A contribution to improvement of design rules on thermal striping

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ABSTRACT
In the first part of this paper, a definition of what is called "Thermal Striping" is proposed and a description of the characteristics of this phenomenon is given. The usual design rule preventing this risk in Fast Reactors is based on a limitation of the maximum temperature variation at the surface of the component. This allowable limit is very low for structures in austenitic stainless steels and we intend to raise it, according to the two ways described in this paper:
- to perform thermal fatigue tests in the FAENA sodium loop in Fast Reactors representative conditions, such as environment, base metal cast, weldments, specimen surface finish, ageing, and then to calculate temperature and strain variations applied to the specimens by finite element method. The aim is to obtain a better knowledge of real margins between the representative test results and design fatigue curves.
- to take into account the precise spectra of temperature fluctuations in case of Thermal Striping, which do not seem to be very well known, and to establish which part of these spectra could be more damaging to the structures. This appears to be necessary since the exact allowed temperature variation in case of Thermal Striping should greatly depend on it.

1. INTRODUCTION
Thermal Striping is a complex phenomenon due to incomplete mixing of hot and cold fluid streams near the surface of components. More precisely, in several mixing areas, turbulent liquid sodium in LMFR's transmits it's thermal fluctuations to the wall structures because of the very high thermal diffusivity and conductivity coefficients existing in sodium, giving rise to random thermal fatigue damage.

It appears that the histories of temperature fluctuations are very important for the estimation of a realistic fatigue damage and only a few studies has been performed on this subject. The thermo-mechanical design rule which is currently used seems to be based on a strong hypothesis, often leading to over conservative damage predictions. We present in the first part of this paper the characteristics of temperature-time histories measured on an AEA experiment, Supersomite, and the interpretations made.

An other important way to improve the maximum temperature variation allowed consists of the acquisition of a better knowledge of the margins between design and mean fatigue curves. This is the aim of the experiments performed in FAENA sodium loop at Cadarache described thereafter.
2. SUPERSOMITE TESTS (AEA)

The tests were also performed in a sodium loop with a maximum temperature difference between hot and cold entry of 400°C. The mixing of jets occurs between two tubular specimens (figure 1 and ref [1]). The specimens were machined in 316L austenitic stainless steel; the outer tube had an internal diameter of 120 mm and a thickness of 6 mm. The axial length was greater than 21 mm. The temperature histories in the fluid were recorded during two thermohydraulics campaigns by number of thermocouples at different distances from the wall specimens (i.e. in radial direction) and at several axial locations. Also, surface temperature were acquired by 0.5 mm thermocouples at 6 positions in external and internal specimens, and some thermocouples were placed into the tubes at 1 mm from the surface.

During all the tests, in line Rainflow counting was applied to the surface temperature signals, and time histories were recorded by samples of 4 hours duration.

It was found the following thermohydraulics characteristics:

- the internal specimen was submitted to very low temperature fluctuations, so that cracking was never observed at it's surface.
- the thermal fluctuations were greater at the outer specimen lower part, but thermal field amplitude was not axisymmetric at this axial position. The fluctuations lessen progressively along the axial coordinate and maximum temperature variation becomes more symmetric.

About histograms of cycle of a given temperature amplitude from Rainflow counting method, it has been observed the typical form presented on figure 2. It can be seen that cycles of amplitude 90°C does not occur at frequency 1/second.

Then, the equivalent strain variation is calculated by a classical formula:

\[
\bar{\Delta e} = \frac{2}{3} \left( \frac{1 + \nu}{1 - \nu} \right) \lambda \alpha \Delta T
\]

where \( \lambda \) is a coherence factor taken in account the effect of thermal field heterogeneity on the stresses, \( \alpha \) is the thermal expansion coefficient, \( \nu \) is the poisson's coefficient, \( \Delta T \) is the temperature variation.

This permits the estimation of damage rate by Miner's summation:

\[
\cdot \frac{1}{t_{rec}} \sum i \frac{n(\Delta e_i)}{N_f(\Delta e_i)}
\]

where \( t_{rec} \) is the recording length of Rainflow histogram which gives \( n(\Delta e_i) \), number of cycles of a given strain variation, \( N_f \) being the cycles of failure at this strain variation level on the fatigue curve.

The analysis shows that damage comes principally from cycles of amplitudes between 110 - 130° C for the Supersomite experiments (figure 3). This cycles have a frequency of occurrence of 1/hour and fatigue damage evaluation at constant frequency of 1/hour is consistent with thermal striping results plotted on a curve of maximum temperature observed in a give sample duration versus calculated damage rate (figure 4).
So, the frequency of occurrence to use in thermal striping analysis is of about 1/hour in this case, which is far from 1/second assumed in the current design rule (this rule consists on an allowable maximum temperature variation at the surface of a component equal to ~ 40°C for a type 316 L metal). It is necessary to determine if this point is general or if it is particular to Supersomite experiments.

More data from other tests or power plant measurements for all the possible configurations of geometry, sodium jet velocity, source temperature differences must be interpreted, in view of answer to the following questions:

- cycles preponderent in damage rate calculation are they always in 110 - 130°C range, with an occurrence frequency near 1/hour ?
- what are the respective influence of the source temperature difference, the sodium jet velocity... ?

At the present time, a possible alternative design rule could be based on realistic damage rate calculations. That means the development of a data bank of histograms depending of all possible cases, and the determination of λ coherence factors for each case. To use results of figure 4 as a new allowable limit is not possible before further investigations answer to the precedent questions and, in any case, such a limit should always be related to rainflow histogram or a frequency of occurrence.
An other way to attempt to reduce conservatism in design rules is presented thereafter.

3. FAENA EXPERIMENTS (CEA)

These experiments are carried out in the FAENA sodium loop at Cadarache. The objective of the tests is to obtain a better knowledge of margins between mean and design fatigue curves. In fact, a margin of 2 on the strain variation is assessed on high cycle fatigue but the effects covered (surface finish, environment, cast to cast variation...) are not well known. Additionally, a lot of studies has shown that these parameters should be near than reactor cases to give representative life reduction factor.

The sodium experiments consist of thermal fatigue tests at constant frequency adjusted between 0.07 and 0.3 Hz, with an inlet temperature difference of ~ 400°C. Two electromagnetic pumps inject alternatively the hot and cold jets in the specimen with a flow rate of ~ 730 l/h. The figure 5 presents a schema of the test facility.

3.1. Damage assessments

After test completion, it can be observed a gradient in crack pattern along the height of the specimen because of the temperature variation gradient due to progressive heat exchange between fluid jet and wall specimen.
For the frequency 0.07 Hz, typical temperature variation in sodium are approximately 280°C at level z = 43 mm, and 200°C at level z = 220 mm, in the specimen internal channel. For the frequency 0.3 Hz, we measured about 180°C at level z = 43 mm and 100°C at z = 220 mm location.

Then, we have to determine the level of the last crack with a depth corresponding to our initiation criteria (depth near 100 - 200 μm has been chosen).
Several methods of surface specimen examination are successively used:

- classical dye penetrant
- scanning electron microscopy
- observation of metallographic samples with optical microscope.

The strain variation corresponding to our crack initiation criteria is calculated by finite element method.

Thermal stresses are estimated with an elastic behaviour following a temperature fields evaluation. After this, we apply the RCC-MR fatigue procedures to calculate the equivalent strain variation.

3.2. Reference tests

FAENA tests 1 to 9 and "cyl2" to "cyl3" have been performed with hollow cylinders machined in 316 L type steels. The objective of these tests was to establish a reference fatigue curve for specimens with a good surface finish (Center Line Average lower than 5 μm) and in high purity sodium (content lesser than 10 ppm) for a maximum temperature of 550°C. Also the effect of prior high strain fatigue cycling has been investigated by Y. BERGAMASCH.

Results agree very well with other fatigue experiments (ref [2] - [7]) carried out in non oxidising environment, on figure 6 and Table 1.

3.3. Representative experiments on welded specimens

Several thermal fatigue tests are nowaday in progress in FAENA sodium loop. They are called representative because the same base and weld metal as those existing in fast reactors are used (the base metal is also a type 316 L steel, and several TIG welds are not ground flushed). Surface finish is also typical of reactor case (i.e. rough cast). These tests are called PLA 1 to PLA 5 in Table 1. Specimens PLA 4 and PLA5 have been thermally aged 1000 hr at 700°C to simulate 100 000 hr in service ageing. All the tests will be carried out at frequency 0.125 Hz, with the special geometry presented on figure 7. The temperature variation is equal to 272°C in the fluid at z = 43 mm, leading to a strain variation \( \Delta e = 0.52 \% \) at this level (neglecting stress concentrations as presented in Table 1).

The first analysis seems to suggest that taking in account stress concentrations is sufficient to plot all the results on the reference curve. But metallurgical examination have to be continued on PLA 4, and other future tests with ground flushed welds will be helpful to confirm this interpretation.

4. CONCLUSION

We have presented in this paper two ways used at CEA Cadarache to improve the current design rules for components submitted to thermal striping damage.

The first consists of the precise study of thermal striping signals as it has been made by M.W.J. LEWIS (AEA) on Supersomite experiments. He found that cycles of amplitude between 110 - 130°C which appears at frequency 1 cycle/hr had the most important contribution in the damage rate calculation. This point must be confirmed in other mixing conditions, and a data bank of Rainflow temperature histograms should be built for design purpose.

The second should be obtained by a better knowledge of the margins between design and mean fatigue curves. Sodium fatigue experiments in reactor representative conditions (excepted irradiation) are in progress at CEA Cadarache, the end being planed in 1997.
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"Creep fatigue behaviour of type 304 and 316 L (N) in flowing sodium"
Table 1: Results of FAENA experiments and calculations

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(*) : \( z, \Delta T(z), \Delta e_{\text{eq}}(z), N_a(z) \), are calculated at \( z = 43 \, \text{mm} \), level of maximum strain variation

\( F (H_f) \): Frequency of cycles

\( N \): Number of cycles applied

\( n_m \): Instautaneous flow rate

\( R_a \): Center line Average of specimens

\( \Delta T_E \): Calculated temperature variation at the surface of the specimen, at inlet

\( \Delta e_{\text{eq}}(z) \): Uniaxial strain variation at z position

\( N_a(z) \): Number of cycles to initiation estimated on Fatigue curve

\( \Delta T_s \): Calculated temperature variation at the surface of the specimen, at outlet

\( T_m \): Experimental mean temperature

\( Z \): Axial position of the last crack initiated

\( \Delta T(z) \): Surface temperature variation at the precedent level (calculated or measured)

\( \Delta e_{\text{eq}} \): Equivalent strain variation calculated at the precedent level
Figure 1: Supersomite test vessel

Figure 2: Typical temperature variation histograms for a period of 150 min

Figure 3: Contribution of cycle of amplitude ΔT in calculated damage rate

Figure 4: Maximum temperature amplitude from Supersomite as a function of fatigue damage rate/hr

Figure 5: FAENA test facility
N.B.: Ni cycles to initiation
- RCCMR : matériau IS, design uniaxial à 550 °C
- RCCMR : matériau IS, moyenne à 550 °C
- Milieu anisé : résultats sur types 316 entre 550 et 625 °C
- Ni air : compilation M. Monot 316L SPH, passage N→Ni
- FAENA 1 et 2 niveaux : Y. Bergamaschi acier type 316L
- FAENA cyl1 et cyl3 : acier type 316L SPH

Figure 6: FAENA test results compared to mean and design fatigue curves (test 1 to 9, and cyl2, cyl3)

Figure 7: Schema of geometry PLA