Creep Crack Growth in an Austenitic Stainless Steel Welded Joint

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The study of the behaviour of materials under fatigue and creep condition is made necessary by the development of structures submitted to high temperatures, such as may be encountered in the nuclear, aeronautical, oil or chemical industries. During their service life, these structures are submitted to start-up and shut-down cycles, and are maintained for long periods at high temperatures, which may lead to their rupture by a combination of fatigue and creep damage. In the case of fatigue, crack growth rate $d/dN$ can be correlated to a mechanical parameter such as $AK$, by using Paris law. As far as creep is concerned, up to now no correlation has been found between crack growth rate and a mechanical parameter. Cracks usually grow from pre-existing flaws: welded joints are particularly prone to the presence of these flaws. It is therefore the aim of this work to study the evolution under creep conditions of such flaws in a welded joint representative of the internal body of the liquid metal fast breeder reactor Superphénix. The studied steel is a 316 L type austenitic stainless steel, developed within the Superphénix project for its good creep properties at the reactor working temperature: $550^\circ C$. The filler metal has also been chosen to obtain creep resistant welded joints and meets Superphénix specifications. By creating an artificial defect in the sample, we wish to study the initiation and propagation of a crack under creep conditions. Several positions of the initial defect with respect to the welded joints have been tried in order to determine whether any was more dangerous. Different sample geometries have also been tried in order to assess their influence. The obtained results have been compared to those already available concerning base metal, within a global fracture mechanics approach, and also by microscopic damage observations.

EXPERIMENTS

Material

All base metal comes from a heat processed in 25 mm thick plates. Its chemical composition is given below:
The initial flaw was machined by thread electroerosion: the notch extremity radius being 75 μm.

The six positions are shown below:

1 2 3

4 5 6

The two CT 20 specimens had an initial fatigue flaw parallel to the welded joint, at the center of it. One of them was side-grooved resulting in an equivalent thickness of BN ≤ 16 mm (20% SG). The welded joint was perpendicular to the axis of the FLE 0.05 specimen, with the notch machined in the weld metal.

In order to understand the influence of sample geometry, it is necessary to point out the following facts:
- in a CT 40-10 specimen, the amount of weld metal represents roughly 7% of the total specimen
- in a CT 20 specimen, the weld metal represents roughly 25% of the specimen
- in the FLE 0.05 specimen, the zone where creep deformation occurs is situated almost entirely in the weld metal.

Testing procedures

Creep crack growth was carried out under a constant load. The following measurements were made on the specimens: Displacement Δ along the load line was measured by an extensometer, Crack length was measured by applying a constant intensity of 9A to the specimen and recording the potential between two points on each side of the crack. The initiation time ti is conventionally taken as the time when crack length measured by the above mentioned technique is found equal to 100 μm.

Testing temperatures were 600°C and 650°C. Initial crack length a/W was equal to 0.35 for CT 40-10 specimens, 0.486 for the plain CT 20 and 0.586 for the side grooved CT 20. The load varied from 13720 N to 22130 N for CT 40-10 specimens leading to initial values of K in the range of 31 MPa√m to 50 MPa√m and was equal to 12420 N and 10780 N for the two CT 20 specimens leading to initial values of K 29 MPa√m and 39 MPa√m. For the FLE 0.05 specimen, mean stress was equal to 312 MPa. In order to assess the influence of flaw position (CT 40-10 specimens), the six positions were tested under the following conditions: 600°C and K = 50 MPa√m. One specimen (numbered 1538-MB) sampled in the base metal plate was tested in the same conditions.

Most tests were interrupted before rupture, which was later obtained by room temperature fatigue.
EXPERIMENTAL RESULTS

Microstructural approach

A visual examination of the broken specimens shows that the creep crack front is not linear and that crack growth occurs preferentially at the center of the specimen (CT specimens): figure 2. The scanning electron microscope observations of figure 3 show that rupture is intergranular in the base metal and interendritic is the weld metal. Similar observations made on specimens with an initial flaw parallel to the welded joint lead to the same conclusion. Sections of the specimens were realised for microscopic observation after etching in order to determine crack path and localise damage. When the initial flaw is parallel to the welded joint, the crack tends to propagate inside the weld metal, along the fusion line. When the flaw is situated in the HAZ, the crack deviates towards the weld metal. When the flaw is perpendicular to the welded joint, the crack crosses the weld metal by propagating along interendritic zones (as shown on figure 3), preferably along ferrite-austenitic interfaces.

Whatever the flaw position, secondary cracks are observed within one millimeter of the rupture surface. Their number and length increase with test duration, which is typical of creep damage. Secondary cracks are mainly observed in the weld metal. Figure 4 represents a longitudinal section of specimen 4B; the weld metal is considerably more damaged than the base metal where only a short secondary crack is observed. Whatever the orientation of the initial flaw (perpendicular or parallel to the welded joint), damage and rupture are mainly localised in the weld metal, along the fusion line.

Global fracture mechanics approach

A displacement versus time curve was obtained for every test from the recording of the extensometer. By an initial calibration [1], the potential value measured across the crack, is correlated to the crack length to obtain a crack length versus time curve. An example is given in figure 5 (specimen 4B): the different zones through which the crack (initially perpendicular to the joint) propagated are indicated. Initiation time $t_i$ is determined.

For a global fracture mechanics approach, parameter $C^{\ast}_{ex}$, which is an estimation of $C^\ast$ using experimental measurements, including $\Delta\Delta\Delta\Delta$, was determined.

For a CT specimen, Benssuan and al. [2] have developed the following expression, using the work of Harper and Ellisson [3]

$$C^{\ast}_{ex} = \frac{n_2}{n_2+1} \cdot \frac{\Delta W}{A(a/W,n_2)} = 2 \cdot \frac{\Delta W}{B(W-a)}$$

in the case of austenitic stainless steel

The experimental value of $\Delta$ depends upon the creep of the specimen and upon creep crack growth. The estimation of $C^\ast$ by $C^{\ast}_{ex}$ is hence only valid for a stationary crack, particularly at initiation time. $C^{\ast}_{ex}$ is considered here as a mechanical parameter taking into account specimen geometry and loading, for $C^{\ast}_{ex}$ an estimation of $C^\ast$ only when secondary creep is predominant in the specimen. However the calculation of transition time $t_i$ and $t_2$ has shown that primary creep is predominant during the tests [4] (the tests are interrupted before rupture). But the parameter $C^{\ast}_{h}$, which represents the stress and strain fields in a situation of predominant primary creep can be estimated from $C^{\ast}_{ex}$ by [2].

$$C^{\ast}_{h} = (p_1 + 1) \cdot (p_1/p_1 + 1)$$

For the asymetric specimen, $C^{\ast}_{ex}$ was calculated according to the formula: $C^{\ast}_{ex} = \frac{P}{2\pi R^2}$ [5], $R$ being the radius of the notched section. The above mentioned remarks and limitations also apply to this formula. Figure 6 represents in logarithmic coordinates, time to initiation $t_i$ and $C^{\ast}_{ex}$ at crack initiation. The scatter band obtained by Benssusan and al. [2] for the base metal is drawn on the diagram.

The results corresponding to the CT 40 specimens are all inside this scatter band. The results corresponding to the CT 20 specimens are on the lower side of it or out of it. The result corresponding to the FLE 0.05 is out of it.

By linear regression, the following relation was obtained by taking into consideration only the results obtained on CT 40 specimens: $t_i \cdot C^{\ast}_{ex} = 0.78$ = constant. The correlation coefficient is 0.94. If all results are included in the linear regression, the following relation is obtained: $t_i \cdot C^{\ast}_{ex} = 0.69$ = constant. The diversity of specimen geometries here reduces the correlation coefficient which dwindles to 0.87.

DISCUSSION

If one takes into consideration CT 40 specimens only, by the global rupture mechanics approach one does not distinguish any difference between base metal and the composite specimen containing weld metal and base metal. This is true whatever the initial flaw position among the six positions which were tested. However, the microscopic observations mentioned in 2.1 indicate that creep damage is preferentially localised in the weld metal along the fusion line. This seeming paradox is due to the fact that a CT 40 contains only 7% weld metal, and the behaviour of the specimen is largely dependent upon the behaviour of the base metal. However, for the CT 20 specimens and the asymetric specimen the proportion of weld metal (especially in high stress zones) is more important and its higher susceptibility to creep damage influences the macroscopic mechanical results. The above remarks indicate that from a safety point of view initiation criteria that would be developed from data obtained on specimens made wholly of weld metal would be conservative for a real structure which contains generally a large proportion of base metal.

CONCLUSIONS

The correlation between $t_i$ and $C^{\ast}_{ex}$ obtained on specimens containing 7% weld metal is the same as the one obtained on base metal. In composite specimens containing both weld and base metal, creep damage and crack propagation tend to localise in the weld metal, close to the fusion line. The macroscopic behaviour of the specimen depends upon the proportion of weld metal present in the specimen. The data obtained on weld metal alone are not representative of the behaviour of composite structures but give conservative initiation rules for real components.
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Fig. 1. Notched axisymmetric specimen FLE 0.05

Fig. 3a. Interendritic creep rupture in weld metal

Fig. 3b. Intergranular creep rupture in parent metal

Fig. 2. Creep crack propagation on a CT 40/10 specimen
Fig. 4. Crack propagation and creep damage in specimen 4B

Fig. 5. $\Delta$ and $a$ as functions of time (specimen 4B)

Fig. 6. $t_i-C^*$ correlation