</th>
</tr>
</thead>
<tbody>
<tr>
<td>387 - 404</td>
<td>591 - 612</td>
<td>22 - 27</td>
<td>+14°C</td>
<td>55 J.cm$^{-2}$</td>
</tr>
</tbody>
</table>

2.2 4th transmission line
The second case of failure did not happen during pipeline service. It appeared at construction (laying) of 4th transmission line OD 1420 x 18.6 mm made of X-70 steel grade spirally welded pipes [4].
During bending of pipes on site a few pipes cracked along the spiral welds. The cracks in length up to 1m always appeared in the same distance from the pipe end (Fig. 10). The crack occurrence corresponded with appearance of a cold impression on the outer spiral weld reinforcement (Fig. 11 and 12). It was found that such impression was formed due to incorrectly installed supporting steel rollers in the furnace used for pipe insulation.

In this furnace the pipes are flame heated prior to PE insulation up to 300°C, whereas they rotate (about 70 revolutions) on the rollers. In certain period of manufacture some pairs of rollers were
taken out for the repair, and therefore the pipe weight (about 12 tons) was supported by the remaining pair (in 11.5 m distance). Since all inspections of pipes were performed prior to pipe insulation, such impression could not be revealed.

This finding resulted in repeated ultrasonic inspection of all bent pipes manufactured in that period (about 300 pipes). The problem was, that the concerned pipes were already distributed in the section about 150 km long, which was already buried under the soil.

Important effect of cold impression and of high weld/reinforcement angle was studied by means of the non-standardized impact test according to Fig.13. Table 2 shows the results of tests.

![Chart of test piece location with the natural notch](image13.png)

**Fig.13 Chart of test piece location with the natural notch**

<table>
<thead>
<tr>
<th>T[^°C]</th>
<th>ISO-V notch</th>
<th>Natural notch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>real impression</td>
<td>artificial impression</td>
</tr>
<tr>
<td>0</td>
<td>51.5</td>
<td>51.3</td>
</tr>
<tr>
<td>20</td>
<td>83</td>
<td>63</td>
</tr>
</tbody>
</table>

Note: α = angle of reinforcement

The unfavorable effect was proved in all cases of surface defects in welds because the impact energy decreased by more than 50% in comparison to the value of convenient angle of reinforcement. The fractographic study of fractured surfaces in test pieces with real geometry weld defects has proved their significant notch effect. The notches in form of cold lap, large angle of reinforcement and cold weld impression initiated transcryalline as it can be seen on the fractured surface (Fig.14) as transcryalline cleavage failure.

![Brittle fracture initiated by cold impression of the weld reinforcement](image14.png)

**Fig.14 Brittle fracture initiated by cold impression of the weld reinforcement**
3 Failures in petrochemical industry

3.1 Sulphide stress corrosion cracking of air coolers in hydrocrack plant [5, 6]

This chapter deals with a case study of cracking in the air cooler of a hydrocrack plant in Bratislava. The air cooler was designed with a plug header (see the scheme of the header in Figs. 15 a, b) with dissimilar welded joints, because the tubeplate \( h = 40 \text{ mm} \), as an internal part of the plug header is made of the 15Mo3 steel and the tubes \( \varnothing 25/2 \text{ mm} \) are made of duplex steel DIN 1.4462. The welds were fabricated by TIG process using a special automatic welding machine and the ER 309Mo wire \( \varnothing 0.6 \text{ mm} \), which is generally recommended for welding the given combination of steels. The chemical composition of the materials used is given in Table 3.

![Fig.15 a,b A scheme of the plug headerc in the aircooler](image)

<table>
<thead>
<tr>
<th>Table 3 Chemical composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>15Mo3</td>
</tr>
<tr>
<td>1.4462</td>
</tr>
<tr>
<td>ER 306Mo</td>
</tr>
</tbody>
</table>

The working medium of air cooler consisted of hydrogen (up to 70%), hydrocarbons (up to 28%) and hydrogen sulphide, water and other admixtures. The working pressure was 13.48 MPa and working temperature 50 to 122°C.

After about three weeks of service a leakage of the working medium through the welds was observed.

The cross section of a specimen extracted from the defective weld is shown in Fig.16. It is evident that a single pass weld is concerned. The crack propagated to weld metal in normal direction to surface (Fig.17). The arrows indicate the initiation points of short crack. The weld metal exhibited martensitic structure (Fig.18). Weld metal hardness attained even the values of HV 435. Chemical microanalysis (EDX) of the weld metal revealed its considerable dilution by the tubeplate material: 10.03 wt.% Cr, 6.42 wt.% Ni, 1.55 wt.% Mo.

From the viewpoint of SSCC the hardness should not exceed the values of HV 248 according to NACE standard for low – alloy steels (for duplex steels the hardness limit is higher, namely HV 285). Mixed intercrystalline – transcryalline fracture surface of the SSC crack is shown in Fig.19. Totally 3240 welded joints in tube tubeplate connections of the air cooler had to be repaired, what was a really demanding job [7, 8].
**Fig. 16** Macrosection of defected welded joint

**Fig. 17** Sulphide stress corrosion cracks in the WM

**Fig. 18** Martensitic microstructure of the WM

**Fig. 19** SSC crack surface
3.2 Welded joint failure of austenitic creep resisting Cr-Mn steel

In the hydrogenation fuel refining process, the hydrogen and hydrogen sulphide mixture attacks the material of the radiation pipes (Ø 219 x 14 mm, seamless) which are subjected to temperatures ranging between 350 and 400°C. The newly developed chromium manganese austenitic steel (08Mn18Cr11V0,6) is concerned see Table 4. It belonged to the so-called economical austenitic steels in which nickel, which was lacking at the time, was replaced by manganese as a cheaper alternative [9].

The pipe failed in the heat affected zone (HAZ) of the circumferential welded joint near the fusion line.

Cracks propagated from the inner surface, through the whole cross section, to the outer pipe surface (Fig.20 – cross section). A more detailed picture shows that intercrystalline stress corrosion cracking was involved (Fig. 21).

Table 4 Chemical composition of the Cr-Mn stainless steel (wt. %)

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>V</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005-0.08</td>
<td>17.0-20.0</td>
<td>0.25-1.0</td>
<td>9.5-11.5</td>
<td>0.45-0.75</td>
<td>max. 0.045</td>
<td>max. 0.035</td>
</tr>
</tbody>
</table>

Fig.20 Breakdown crack, unetched

Fig.21 Intercrystalline character of crack in pipe wall

Fig.22 Intercrystalline character of crack, electrolyte etching. EDX of corrosion products (wt %): S – 23.856, Cl – 4.187, Cr – 2.456, Mn – 7.049, Fe – 62.452
EDX energy dispersion analysis of the corrosion products on the intercrystalline surface of the fractured crack (Fig. 22) showed increased S and partially also Cl contents, which proves the corroding effect of polythionic acids and chloride ions. Sulphur and chlorine can originate from the raw material (MONA gas and H2 circulation gas) but also from the technological process of catalyst regeneration.

It can be assumed that the intercrystalline corrosion attack was caused by a condensate of polythionic acids which were formed by the conjoined effect of sulphides, humidity and air oxygen during equipment shutdowns. The condensate itself was a consequence of the improper N2-filling up process of the furnace at beginning of the shutdown. According to the operator, 11 major overhauls and about 20 catalyst regenerations have been performed on the furnace during its 14 years of service [10].

3.3 Cracking of longitudinally welded thermowell tubes

The small diameter tubes (Ø11 x 2 mm) made of AISI 316 Ti steel serving as thermowells in the crude oil distillation chamber were concerned. Three weeks after changing of a crude oil supplier an extensive appearance of cracks was detected [11, 12]. The cracks had a feature of sulphide stress corrosion cracking (SSCC), see Fig. 23, 24 and a fracture surface with detection of S and Cl on Fig. 25. After etching we could recognize visible traces of cold plastic deformation as they are deformation twins and needles of the strain induces martensite (Fig. 24). It means the tubes were delivered in the cold rolling state, in which a steel becomes susceptible to SCC [13].
A possible remedy is to apply a solution annealing (1050°C/10 mins/water), after what an austenitic microstructure of favourable hardness was fully restored, see Fig. 26 and Table 5.

**Table 5** Hardness HV5 results

<table>
<thead>
<tr>
<th>Location</th>
<th>As delivered</th>
<th>After solution annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>306, 289, 306</td>
<td>125, 130, 126</td>
</tr>
<tr>
<td>WM</td>
<td>321, 332, 336</td>
<td>132, 133, 133</td>
</tr>
</tbody>
</table>

The easiest way how to distinguish proper state of the thermowells is detection by a magnet (ferromagnetic martensite or paramagnetic austenite).

4 Cement works

Shortly after combustion of new wastes (pneumatic tyres, plastics...) shell plates of the cement furnace were expressly attack by hot temperature corrosion. The steel AISI 310 (1.4841 by EN) was concerned (Table 6). An original wall thickness of 4 mm was reduced almost to 0.4 mm (Fig. 27).

**Table 6** Chemical composition of AISI 310 steel [wt%], [14].

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atest</td>
<td>0.058</td>
<td>0.99</td>
<td>0.58</td>
<td>0.024</td>
<td>0.014</td>
<td>23.94</td>
<td>19.45</td>
</tr>
<tr>
<td>VÚZ</td>
<td>max.0.20</td>
<td>max.1.50</td>
<td>max.1.0</td>
<td>max.0.045</td>
<td>max.0.03</td>
<td>24</td>
<td>19</td>
</tr>
<tr>
<td>AISI 310</td>
<td>max.0.20</td>
<td>max.1.50</td>
<td>max.1.0</td>
<td>max.0.045</td>
<td>max.0.03</td>
<td>24</td>
<td>19</td>
</tr>
</tbody>
</table>

Fig.27 Wall thickness reduction

Grain coarsening of the plate surface ($d_{ST} = \text{max.} 1000 \mu m$) and grain boundary oxidation are visible in Fig. 28. A scale thickness reached almost 900 $\mu m$. An EDX microanalysis of the corrosion products showed very high content of S and P (Fig. 29).

The AISI 310 is a heat-resisting steel up to 1100°C (tolerance loss of thickness is 2 mm/104 hours), but the steel is not suitable for reduction gas medium, which contains S, where its range...
of application is reduce down to 650°C, what is a solidus temperature of Ni$_3$S$_2$ (LME attack), [15].

![Fig.28 High temperature grain boundary attack](image)

![Fig.29 EDX microanalysis of corrosion products](image)

5 Conclusion
The paper dealt with some metallurgical and fractographic features of cracks in the welded joints, which where illustrated on selected real cases of the breakdowns. To distinguish the crack types and to know their causes is very important for adoption of proper measures at repair welding.

References