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ANALYSIS OF TWO BENDING TESTS ON AGED CAST DUPLEX STAINLESS STEEL PIPES CONTAINING A CRACK IN THE HEAT AFFECTED ZONE

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ABSTRACT

Some components (elbows, pump casings and lateral connections) of the primary loop of French PWRs are made of static cast duplex stainless steels. This kind of steel may age even at relatively low temperatures (in the temperature range of PWR service conditions), depending on the material composition. An important consequence of this ageing process is the decrease in the ductility and fracture toughness of the material. It is feared that an embrittlement, associated with the occurrence of casting defects, may increase the risk of failure. In order to build the primary loops, these components are welded and the behaviour of the weld heat affected zone (HAZ) is not well known. So a specific program was launched on this topic, involving metallurgical studies, fracture mechanics tests, medium-scale experiments, and finite element analyses.

This paper presents the main characteristics and results of two experiments conducted on 6” aged cast pipes, respectively at 300°C and 100°C. These pipes contained a machined notch in the heat affected zone of a butt-weld and were tested under four-point bending. The chemical composition of the steel was chosen to obtain a fast thermal ageing and low fracture toughness properties. During the tests, the defect initiated and grew subsequently by ductile tearing. The tests showed that it was possible to obtain a significant amount of stable crack growth (about 5 mm) despite the low toughness properties of the aged material.

A detailed fracture mechanics analysis, based on finite element calculations, was performed. These calculations fairly simulated the overall behaviour of the tested structure, gave a conservative prediction of the crack initiation pressure and well predicted the crack size associated with the maximum applied bending moment.

These tests and their detailed analyses contribute to validate and justify the methodology used in the integrity assessment of in-service cast duplex stainless steel components.

INTRODUCTION

Some components (elbows, pump casings and lateral connections) of the primary loop of French PWRs are made of static cast duplex stainless steels [1, 2]. This kind of steel may age even at relatively low temperatures (in the temperature range of PWR service conditions), depending on the material composition [3]. An important consequence of this ageing process is the decrease in the ductility and fracture toughness of the material. It is feared that an embrittlement, associated with the occurrence of casting defects, may increase the risk of failure.

Therefore, an extensive programme was launched in the 90s by EDF in co-operation with Areva NP, in order to determine acceptability criteria for operating cast stainless steel components. This programme relies on a large R&D effort, involving metallurgical studies, large-scale experiments, development of specific finite element tools and J-estimation schemes, and research of methods to assess the ageing state of in-service components [4-7].

In order to build the primary loops, these cast components are welded and the behaviour of the weld heat affected zone (HAZ) is not well known. So a specific program was launched in 2005 on this topic, involving metallurgical studies, fracture mechanics tests, medium-scale experiments, and finite element analyses.

This paper presents the main characteristics and results of two experiments conducted on a 6” aged cast pipes. The pipes contained a machined notch in the heat affected zone of a butt-weld and were tested under four-point bending, either at 300°C or at 100°C.
TEST DESCRIPTION

Description of the 4-point Bending Mock-up

The 4-point bending mock-up is composed of three parts (Fig. 1):

- A central section made of duplex stainless steel and containing a 316L steel butt-weld in its middle,
- Two bending arms made of carbon steel pipes (thickness: 30 mm).

The central section represents, at a reduced scale, the butt-welds found on 900 MWe PWR primary piping. Its main dimensions are as follows:

- outside diameter 6" (168 mm),
- thickness 25 mm,
- length 500 mm.

The distances between the fixed rollers and the mobile rollers are respectively 2 m and 0.7 m. The pipes used to make the central section were made of Z3 CND 19-10 M duplex stainless steel (French standard close to SA 351 CF8M), by static casting. Table 1 shows the main elements of the chemical composition and the significant elements in the thermal ageing phenomenon of duplex stainless steels which are the equivalent chromium content Cr* (Cr* = Cr + Si + Mo) and the δ ferrite content (measured by a magnetic method: specific saturation magnetization). The chemical composition chosen for the pipes leaded to a fast thermal ageing and low toughness properties (a duplex SS is prone to significant thermal ageing if Cr* > 23.5 %). Prior to the test, the central section was thermally aged at 400°C during 10,000 hours.

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cr*</th>
<th>δ Ferrite</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3318</td>
<td>1.0</td>
<td>10.40</td>
<td>21.3</td>
<td>2.40</td>
<td>24.7</td>
<td>27</td>
</tr>
</tbody>
</table>

A circumferential semi-elliptical notch was machined by the electric discharge machining process on the outer surface of the pipe, at 2 mm of the weld fusion line, in the heat affected zone of the cast stainless steel (Fig. 2). Its dimensions are as follows:

- depth at the centre a = 8 mm (projected length, normal to the pipe surface),
- total surface length 2c = 32 mm,
- inclination to the normal to the surface 20° (parallel to the fusion line),
- width of the EDM notch 0.3 mm.

Theoretically, the notch is not plane since its lies on the conical surface of the fusion interface. However, for machining reasons, an approximate shape lying on a cylinder was used.

Fig. 3 gives an overall view of the test facility.
Description of the Test Conditions

The tests were conducted at a quasi-static loading rate (ram displacement speed: 1 mm/min). The mock-up was heated at 300°C (first test) or at 100°C (second test) by circulating hot air.

Several measurements were made during the tests:
- applied load and ram displacement,
- crack mouth opening displacement at the centre of the notch and at 10 mm (both sides) from the centre,
- rotation of the pipe sections at five locations with clinometers,
- electric potential drop measurements at 7 points along the notch edge (every 7 mm),
- temperature at several points on the pipe outside surface.

The direct-current electric potential drop method was used to detect crack initiation and to follow the crack growth. A calibration of the method was done during the machining of the crack. The CMOD was measured with 5 clip-gages. At the centre of the notch, a double measurement was made: close to the surface and at 64 mm from to surface, in order to calculate the rotation of the crack lips.

Material Data

The material characterization programme included chemical analysis, hardness measurements, tensile tests, Charpy impact tests and J-resistance curves. The specimens were manufactured from a special mock-up made of four cast pipes welded together (i.e. containing three butt-welds). The thickness of this mock-up is 45 mm (the thickness of the central section of the 4-point bending mock-up was reduced to 25 mm by machining the outside surface). The characterization programme covered four materials:
- the aged cast duplex stainless steel pipe,
- the 316L butt-weld,
- the aged cast pipe HAZ,
- the carbon steel extension pipes.

Tensile tests were made on 6 mm diameter round tensile specimens. Fig. 4 shows the true stress-true strain curves obtained on the cast duplex stainless pipe, the 316L butt-weld, and the carbon steel pipes. At 300°C, the yield stress $R_{p0.2}$ and the ultimate stress $R_m$ of the duplex stainless steel are respectively equal to 213 MPa and to 612 MPa. A through-thickness variation of the tensile properties was observed, particularly on the 316L butt-weld (strain hardening induced by the welding).
J-resistance tests were conducted by the multiple specimen technique on 1T-CT (CT25) specimens, taken in the aged cast duplex stainless and in the heat affected zone. These tests have given the value of $J_{0.2}$ (value of $J$ for 0.2 mm of crack extension) and a $J$-R curve fitted by a power law: $J = C(\Delta a)^n$. The data exhibit some scatter and a statistical analysis was used to obtain the mean and ±1 sigma power law curves shown on Fig. 5. Table 2 gives the mean $J_{0.2}$ so obtained with the coefficients $C$ and $n$ of the mean power law $J$-$R$ curve. The scatter has been related to the coarse solidification macrostructure of cast duplex steels.

Table 2 – Fracture toughness properties of the cast duplex stainless steel after thermal ageing.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>KCV energy (daJ/cm²)</th>
<th>$J_{0.2}$ mean value (kJ/m²)</th>
<th>C mean value (kJ/m²)</th>
<th>$n$ mean value ($\Delta a$ in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3318</td>
<td>300</td>
<td>5.3</td>
<td>58</td>
<td>114.9</td>
<td>0.472</td>
</tr>
<tr>
<td>HAZ</td>
<td>300</td>
<td>4.5</td>
<td>54</td>
<td>87.4</td>
<td>0.328</td>
</tr>
<tr>
<td>F3318</td>
<td>100</td>
<td>2.8</td>
<td>55</td>
<td>82.9</td>
<td>0.280</td>
</tr>
<tr>
<td>HAZ</td>
<td>100</td>
<td>2.3</td>
<td>41</td>
<td>54.2</td>
<td>0.192</td>
</tr>
</tbody>
</table>

Figure 5 – $J$-$R$ curve of the cast duplex stainless steel after thermal ageing (left side: 300°C – right side: 100°C).
EXPERIMENTAL RESULTS

Main Experimental Results

Fig. 6 shows the electric potential drop versus load curve for pair P4, located at the centre of the notch. From this last curve and based on the departure from linearity, the value of the initiation load is estimated to be comprised between 385 and 425 kN for the first test and between 430 and 460 kN for the second test.

Figure 6 – Electric potential drop versus load for the pair of electrodes P4 (centre of the notch). Left side: first test at 300°C – right side: second test at 100°C.

Measurement of the Final Crack Shape

For the post-test examination of the machined notch, the notch area was cut out from the pipe, then heat tinted, the crack was extended by fatigue loading, and finally the remaining ligament was broken open (Fig. 7). The flat brown surface corresponds to the EDM notch whilst the irregular brown areas correspond to the crack extension.

This figure shows that the crack initiated all along the front and that the propagation was somewhat irregular, which is typical of this kind of steel after ageing. The final crack shape was measured optically at every millimetre of the front. The maximum crack extension reached 6 mm in a zone close to the centre of the notch whilst the average extension was equal to 4 mm. The extension is not symmetrical regarding to the notch centreline.

Figure 7 – First test. View of the crack surfaces.

Fig. 8 shows that the crack deviated from its initial plane (20° along the fusion line) to turn in a direction normal to the pipe surfaces (mode I loading). The fusion line appears not to be a weak zone. For the second test, the crack extension is close to that obtained on the first test and the crack also deviated from its initial plane.

Figure 8 – First test. Cut view of the notch in its symmetry plane, showing the fusion line and the crack deviation.
NUMERICAL ANALYSIS OF THE TEST

Description of the FE model
The aim of the computations was double:
- before the test: choose the size of the notch and evaluate the level of the load to be applied,
- after the test: show the capacity of the computations to accurately simulate the test by conducting systematic comparisons between experimental and numerical results. These results were related first to the global behaviour of the structure (load versus displacement, pipe section rotation) and secondly to the local behaviour of the notch (CMOD, crack initiation and crack propagation).

All the calculations were conducted with the FE code Code_Aster.

The mesh of the tested structure was built up using solid elements (15 and 20 node elements). Due to the location of the crack close to the weld joint fusion line, the construction of the mesh was not easy. The mesh was particularly refined in the crack area, with 16 elements along the crack front. Due to the symmetry of both the circumferential notch and the loading conditions, a FE model limited to the half-structure was used. The model comprises the carbon steel extension pipes. Fig. 9 shows the mesh and an enlarged view of the crack area.

The loading is imposed by applying an uniform vertical displacement on the nodes situated under the mobile rollers; the vertical displacement of the nodes situated under the fixed rollers being null (see Fig. 1 – note that the notch is at the opposite side on Fig. 9).

Three stress-strain curves were used: one for each constituent material (see Fig. 4). At 300°C, the value of the Young's modulus was taken equal to 176,500 MPa for the stainless steels (duplex stainless steel and 316L weld) and equal to 185,000 MPa for the carbon steel.

Figure 9 – Views of the mesh.
Overall Behaviour of the Structure

The overall behaviour of the structure was assessed in terms of load versus displacement. Fig. 10 shows that the initial elastic slope matches well to the experimental slope, without any adjustment for the 4-point bending facility compliance. However, after a certain point, the load becomes underestimated, the difference being close to 50 kN – for the first test – at the end of the test. A part of this difference may be due to the way the loading is applied (the rollers are not modeled), but more surely, the stress-strain curves used in the computation are lower than the real ones. Some additional tensile tests will be done to check this hypothesis.

![Figure 10 – Load versus ram displacement curve: comparison between measured and calculated values. Left side: first test at 300°C – right side: second test at 100°C.](image)

As a conclusion, the overall behaviour of the structure is rather well reproduced by the simulation. Regarding the applied load, the agreement could be improved by using stress-strain curves of the aged cast steel and the 316L weld measured on the inner side of the cast pipe (for the 4-point bending test, the thickness of the pipe was reduced from 45 mm to 25 mm by machining the pipe from the outer side).

Local Behaviour of the Notch

The local behaviour of the notch was assessed in terms of CMOD and crack initiation. The CMOD was measured by clip-gages at the center of notch and at 10 mm both sides of the center. The supports of the knives were fixed at some distance of the notch edge (10 or 14 mm). To compare the CMOD measurements to the computation, the supports and the knives were modeled with beam elements in the FE model so the displacements are directly given by the computation. The calculated opening displacement is slightly higher than the measured one, but the agreement remains acceptable. The difference is partly due to the stress-strain curves used in the computation. In the first test, the clip saturated before the end of the test, so the experimental curve is truncated.

The analysis of crack initiation is made by comparing the toughness of the material $J_{0.2}$ to the applied $J$ versus applied load curves (Fig. 11). The initiation load depends on the location of the point on the crack front. For the point where the applied $J$ is the highest (center of the crack), the calculated initiation load is about 415 kN, considering the $J_{0.2}$ mean value. For the surface points, the calculated initiation load is about 525 kN. The initiation load deduced from the electric potential measurements (from 385 to 425 kN) is in good agreement with the calculated one. All these figures are relative to the first test.

![Figure 11 – First test. Analysis of crack initiation.](image)

![Figure 12 – First test. Analysis of crack growth.](image)
The analysis of crack growth is made on a J-Δa diagram by comparing the material J-R curve to the applied J versus crack depth curves (Fig. 12). This analysis is made for the point of the crack front where the applied J is the highest, assuming that the crack shape remains semi-elliptical and that the crack extension stays in its initial direction (along the fusion line). Three crack sizes were investigated:

- depth a = 10 mm – half surface length c = 16 mm,
- depth a = 12 mm – half surface length c = 16 mm,
- depth a = 12 mm – half surface length c = 18 mm.

These computations showed that the applied load versus ram displacement curves remain unchanged when the crack size increases, so the underestimation of the load observed on Fig. 10 is not due to crack extension.

The crack stability analysis is done on Fig. 12. For an applied displacement of 48 mm (end of test) and using the mean J-R curve of the aged cast steel, the calculated crack growth is in good agreement with the measured one. Using the mean J-R of the HAZ would give a much larger crack growth at the end of the test. It should be noted that this analysis is preliminary, due to the various assumptions made. The possible improvements are a better modeling of the crack shape and the use of specific stress-strain curves in the “mechanical” HAZ area.

CONCLUSIONS

EDF performed two 4-point bending tests, respectively at 300°C and 100°C, on aged cast duplex stainless steel pipes containing a machined notch in the heat affected zone of a butt-weld. The tests showed that it was possible to obtain a significant amount of stable crack growth (average value: 5 mm) despite the low toughness properties of the aged material. The crack deviated from its initial plane (20° along the fusion line) to turn in a direction normal to the pipe surfaces (mode I loading). The fusion line appears not to be a weak zone.

The finite element analysis of the test simulates rather well the overall behaviour of the structure. However, after a certain displacement, the load becomes underestimated, the difference being close to 50 kN – for the first test – at the end of the test. The most credible reason is that the stress-strain curves used in the computation are lower than the real ones. For the first test, the calculated initiation load (415 kN) is in good agreement with the initiation load deduced from the electric potential measurements (385 to 425 kN).

The accuracy of the crack growth analysis is good. The calculated crack growth at the end of the test is in good agreement with the average measured crack growth (4 mm), using the mean J-R curve of the aged cast steel. It should be noted that this analysis is preliminary, due to the various assumptions made. Some improvements will be carried out:

- conduct additional tensile tests on the aged cast steel and the 316L weld using specimens taken on the inner side of the cast pipe,
- make a more accurate FE model of the final crack shape,
- improve the way the loading is applied on the pipe: model the rollers and take into account the contact.

These tests and their detailed analysis contribute to the validation of the integrity assessment of cast duplex stainless steel components from the primary circuit of French PWR units.

REFERENCES