THE EVALUATION OF BRITTLE FRACTURE BEHAVIOUR OF HIGH STRENGTH STEELS WELDMENTS

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Three different testing methods (instrumented impact, explosion crack starter and fracture mechanics tests) had been applied for brittle fracture behaviour evaluation of two kinds of welded joints, produced of high strength steels by manual arc welding. The results, obtained for BM, WM and HAZ are analyzed and compared. It was concluded that applied testing methods do not exclude each other, since they produce complementary results, helping to understand better brittle fracture behaviour of welded joints heterogeneous structure.

INTRODUCTION

The application of high strength steels for welded constructions is dependent on the properties of their welded joints. One of the most important requirements for service safety of welded structures, produced of high strength steel, is to achieve corresponding level of toughness in all three weldment constituents: base metal (BM), weld metal (WM) and heat-affected-zone (HAZ). The evaluation of weldments toughness is very complex, because of microstructures heterogeneity of WM and HAZ, as well as the heterogeneity of their mechanical properties. Charpy test, although very old method, is generally accepted for the evaluation of the impact toughness due to its simplicity. Recently developed instrumentation of Charpy test significantly extended its capacity (1), enabling not only the separation of energy portions required for crack initiation and fracture process. Specifications for heavy loaded welded structures normally include impact energy values for BM and WM, as well as HAZ, since it is difficult to position notch precisely in HAZ region of lowest toughness.

In order to establish more severe testing loading, explosion crack starter test had been introduced (2). Fast loading rate assured brittle fracture in plate specimen with severe notch. Applied to welded joint specimens (3), this test enables to determine the most critical region in weldment, in which fracture would occur. In this way by the global test critical local property could be defined.

Further improvement in crack resistance testing is offered by introduction of fracture mechanics tests, that involved pre-cracked...
specimens. The application to welded joints allows for convenient
determination of crack resistance of BH and WH, but it is followed
again by uncertainty in defining of critical crack tip position in
HAZ (4), since in prescribed preparing method fatigue crack would
follow the path of notch root rather than direction of critical HAZ
region.

The application of all three above described methods for the
evaluation of brittle behaviour of welded joints, performed of high
strength steels by manual arc welding, are presented in the paper.

**BASIC PROPERTIES OF TESTED WELDED JOINTS**

**Parent Steels**

Two kinds of high strength steels were used in these tests: NN70,
Yugoslav product of HY100 type steel, d = 18 mm thick, designed in
next text as "A", and C.5432 according to Yugoslav Standards (JUS),
Q&T Cr-Ni-Mo steel of 1000 MPa nominal ultimate tensile strength,
d = 20 mm thick, designed as "B" in next text. Their typical heat
analysis and tensile properties are given in Table 1.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;A&quot;</td>
<td>0.1</td>
<td>0.27</td>
<td>0.35</td>
<td>0.014</td>
<td>0.012</td>
<td>1.11</td>
<td>2.65</td>
<td>0.26</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>&quot;B&quot;</td>
<td>0.3</td>
<td>0.28</td>
<td>0.73</td>
<td>0.02</td>
<td>0.008</td>
<td>2.05</td>
<td>1.87</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Mechanical properties**

<table>
<thead>
<tr>
<th>Steel</th>
<th>Yield strength</th>
<th>Tensile strength</th>
<th>Elongation</th>
<th>Reduction of cross-section area</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;A&quot;</td>
<td>780</td>
<td>825</td>
<td>18</td>
<td>68</td>
</tr>
<tr>
<td>&quot;B&quot;</td>
<td>940</td>
<td>1015</td>
<td>15.7</td>
<td>58.2</td>
</tr>
</tbody>
</table>

**Electrodes**

Welding of steel "A" had been performed using Tenacito 80 covered
basic electrode. Chemical composition of Tenacito 80 is (%):
C: 0.06  Si: 0.50  Mn: 1.80  Cr: 0.35  Ni: 2.20  Mo: 0.40
Yield strength of all weld metal Tenacito 80 is above 750 MPa, its
ultimate tensile strength 810 to 910 MPa, and elongation > 15 %.

Welding of steel "B" had been performed using an austenitic basic
electrode 18/10/Ti with chemical composition (%): C:0.1  Si:0.3-0.7
Mn: 5-7  P: 0.035  S: 0.013  Cr: 19-22  Ni: 9.5-10.5  Ti: 0.2-0.5.
Yield strength of all weld metal is 380-580 MPa, ultimate tensile
strength 550-700 MPa, elongation > 22 %.

**Welded Joints**

Welding direction was transverse to steel rolling direction. Deposit
weld metal of steel "A" exhibited Y.S. of 747 MPa, U.T.S. - 785 MPa
weld metal of steel "B" exhibited Y.S. of 747 MPa, U.T.S. - 785 MPa,
that fractured and elongation of 19.3%. For steel "B" welded joint, that fractured
in specimen weld metal region. U.T.S. was 650 MPa. In the case of
steel "B" defect free welded joint had been required and strength
level was not specified for this application.

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Brittle fracture resistance of steel "A" and its welded joints is evaluated by instrumented impact, explosion and fracture mechanics tests, performed for BM, WM and HAZ. Only instrumented impact and explosion tests were performed for steel "B" and its welded joint specimens, having in mind exaggerated mismatching effect.

Charpy V specimens were tested at different temperatures in the instrumented impact test. Parent plate specimens were cut in the rolling (L) and in transverse direction (C) with notches normal to these directions. The notches in weldment specimens were positioned in WM and in HAZ. Typical results are presented in Fig. 1.

Explosion crack starter test specimens (S, 6) were 500x500x10 mm. Brittle bead was welded in both directions on steel "A" plates, in (C) direction on steel "B" and in the direction of tested weldment, and the notch as crack starter was normal to the bead direction. Figure 2 presents scheme for explosion crack starter test, and test results are given in Fig. 3, expressed by bulge development B and thinning δ as with explosions number. Typical development of crack in explosion tests is presented in Fig. 4 for welded joint specimens.

Fracture mechanics parameters were tested on SEN (B) specimens 14x28 mm cross-section for steel "A", its WM and HAZ, using single specimen J_{IC} procedure. Critical crack-opening displacement δ, for maximal load could also be determined in this test. The results of fracture mechanics tests are listed in Table 2.

Table 2.

<table>
<thead>
<tr>
<th>Critical J integral J_{IC}, kJ/m²</th>
<th>Critical crack opening displacement, δ, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>165</td>
</tr>
<tr>
<td>WM</td>
<td>167</td>
</tr>
<tr>
<td>HAZ</td>
<td>202</td>
</tr>
</tbody>
</table>

Weed joints hardness numbers are given in Fig. 5.

Nil-ductility-transition temperatures, °С

Table 3 Nil-ductility-transition temperatures, °C

<table>
<thead>
<tr>
<th>Steel &quot;A&quot;</th>
<th>Steel &quot;B&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L)</td>
<td>(L)</td>
</tr>
<tr>
<td>50% Charpy V</td>
<td>-138</td>
</tr>
<tr>
<td>Impact energy</td>
<td>-103</td>
</tr>
</tbody>
</table>

**DISCUSSION**

The obtained results can be considered from two stand-points. One of them is related to brittle fracture properties of welded joints constituents, the second is the comparison of three test methods.
Steel "A" impact toughness is satisfactory in both directions, and its behaviour at low temperatures is also satisfactory. Anyhow, this is not the case with its weld metal, because NDT temperature for impact energy of 27 J is only -25 °C, higher than the value for 50% upper shelf energy. Heat-affected zone in this test was found to be superior compared to weld metal.

Having in mind high strength of steel "B", impact energy values can be accepted as satisfactory, including transition temperature. Higher impact values of WM compared to BM corresponds to high alloy consumable. The results for HAZ are comparable to BM results. High quality of steel "A" welded joints is proved in explosion crack starter test. The cracks, emanated from brittle bead notch, are arrested in base metal (Fig. 4a) in most specimens, and in some cases fusion line of HAZ was critical welded joint region as regard brittle fracture (Fig. 4b). No significant difference was found comparing base metal and welded joint specimens, e.g. after sixth shot thinnings and bulge developments were comparable (Fig. 3a,b) for same explosive charge.

Extremely low reduction of thickness in explosion test of steel "B" (less than 4% after eight shots), followed by small bulging of only 40 mm is an evidence of brittle behaviour, better expressed than by impact test. In all tested welded joints specimens fracture was limited to weld metal (Fig. 4c), due to lower strength of WM.

Hardness values in Fig. 6 correspond to the expected levels for both (steel "A" and "B") welded joints, some scatter in WM of steel "A" can be attributed to multipass welding.

The results of fracture mechanics tests (Table 2) show that best crack resistance is typical for HAZ, and the lowest for WM. Since the precise position of crack tip in HAZ can not be defined, this behaviour can be considered as an average result. Comparing to impact test results, some disagreement can be found, since they show best resistance in BM, and not in HAZ. General view of fracture appearance, Fig. 4b, c, indicates that HAZ can be critical region, but this conclusion scarcely could be described by fracture mechanics test, or impact test.

REFERENCES

Figure 1 Instrumented impact test results obtained with Charpy V specimen.

W - weld metal
HAZ - heat-affected-zone
1 crack initiation energy
2 crack propagation energy
3 total energy
L-notch in cross-rolling direction
C-notch in rolling direction
Figure 2 The scheme for explosion bulge test

Figure 3 Typical results of explosion bulge test, expressed by reduction of thickness \( \Delta R \) and bulge development \( B \) vs. number of explosions for indicated specimens

L-notch in cross-rolling direction
C-notch in rolling direction
WM-weld metal
Figure 4 Scheme of crack propagation in explosion bulge test
A brittle bead
B notch-crack starter
C crack

Figure 5 Results of hardness measurements along welded joints