Thermal Ratchetting in Pipes Subjected to Cyclic Thermal Downshocks and Primary Traction Charge

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SUMMARY

The paper presents the study about the structural behaviour in ratchetting regime at elevated temperature of an AISI 316 pipe (nominal dimensions are: diameter D = 71 mm, thickness t = 4.26 mm).

The work is part of the research program of collaboration between ENEA and CEA and takes place in the ENEA CRE Casaccia.

The experimental-theoretical comparison is showed.

The numerical calculations are performed by codes of the finite elements system CASTEM developed at the CEA in Saclay using different constitutive laws for the material.

Testing is carried out in a special sodium test facility, built for the purpose.

It's given a brief description of the plant and of the used instrumentation on the test section.

The specimen is subjected to the combination of cyclic primary and secondary loads. The primary load, a uniform traction stress, is applied by hydraulic jacks whereas the secondary load is a cold radial shock obtained with a sodium flow at lower temperature (300°C) in the test section initially at uniform temperature (500°C).

Ten cycles are executed.

The principal aim of this effort was to analyze in detail the 'Ratchetting' phenomena but on the same time the study allowed to compare different strain measurement techniques (the test section was instrumented with capacitive and resistive gages) and to validate the used finite element system in cyclic non-linear field.
1. Introduction

The paper reports some results of the structural analysis performed on 316 AISI stainless steel specimens in elastic-plastic-creep regime at elevated temperature and plastic cycling. The work is arranged in a numeric and an experimental part. About the numeric calculations, one of the appeared limitations is that the classical mathematical models which describe the material behaviour don't give acceptable results in plastic cycling range.

As shown by previous works and confirmed by this one, the hardening laws at the moment implemented in calculation codes (Kinematic and isotropic hardening), give results that don't agree well with the experimental measurements in cyclic plastic range for AISI steel. For this reason in the last years it came out the necessity to develop new models which better describe the material behaviour. In this work we have used one for these models, developed by Chaboche at the ONERA in Chatillon, France, comparing the results obtained with the different constitutive laws.

About experimental part thermocouples and resistive and capacitive strain gages are applied on the specimen. The experimental recordings of a first series of shocks and the comparison with numeric calculations are presented.

2. Description of the Experimental Facility, Loading Conditions and Used Instrumentations

Testing execution is just carrying out in a special sodium test facility built for the purpose. The operative simplified diagram is shown in fig. 1.

The loop operation is very simple and allows to perform cyclic loading on the test piece. A relatively thin-walled bladder was mounted inside the test piece to reduce the volume of sodium required for the thermal transient. The specimen is subjected to the combination of cyclic primary and secondary loads. The primary load is an uniform traction stress applied by four hydraulic jacks, whereas the secondary load is a cold radial shock obtained with a sodium flow at lower temperature in the specimen initially at uniform temperature.

The nominal dimensions of the specimen are:
External diameter = 71 mm; thickness = 4.26 mm; length = 200 mm.

The research program about the thermostructural material behaviour, will be the following one, with three different test series:

1) The thermal shock has a temperature step of 200°C from an initial temperature of 500°C to 300°C. This case allows to acquire the measurement technique for capacitive strain gages in transient registration by comparison with experimental recording obtained with the resistive gages, about which we have a large use experience, but limited to about 450°C temperature extreme limit. It is scheduled to perform ten cycles.

2) In the second set the temperature step is always 200°C, but from 650°C to 450°C. This in fact is the temperature field of Fast Breeder Reactors as the Italian FPC. Naturally, specimens are instrumented only with capacitive gages. Ten cycles are to perform.

3) In the final test the temperature step is from 650°C to 450°C, but in this case the structure is maintained at elevated temperature between a cycle and the following one, with consequent creep effects. The dwell creep time between two successive shocks is a week.

Both thermocouples and resistive and capacitive strain gages are applied on the specimen. The relative positions of the various instrumentations are shown in fig. 2. The following measurements are made:
- Measurements of temperature both on the inner and outer surfaces of the pipe upstream and downstream from the midpoint, providing the temperature distribution as a function of time during the transients and the uniformity of the specimen temperature at any time. All the thermocouples, whose diameters are 0.50 mm, are in Chromel-Constantan protected by stainless steel and insulated with MgO.
- Measurements of the sodium temperature just upstream the test piece by thermocouples whose diameters are 1.6 mm, located in the sodium flow.
- Measurements of strain just in the middle point of the test piece, both in the axial and circumferential directions. All the resistive strain gages are ALTECH weldable model SG 425 with Magnesium Oxide insulated lead with a gage length of about 15 mm. The high temperature capacitive strain gages are CERL-FLAHER C9 types. All the strain measurements are
made on the external surface of the structure.
- Measurement of the total final axial deformation by displacement transducers HOTTINGER W2K.

3.1. Description of the finite element structural analysis

To define the structural behaviour fields of this load combination a series of preliminary calculations were performed. Three different constitutive laws were used for the material: kinematic, isotropic, Chaboche’s hardening.

We report the list of the examined cases:

<table>
<thead>
<tr>
<th>Thermal charge</th>
<th>Traction charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shock from 500°C to 300°C</td>
<td>35 MPa (variable and constant)</td>
</tr>
<tr>
<td></td>
<td>50 MPa (variable and constant)</td>
</tr>
<tr>
<td></td>
<td>100 MPa (variable)</td>
</tr>
<tr>
<td>Shock from 650°C to 450°C</td>
<td>50 MPa (constant)</td>
</tr>
<tr>
<td></td>
<td>50 MPa (constant), creep</td>
</tr>
</tbody>
</table>

Fig. 3a and 3b show respectively the transients with variable traction and with creep.

3.2. Obtained Results

The thermal transient during the shock has been calculated by DELFINE code, imposing upon the inner surface of the tube a forced convection heat exchange, with exchange coefficient \( H = 20000 \text{ W/m}^2\cdot\text{°C} \). In fig. 4 the thermal transient is shown (shock from 500°C to 300°C). About the structural analysis results, we can say that without creep effects, the ratchetting appears only with the traction charge of 100 MPa. For this case, in fig. 5, 6, 7 the strain–strain diagrams obtained with the three used hardening laws are shown. We can note the great difference between fig. 5 and fig. 6; in fact also in this case with the kinematic hardening the ratchetting is negligible, while with the isotropic hardening the medium value of ratchetting is about 180 \( \mu \text{E} \)/cycle. The Chaboche's model furnishes a medium value of ratchetting of about 110 \( \mu \text{E} \)/cycle. Also in the other studied cases we have found, as expected, that the results obtained with this new model are placed between those obtained with the kinematic and isotropic hardening. It is clear therefore, as pointed out in other works, that the kinematic and isotropic hardening give results respectively in defect and in excess with regard to exact results. The creep effects have a great influence on the structural behaviour. Fig. 8 and 9 show the ratchetting diagrams for the shock from 650°C to 450°C and axial charge of 50 MPa. In this case we find a medium value of ratchetting of about 115 \( \mu \text{E} \)/cycle, while without creep the ratchetting is practically negligible. This result is obtained with the kinematic hardening too (110 \( \mu \text{E} \)/cycle). In fig. 9 the creep effect is evident. Without creep the structure would return to work elastically after the seventh cycle, while, on account of the creep effects, the total plastic strain increase.

4. Experimental recording of the first series of tests

With regard to the instrumentation of fig. 2, in figs. 10a,b the experimental recordings of a series of ten shocks from 500°C to 300°C with 50 MPa traction charge are presented (*). The strain gages mark the zero at 500°C and with the traction charge applied; for this reason only the thermal strains are measured. The engine performances of the experimental facility allow to realize thermal transients of gradient intensity much slower of those supposed in the preliminary calculations (15°C/s in the place of 50°C/s). Besides the final temperature

(*) The graphical strain curves are clearly to be evaluated with the various correction factors to have the maximum "clean" values.
settles about 340°C, with a thermal step of only 160°C. With these loading conditions the specimen outer surface remains in elastic range, as the recordings and numeric calculations show. Whereas the inner surface, works in shakedown regime. With regard to Figg. 10 a,b in Tables I and II the maximum corrected values of the experimental thermal strain and the numeric results are reported. We have obtained the numerical values simply carrying off the mechanical from the total strain. This procedure is not completely correct because it doesn't take into account the influence of the inner surface plastic zone. The experimental data reported in Tables I and II seem to show that the sodium flow don't cool uniformly the specimen. Modifications of the experimental facility are foreseen to improve the axial simmetry of the cooling shock and realize higher thermal transients.

5. Conclusions

The results till now obtained are just in agreement with theoretical predictions. The comparison of the different constitutive laws shows the importance, on the final results, of the use of a proper law. The analysis, besides, shows as indicated by the long and narrow form of the Bree diagram, that the structure, without creep effects, is in ratchetting regime only for high values of the primary charge.

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REFERENCES


Table I - Maximum axial thermal strain

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<th>Experimental Values</th>
<th>Numeric calculations</th>
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<tr>
<td>Nº Strain gage</td>
<td>με</td>
</tr>
<tr>
<td>2</td>
<td>- 390</td>
</tr>
<tr>
<td>4</td>
<td>- 330</td>
</tr>
<tr>
<td>5</td>
<td>- 571</td>
</tr>
<tr>
<td>6</td>
<td>- 570</td>
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Table II - Maximum circumferencial thermal strain

<table>
<thead>
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<th>Numeric calculations</th>
</tr>
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<tr>
<td>Nº Strain gage</td>
<td>με</td>
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<tr>
<td>1</td>
<td>- 700</td>
</tr>
<tr>
<td>3</td>
<td>- 235</td>
</tr>
</tbody>
</table>

Fig. 1 - AST-2 scheme
**Fig. 8** - Stress-strain curve; Kinematic hardening-Creep.

**Fig. 9** - Stress-strain curve; Isotropic hardening-Creep.

**Fig. 10a** - Experimental recordings.

**Fig. 10b** - Experimental recordings.