Thermal Shock Testing Without Primary Stresses on a Plate Shell Junction Mock-up

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Abstract

These tests were designed to study the high-temperature fatigue strength of a structure representing a plate-to-shell junction subjected to thermal shocks in sodium without primary stress loading. As it is frequently the case in EMPFR structures, the holding time does not occur at the cycle extreme values, but in the presence of residual stresses arising from inelastic deformation due to thermal shocks. The tests were conducted at the CEA's Cadarache Nuclear Research Center with the financial assistance of EDF. Two mock-ups were studied: a machined steel cylinder and a welded plate-to-shell junction. The initial test results on both test mock-ups are presented together with the results of nondestructive examinations. These findings confirm the interest of sodium testing with small structures: despite the relatively high unit cost of such tests, they appear necessary for developing and qualifying new creep fatigue design criteria applicable to structures with complex geometries rather than to test specimens submitted to simple uniaxial loading.

1 Introduction

These tests are part of a research program investigating the safety margins provided by existing or future design criteria concerning fatigue creep damage. This paper describes the test facility and procedures, reviews the structure parameters monitored during the test, and presents the initial results obtained.

2 Test Facility and Monitoring Program

2.1 Description of the Test Facility

The test device (Figure 1) is attached to the mounting flange of a 1080 mm diameter sodium pot. This flange supports a 600 mm diameter flange from which the test section is suspended.

The test section is a heat-insulated housing in which the mock-up is installed. The bottom of the housing can be supplied with sodium by an electromagnetic immersed pump to produce thermal shocks. Six electric immersed heaters rated at 1.5 kW are placed between the mock-up and the housing to ensure a sodium temperature of 600°C around the outer surface. Inside the mock-up, an inert core is used to ensure circulation of the cold sodium injected by the electromagnetic pump along the shell-spacer junction. Three thermal baffles are installed at the top of the mock-up and insulated housing to confine the high-temperature section of the test facility.

The mock-up itself comprises the following:

- a 160 mm O.D. shell measuring between 3 and 8 mm thick and 392 mm high;
- a 10 mm thick spacer plate located 45 mm from the lower face, with seven 10 mm diameter holes to allow sodium flow.

The purpose of the tests is to study the fatigue endurance of the plate-to-shell junction. Two mock-ups were prepared for testing: a one-piece nodal entirely machined from solid cylindrical stock, and a mock-up with a welded plate-to-shell junction.

In this case, the weld is a full penetration one and the mock-up has been lightly machined after welding to obtain perfect geometry.

Figure 2 shows the thermal loading procedure adopted for the test, and the resulting stresses.
With the device stabilized at 600°C, a thermal shock is produced by pumping cold sodium inside the shell on either side of the plate. The plate thus cooled on both faces has a lower mean temperature than the shell, resulting in substantial bending loads at the plate-shell junction; tensile loads on the inside, compression loads on the outside. The radial temperature gradient in the shell also induces similar stresses.

After the thermal shock, the mock-up is again heated to 600°C for 6 hours. Since the elastic limit is exceeded in the plate-to-sheet junction during the thermal shock, reverse stresses appear during the subsequent high-temperature holding period: compression in the inside and tensile loading on the outer face.

The cyclic strains caused by repeated shocks result in fatigue damage; the residual stresses after the 600°C holding period tend to relax resulting in creep damage.

2.2 Parameter Monitoring

The temperature evolution of the device is monitored by 27 thermocouples, ten of which are installed in the mock-up itself (refer to figure 3 for the thermocouple layout).

- Ultrasonic examination
  - The shell is examined from the exterior along a spiral pattern on a 0.5 mm pitch, at five incidence angles relative to a plane perpendicular to the shell centerline: -25°, -10°, 0°, +10°, +25°.
  - Fluorescent penetrant examination
  - Dimensional examinations
    - surface roughness
    - distortion along 8 generatrices
    - plate flatness
    - shell out-of-roundness
    - residual stresses (by X-ray diffraction, providing data only on superficial stresses, i.e. in the outer 15-20 microns).

3 Initial Results

The mock-ups were tested as follows:

- Machined mock-up: 100 cycles, dismantling, 230 cycles (i.e. a total of 330 cycles, from October 1982 to May 1983).
- Welded mock-up: 440 cycles, dismantling, 360 cycles, dismantling (i.e. a total of 800 cycles, from July 1983 to April 1984).

3.1 Thermal Data

Figure 4 shows the temperature values recorded from thermocouples 3 and 6, representing the shell and the plate, respectively. It can be seen that the plate temperature dropped well below the shell temperature, in accordance with the expected thermal loading. A maximum temperature difference of 110°C was reached 5 seconds after the initiation of the thermal shock.

3.2 Nondestructive Examination Results

3.2-1 Metrology

The results obtained after 100 thermal shocks on the machined mock-up can be illustrated by the dimensional recordings along the 8 generatrices (cf figure 5). In each case, a characteristic shrinkage of about 20 microns was recorded at the level of the plate-to-sheet junction. This result is consistent with the expected plastic strain, and did not evolve significantly after 330 thermal cycles.

The shrinkage observed on the welded mock-up was of greater magnitude; on the order of 100 microns.

This greater shrinkage is probably related to the action of the residual weld stresses at the plate-shell junction. Indeed, a circumferential tensile stress in the weld can explain the shrinkage observed.

A simplified numerical approach of the effect of welding is covered by the paper (22/4).

3.2-2 Fluorescent Penetrant Examination

All of the fluorescent penetrant inspections gave negative results: no distinct cracking was detectable.
3.2-3 Ultrasonic Examination

No significant echoes were obtained by ultrasonic examination of the machined mock-up. On the welded mock-up, several indications were observed at 0° incidence after 440 thermal cycles, as shown in Figure 7. The defect locations are identified on a vertical radial cross section, and the circumferential angular position relative to the longitudinal weld seam is indicated for each defect noted. It can be seen that these defects are located near the plate-shell weld seam. The same defects were observed after 800 thermal cycles, but no significant evaluation occurred. The size of the defects was quantified as about 2 mm in height by 4 mm in circumferential length.

3.4 Residual Superficial Stresses

As mentioned earlier, these measurements only concern the outer 15-20 microns of metal thickness. Figure 8 shows the results obtained on the welded mock-up. The evolution of the axial stress $\sigma_a$ is shown on five levels on the outer surface. The initially very high compression stresses (600 MPa) decreased appreciably (to 300 MPa) and then stabilized. These were superficial machining stresses that tend to relax at high temperatures.

4 Conclusion

The first results of these tests shows that no distinct surface cracking was detected. The fatigue damage $D_{\text{eff}}$ estimated using an elastic analysis according to the ASME code case N-47 has reached about 50 on the machined mock-up and about 60 on the welded mock-up.

The estimated service life inelastic calculations are covered by another paper also presented here (E9/4).

The thermal shock tests are being pursued on both mock-ups in order to obtain definite cracking and thus to estimate the safety margins provided by existing or future design criteria. The nature and mechanisms of the damage sustained will then be determined by destructive analysis. Nevertheless, the initial nondestructive examination results show that the shrinkage measured at the plate-to-shell junction is greater on the welded mock-up. This suggests that the presence of the circumferential weld seam appreciably modifies the structural stress pattern, especially as the first indications logged by ultrasonic inspection were found near the weld zone.

The tests described here are conducted in sodium on a small structure. Such tests are costly from the standpoint of the number of results obtained, but appear to be necessary for developing and qualifying design criteria applicable to reactor structures subjected to high-temperature cyclic stress loading.
Fig. 1: Overall view of the test device

Fig. 2: Thermal loading principle

Fig. 3: Thermocouple layout on the test device

Fig. 4: Temperature recordings from the plate and shell during a thermal transient
Fig. 5: Machined mock-up: external profile after 100 thermal shocks

Fig. 6: Welded mock-up: external profile after 440 thermal shocks

Fig. 7: Ultrasonic observations after 440 thermal shocks

Fig. 8: Typical X-ray diffraction measurement results for residual surface stresses