Value Estimation of Specimen Containing Dissimilar Metal Welds

Igor Simonovski, Oliver Martin, Gangadhar Machina
European Commission, Joint Research Centre, Institute for Energy and Transport
P.O. Box 2, NL-1755 ZG Petten, The Netherlands
Igor.Simonovski@ec.europa.eu, Oliver.Martin@ec.europa.eu, Gangadhar.Machina@ec.europa.eu

Szabolcs Szávai, Robert Beleznai
Bay Zoltán Nonprofit Ltd. for Applied Research, Institute for Logistics and Production Engineering
H-3519 Miskolc, Iglói út 2, Hungary
szabolcs.szavai@bayzoltan.hu, robert.beleznai@bayzoltan.hu

ABSTRACT

In 2012 the research project MULTIMETAL was started within the 7th Framework Programme for Research and Technological Development of the European Union. The aim of the project is to develop a standard for measuring the fracture resistance of multi-metallic specimen and the development of harmonized procedures for dissimilar metal welds (DMWs) brittle and ductile integrity assessment. DMWs connect ferritic and austenitic stainless steels and are present in a number of primary piping systems in light water reactors. They contain a number of different material zones, i.e. ferritic zone, austenitic zone, weld material and heat affected zones which differ significantly in their material properties and fracture behavior. The MULTIMETAL project involves an extensive test program in which standard geometry specimens (CT, SENB, SENT) are cut from mock-ups containing DMWs resembling real DMWs from NPPs in terms of geometry, material and weld procedure. These specimens contain different material zones as described above. A part of the project includes performing numerical analyses to estimate fracture parameters such as stress intensity factors $K$, $J$-integral values and extraction of $\eta_{pl}$ factors for different crack positions and crack lengths. In this paper the results of the numerical analyses performed by JRC so far in multi-metallic specimens are presented.

1 INTRODUCTION

At the moment there is no existing standard for the fracture resistance testing of multi-metallic components or specimens that are made up of different material sections joined together via a weld. Existing standards for fracture resistance testing like ASTM E1820-13 [1] only cover homogeneous specimens. Also there are no existing engineering procedures or schemes for the estimation of $J$ integral values of cracked multi-metallic components or specimens. Thus in early 2012 a group of 11 European organisations started a R&D project MULTIMETAL with the aim to fill the above gaps. The objectives of the project are the development of a standard for fracture resistance testing of multi-metallic specimens and the development of harmonized procedures for dissimilar metal welds (DMWs) brittle and ductile integrity assessment. The underlying aim of MULTIMETAL is to provide recommendations for a good practice approach for the integrity assessment of DMWs as part of overall integrity analyses and leak-before-break (LBB) procedures. The project has a duration of three years and is funded by the European Commission (EC) within its 7th Framework Program. The work presented in this paper is part of the contribution of the Joint Research Centre (JRC) in Petten, The Netherlands to Work Package (WP) 4 "Numerical Analyses of DMW Behaviour" of the project.
2 MOCK-UPS AND SPECIMENS

Three mock-ups are used in the project, each consisting of an austenitic stainless plate and a ferritic steel plate, that are welded together. This paper deals only with the Mock-up 3 (MU3), Fig. 1. MU3 resembles a DMW in primary circuits of VVER-440 reactors. It is composed of a 15H2MFA ferritic steel plate, two heat affected zones on the ferritic side, three buttering layers, weld, heat affected zone on the stainless steel side and the X6CrNiTi18-10 stainless steel plate.

The specimens are cut out from the weld region of a mock-up. Since the mock-ups themselves must resemble typical DMW in NPPs, the used materials are of nuclear grade. Also, the applied welding procedures are real procedures applied in nuclear industry for the NPPs components involving the DMW [2].

![Figure 1: MU3 macrograph (left) and a sketch of the weld (right).](image)

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Crack position [mm]</th>
<th>a/W=0.5</th>
<th>a/W=0.6</th>
<th>a/W=0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENB10x20</td>
<td>FS-HAZ, -2 mm from FL</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SENB10x20</td>
<td>Centre BL1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SENB10x20</td>
<td>Centre BL2</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SENB10x20</td>
<td>Centre BL3</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SENB10x20</td>
<td>Weld, 2mm from BL3 border</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SENT20x20</td>
<td>FL</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SENT20x20</td>
<td>Centre BL1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Cracks are assumed to be positioned either in the ferritic steel heat affected zone (FS-HAZ), buttering layers (BL1, BL2, BL3), on the fusion line (FL) or in the weld, see Fig. 1. Positions of the specimens within a mock-up is adjusted so that an appropriate crack position is achieved, see Fig. 2. Standard SENB10x20\(^1\) and SENT20x20\(^1\) fracture toughness specimens are used [1, 3] with crack length (a\(^2\)) to specimen width (W\(^2\)) ratios of 0.5, 0.6 and 0.7, see Table 1.

3 NUMERICAL ANALYSIS

3.1 Material properties and model set-up

An extensive material characterization of the MU3 has been performed to obtain the material properties [4]. Measured stress-strain data and Young’s moduli are then applied to the numerical models: SENB10x20 and SENT20x20 two dimensional finite element models.

---

\(^1\)Thickness x W

\(^2\)As defined by [1].
Figure 2: Positions of specimens relative to the MU3. Colors indicate different material zones.
The models are built using ABAQUS/CAE [5] through dedicated Python scripts. Each model is partitioned in sections, with each section corresponding to an individual material zone of the DMW. Fig. 2 shows the various material zones of the MU3 and positioning of the specimens within those zones. All the material sections are modelled as homogeneous sections, including the weld. No effort is made to model weld beads.

Sufficiently fine finite element mesh is applied, with a spider-type mesh around a crack tip, see left part of Fig. 3. Finite elements with a built in strain singularity for a perfect plasticity material are used (\( \epsilon \propto r^{-1} \)) around the crack tip, Fig. 3 center. In a previous work [6] an effect of the strain singularity type on the computed \( J \)-integral values was studied. It was shown that, for a sufficiently dense mesh, the difference between the perfect plasticity (\( \epsilon \propto r^{-1} \)) and the power law hardening (\( \epsilon \propto r^{-\frac{1}{3+\nu}} \)) type of singularity is lower than 2%. On the other hand, the singularity corresponding to a linear elastic material underestimated \( J \)-integral and \( \eta_{pl} \) values by \( \approx 10\% \).

![Image](image.jpg)

Figure 3: Crack tip mesh detail (left), applied crack tip strain singularity elements (center) and \( \Gamma \) contour for computing \( J \)-integral values (right) [1].

The analyses are performed under small displacements assumption and plain strain conditions. Displacement-controlled load is used. Sufficiently high load is applied to result in \( J \)-integral value of up to 500 kJ/m². Loads and boundary conditions are given in Fig. 4. SENB specimens are supported by two rigid cylinders. The load is applied by moving downwards the top rigid cylinder. The load from the cylinders to the specimen is transferred through frictionless contacts between the cylinders and the specimen. Since relative movements of the contact surfaces are larger than the size if finite elements at the contact surfaces, the relative movements of the contact surfaces can not be considered as being small. Finite sliding contact definition [5] that enables large relative movements is therefore used. Contact surfaces are defined as "Node to surface" although no significant difference was observed when using "Surface to surface". The "Surface to surface" formulation enforces contact conditions in an average sense over regions nearby slave nodes rather than only at individual slave nodes with the "Node to surface" formulation [5].

For SENT specimens, horizontal displacements are prescribed to the left and right edges through reference points which transfer the prescribed horizontal displacements to the left and right specimen edge. Such a load definition enables a simple calculation of the horizontal reaction forces on the reference points. These forces are needed for computing \( \eta_{pl} \), see the following section.

### 3.2 \( J \)-integral and \( \eta_{pl} \)

The \( J \)-integral [7] is one of the path-independent integrals used to characterize a singularity of a field in the vicinity of a crack. It can be viewed as a nonlinear, stress-intensity parameter as well as
an energy release rate. The original \( J \)-integral definition is valid only for homogeneous materials and is path independent. For inhomogeneous materials a contribution due to the material inhomogeneity \( C_{inh} \) needs to be added, Eq. (1) [8, 9]. However, if the phase boundary between the two materials is parallel to the crack line (as in our case), the additional contribution \( C_{inh} \) becomes zero [9, 10, 11]. \( \Gamma \) and \( \Gamma_{pb} \) are contours, encircling the crack and the phase boundary in the counter clock-wise direction, Fig. 3. \( w \) stands for strain energy density \( (w = \int_0^{\epsilon_0} \sigma_{ij}d\epsilon_{ij}) \), \( n \) normal to the contour, \( \sigma \) the stress tensor while \( u \) is displacement vector. Domain integral method is used to convert the \( J \)-integral into an area integral using the convergence theorem [12].

\[
J_i = J_{homog} + C_{inh} = \oint_{\Gamma} [wn_i - \sigma_{ij}n_ku_{ji}] ds = \oint_{\Gamma_{pb}} [wn_i - \sigma_{ij}n_ku_{ji}] ds
\]

During fracture resistance testing force versus load-line displacement curves are often measured. \( J \)-integral values can be computed from these curves using a relation: \( J = J_{el} + J_{pl} = \frac{K^2(1-\nu^2)}{E} + J_{pl} \) [1]. \( K \) stands for stress intensity factor, \( E \) for Young modulus and \( \nu \) for Poisson’s ratio. The plastic contribution, \( J_{pl} \), to the \( J \)-integral is computed from the force versus load-line displacement curve by applying a factor \( \eta_{pl} \) [1], Eq. (2). \( B_N \) stands for the net specimen thickness and \( b_o \) is the length of the ligament behind the crack. In this work we compute \( \eta_{pl} \) for the given multi-metallic cases.

\[
J_{pl} = \frac{\eta_{pl}A_{pl}}{B_Nb_o}
\]

### 3.3 Results

Fig. 5 displays the computed \( J \)-integral values for the SENB and SENT cases for various assumed crack positions and three \( a/W \) ratios: 0.5, 0.6 and 0.7. One can see that in the linear elastic part (initial low curve slope area) the position of the crack does not influence the results much. As the load increases, the plastic deformation becomes larger and the \( J \)-integral values significantly increase. Here the crack position plays a significant role. For the SENB specimens, the most critical crack position at smaller crack length \( (a/W=0.5) \) is a crack in the BL3. This crack results in the highest \( J \)-integral value at a given load. For a longer crack, crack in the weld \( (a/W=0.6) \) results in a similar \( J \)-integral values as a crack in the BL3 so both positions are of the similar concern. For the longest crack \( (a/W=0.7) \), crack in the weld seems to be the most critical up to almost the highest load. For SENT specimens only two crack positions are compared: crack in the BL1 and along the FL. The crack along the fusion line is the most critical, no matter what \( a/W \) ratio.
Figure 5: MU3: computed $J$-integral values.
Figure 6: MU3: computed $\eta_{pl}$ values.
Fig. 6 displays the computed $\eta_{pl}$ values for the SENB and SENT cases for various assumed crack positions and three $a/W$ ratios: 0.5, 0.6 and 0.7. $\eta_{pl}$ values at small displacements should not be considered significant as the $J_{pl}$ part contribution to the $J$-integral is negligible. The left column shows the results for the SENB specimen. One can see that the $\eta_{pl}$ values are approximately 2.5 but they do not stabilize. Continuous change in the $\eta_{pl}$ values was also observed for other multi-metallic cases [13]. Various crack positions can result in about 15% change of the $\eta_{pl}$ values. Similar pattern can be observed for the SENT specimens, right column in Fig. 6. However, for the SENT specimen the differences in $\eta_{pl}$ values significantly decrease with increased crack length.

4 CONCLUSIONS

The work is a part of the EC funded MULTIMETAL project. Three dissimilar metal welds (DMW) mock-ups are used in the project: (1) MU1 resembles a weld configuration in the primary circuit of the European Pressurized Water Reactor, (2) MU2 is similar to Mock-up 1, but the filler material is austenitic stainless steel 316L and there is a buttering layer made of 309L on the ferritic side and (3) MU3 which resembles a DMW in primary circuits of VVER-440 reactors. Only MU3 results are presented in this work. The work on the other two mock-ups is ongoing.

FE approach for computing $J$-integral values and $\eta_{pl}$ factors of multi-metallic specimens is presented. The DMW is composed of a 15H2MFA ferritic steel plate, two heat affected zones on the ferritic side, three buttering layers, weld, heat affected zone on the stainless steel side and the X6CrNiTi18-10 stainless steel plate. Standard SENB and SENT specimens are used. Cracks are assumed to be positioned either in the ferritic steel heat affected zone (FS-HAZ), buttering layers (BL1, BL2, BL3), on the fusion line (FL) or in the weld. $J$-integral values for all these cases are computed for three different $a/W$ ratios. It is found that the crack position significantly affects the $J$-integral values. For the SENB specimen the highest $J$-integral values are obtained for a crack in the BL3. With longer cracks a crack in the weld starts to generate higher $J$-integral values. For the SENT specimens only two crack positions were compared: crack in the BL1 and crack along the FL. For all the SENT cases higher $J$-integral values were obtained with a crack along the FL.

ACKNOWLEDGMENTS

The authors would like to thank Péter Rózsahegyi from “Bay Zoltán Nonprofit Ltd. for Applied Research” for kindly providing the material data. This project has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement number 295968.

REFERENCES


