FRACTOGRAPHIC ANALYSIS OF WELDED JOINT SURFACES

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Abstract: In this paper are presented some macrofractographic and microfractographic analysis of welded joint fracture surfaces, respectively welded seam (W), heat affected zone (HAZ) and base metal (BM), of spiral and longitudinal steel welded pipes after conducting the laboratory destructive testing. Destructive testing are conducted to assess the quality of the steel welded pipes and besides the numerical results, the fracture surface of the tested samples offers additional information, very important for assessing the quality of steel welded pipes. Given this, in the paper are treated the macrofractographic and microfractographic analysis (LOM-Light Optical Microscopy and Scanning Microscopy-SEM) of the fracture surfaces of samples which are fractured after destructive testing. The morphology of the fracture surfaces is compared with the numerical results and it concludes that there is a direct correlation between the obtained results and deformation that causes fracture, providing thus additional information for assessing the quality of the welded pipes.

KEYWORDS: MACROFRACTOGRAPHY, MICROFRACTOGRAPHY, FRACTURE SURFACE, DEFORMATION.

1. Introduction

A fracture is the separation of an object or material into two, or more, pieces under the action of stresses and fractography can be defined as the science which deals with the description, analysis and interpretation of fracture surface morphologies (fracture topographies) and links them to the causative stresses, mechanisms and subsequent evolution of the fractures. Fractography can be classified according to the field (scale) of observation into [1]:

- macrofractography, dealing with features which can be studied visually using the naked eye or hand lens, and
- microfractography, dealing with features which can be studied at low magnification using Light Optical Microscopes (LOM), or at high magnification with Scanning or Transmission Electron Microscopes (SEM or TEM). Energy-dispersive X-ray (EDS) spectroscopy, used in conjunction with the SEM or TEM, is a very practical tool for elemental chemical analysis [1, 2, 3].

Fracture of materials depends upon many parameters like the state of stress, strain rate, the defect size, crystal structure, chemical homogeneity, grain size, grain boundary, formation of twins and slip plane, temperature and environmental conditions [4].

Based on the ability of a material to experience plastic deformation, for engineering materials, two fracture modes are possible: ductile and brittle [5]. Ductile fractures typically exhibit substantial plastic deformation with high energy absorption before fracture. On the other hand, brittle fractures display little or no macroscopically visible plastic deformation and require less energy to form. Fractured surfaces display both macroscopic and microscopic features.

Ductile fractures exhibit certain characteristic macroscopic features:
- a relatively large amount of plastic deformation precedes the fracture,
- shear lips are usually observed at the fracture termination areas,
- the fracture surface may appear to be fibrous or may have a matte or silky texture, depending on the material,
- the cross section at the fracture is usually reduced by necking,
- crack growth is slow.

Macroscopically, brittle fractures are characterized by the following:
- little or no visible plastic deformation precedes the fracture,
- the fracture is generally flat and perpendicular to the surface of the component.

-the fracture may appear granular or crystalline and is often highly reflective to light. Facets may also be observed, particularly in coarse-grain steels,
- herringbone (chevron) patterns may be present
- cracks grow rapidly, often accompanied by a loud noise.

On a microscopic scale, ductile fracture in metals displays a dimpled surface appearance created by microvoid coalescence and transgranular separation.

Microscopically, brittle fractures have the following characteristics:
- transgranular cleavage or quasi-cleavage,
- intergranular separation,
- features on transgranular facets, such as river marks, herringbone patterns, or tongues.

2. Experimental procedure

Spiral line pipes Ø813x12mm were fabricated using high strength steel coils X65 according to API 5L (American Petroleum Institute) standard, which chemical composition and mechanical properties are given in table 1 and 2, according to the Certificate of Quality. Spiral line pipes Ø813x12mm were welded in two-stage process by double sided Submerged Arc Welding (SAW) through an “X” groove configuration, according to the BLOHM+VOSS, figure 1.
### Table 1: Chemical composition of steel API Grade X65

<table>
<thead>
<tr>
<th>Steel coils</th>
<th>Chemical composition [wt-%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>API grade X65</td>
<td>C  0.09</td>
</tr>
</tbody>
</table>

### Table 2: Mechanical properties of used steel API Grade X65

<table>
<thead>
<tr>
<th>Steel coils</th>
<th>Re</th>
<th>Rm</th>
<th>Re/Rm</th>
<th>KV</th>
</tr>
</thead>
<tbody>
<tr>
<td>API grade X65</td>
<td>549</td>
<td>649</td>
<td>0.845</td>
<td>23.6</td>
</tr>
</tbody>
</table>

Charpy V-Notch (CVN) specimens were cut out from the double sided weld metal, perpendicular to the welding direction, as shown in figure 2.

**Fig. 2 Schematic representation of the Charpy V-Notched specimens**

The standard CVN specimens (10x10x55mm) with V groove were cut from base metal (BM), heat affected zone (HAZ) and weld metal (WM) and tested at (-20°C), (0°C) and (20°C) by use of the MOHR-FEDERHAFF LOSSENHAUSEN pendulum.

During Charpy impact testing, usually three key parameters are typically determined:

1. Impact toughness
2. Presence of shear and brittle fracture area and
3. Lateral extension.

A methodology for measurements of the presence of shear (ductile) fracture area and brittle fracture area on the total fractured surface of a CVN tested specimens is shown in figure 3. The specimen cross-section after fracturing is divided into equal millimetric units and then by counting of the relevant squares into the entire cross-section, using Autocad software, determines percent of shear fracture (ductile) area and percent of brittle fracture area.

**Fig. 3 Shear and brittle fracture surface**

In order to obtain a more complete assessment of the fracture surfaces of Charpy V-notched specimens, lateral extension were measured [6], in the height direction ($h_1$, $h_0$) and in the width directions ($a_1$, $a_0$), figure 4, where:

$$
\varepsilon_h = \frac{h_1 - h_0}{h_0} \times 100 \text{[%]} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1)
$$

$$
\varepsilon_a = \frac{a_1 - a_0}{a_0} \times 100 \text{[%]} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)
$$

**Fig. 4 CVN Specimens cross section after fracture**

All fractured surfaces of CVN specimens after testing were examined visually with the unaided eye, at low magnification using an Light Optical microscope (LOM-NEOPOT 21) and at high magnification using Scanning Electron Microscope (SEM-Leo 1530).

### 3. Results and discussion

#### 3.1 Impact toughness

Impact toughness results of the Charpy-V-Notch specimens are presented in figure 4. These values represent average of three specimens measurements at different temperatures (-20°C), (0°C) and (20°C).

**Fig. 5 Impact toughness (CVN)**
It can be seen from the figure 5 that the base metal (BM) has the highest absorbed energy, followed by the weld metal (WM) and coarse grained heat affected zone (CG HAZ). Each data point represents the average value of three samples and the test results revealed a general decreasing tendency with decreasing temperature.

Visual analysis of the Charpy V-notch fracture surfaces clearly shows differences between base metal (BM), heat affected zone (HAZ) and weld metal (WM), figure 6 [7].

From the visual analysis, figure 5, there is notable evidence of plastic deformation in the fracture surfaces in all tested specimens of base metal (BM), heat affected zone (HAZ) and weld metal (WM). Post-fracture visual analysis in all fractured surfaces shows presence of shear lips which are located at the opposite sides of the specimen's width, figure 7. Presence of shear lips is also a characteristic of ductile fracture.

Macroscopic view of the fracture surface of the Charpy V-notch specimen of BM, specimen marked as C2, with lowest impact energy (Kv=64.2 J/cm²), figure 4, tested at (-20°C) is presented in figure 7.

Fracture surfaces of some specimens of base metal (BM) show some cracks like separations perpendicular to the axis of the V-notch, figure 6 and 7. These cracks are referred to as delamination [7].

The scanning electron micro-fractography (SEM) of the central portion of the base metal (BM) specimen, marked with circle 1, in figure 8, reveals numerous coarse and fine concave equiaxed dimples, characteristic of a ductile area. Partially in this micro-fractography (SEM) exist some cleavage facets, characteristic of brittle fracture, figure 8(a), while in the rest of fracture surface dominates ductile fracture, figure 8(b, c). Microanalysis (EDS-EPMA), figure 9, of precipitation marked with number 2, figure 8(c), besides presence of other elements shows also presence of Mn, probably in form of the sulfides, which are characteristic for ductile fracture.

In general, all fracture surfaces of the base metal (BM), heat affected zone (HAZ) and weld metal (WM) comprises mainly of a large ductile region and small amounts of brittle area. The fracture surface of base metal (BM) is fibrous and its color is dull. Fracture surfaces of the weld metal (WM) and heat affected zone (HAZ) are also fibrous with a little presence of bright shiny color. In the case of base metal (BM) with lowest impact energy (Kv=64.2 J/cm²), specimen marked with C2 and tested at (-20°C), brittle area appears flat and shiny, figure 7.

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**Fig.6** Typical fracture surfaces of BM, HAZ and WM

**Fig.7** Macroscopic view of the fracture surface of BM

**Fig.8** SEM micro-fractography of fracture surfaces
3.2 Presence of shear and brittle fracture area

The presence of shear or ductile and brittle fracture area of CVN tested specimen in (-20°C) is shown in table 3. These values represent average of three specimens measurements.

Table 3: Presence of ductile and brittle fracture area

<table>
<thead>
<tr>
<th>Steel coils</th>
<th>Specimens</th>
<th>Presence of ductile and brittle fracture [%]</th>
<th>Temperature [-20°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[BM]</td>
<td>[HAZ]</td>
</tr>
<tr>
<td>X65</td>
<td>C0</td>
<td>79.6</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>82.7</td>
<td>17.3</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>70.9</td>
<td>29.1</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>89.4</td>
<td>10.6</td>
</tr>
</tbody>
</table>

Table 3 shows that shear or ductile fracture dominated in all cases. The largest percentage (29.1%) of brittle fracture is only in the sample marked with C2, which is in accordance with the numerical value of the impact toughness obtained during testing.

3.3 Lateral extension

Lateral extension in height ($\varepsilon_h$) and in width ($\varepsilon_a$) determined by formula (1) and (2), respectively relative strain in height and in width are presented in table 4. Results of lateral extension shows that with the increasing of the absorbed energy, lateral in height ($\varepsilon_h$) and in width $\varepsilon_a$) also increased. It must be noticed that the results of lateral extension not used for practical needs because their determination is difficult and is not standard method. Results of lateral extension only certify the preliminary obtained values of absorbed energy and percentage of shear and brittle fracture area.

Table 4: Relative strain of height ($\varepsilon_h$) and width ($\varepsilon_a$)

<table>
<thead>
<tr>
<th>Steel coils</th>
<th>Specimens</th>
<th>[BM]</th>
<th>[HAZ]</th>
<th>[WM]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\varepsilon_h$</td>
<td>$\varepsilon_a$</td>
<td>$\varepsilon_h$</td>
<td>$\varepsilon_a$</td>
</tr>
<tr>
<td>X65</td>
<td>C0</td>
<td>79.6</td>
<td>20.4</td>
<td>90.2</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>82.7</td>
<td>17.3</td>
<td>88.7</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>70.9</td>
<td>29.1</td>
<td>92.1</td>
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<tr>
<td></td>
<td>C3</td>
<td>89.4</td>
<td>10.6</td>
<td>90.5</td>
</tr>
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</table>

4. Conclusion

On the basis of the results presented in this work, it is possible to draw the following conclusions:

- Impact toughness values accompanied with visual analysis of fractured surfaces of CVN specimens can provide additional information for quality evaluation of the welded joint, respectively base metal (BM), heat affected zone (HAZ) and weld metal (WM).
- The presence of shear or ductile and brittle fracture area in all cases is in accordance with numerical value of the impact toughness obtained during testing.
- Lateral extension measurements with determination of the percentage of ductile and brittle fracture in the total fracture area are additional parameters and facilitate the assessment of the quality of the welded joint, respectively base metal (BM), heat affected zone (HAZ) and weld metal (WM).
- Microscopic analysis with Light Optical Microscopy (LOM) and Scanning Electron Microscopy (SEM) can provide very important additional data for qualitative and quantitative assessment of fractured surfaces and mechanisms of fracture of welded joint, respectively base metal (BM), heat affected zone (HAZ) and weld metal (WM).

5. References