

Some Aspects of Thermal Fatigue in Stainless Steel

A. F. Iorio and J. C. Crespi

Departamento Materiales, Gerencia de Desarrollo,
Comisión Nacional de Energía Atómica, 1429 Buenos Aires, Argentina

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ABSTRACT

This paper is concerned with the analysis of failures in the moderator circuit branch piping of the ATUCHA-1 pressurized heavy water reactor (PHWR), which is made of austenitic steel to DIN 1-4550 specification (similar to AISI 347). These failures are considered to result from thermal fatigue processes induced by fluctuations in a zone where stratified temperature layers occurred, the fluctuations being associated with variations in moderator flow.

The first section evaluates the possibility of cracking due to thermal fatigue phenomena and concludes that under service conditions a crack may initiate and grow through 7 mm thickness of the branch pipe. In laboratory thermal fatigue tests that simulated the thermomechanical conditions for such a component, the number of cycles required to initiate a thermal fatigue crack in a notched modified standard fatigue specimen was about 10^3 . This value may be used to give a conservative prediction of the number of thermal cycles for crack initiation in actual branch pipes, including those subject to the cold plug condition which is produced in some emergency shut-down and valve testing situations.

It was also demonstrated that beyond a crack depth of 7 mm stress corrosion cracking is the main process in further crack propagation. The relevance of this prediction is confirmed by microfractographic observations, since the brittle nature of the fracture surfaces under service conditions appears very different from the transgranular ductile striations found in both thermal and mechanical fatigue test specimens as a result of interacting environmental effects.

NOMENCLATURE

a	Crack length
b	Tube wall thickness
E	Young's modulus
K'	Cyclic strength coefficient
K_{eff}	Effective stress intensity factor
K_{max}	Stress intensity factor at peak stress
K_T	Theoretical stress concentration factor
K_c	Strain concentration factor ($= \Delta\varepsilon/\Delta\varepsilon_n$)
K_σ	Stress concentration factor ($= \Delta\sigma/\Delta\sigma_n$)
m	Empirically determined exponent dependent upon material and temperature
n'	Cyclic strain-hardening exponent
N_f	Number of cycles to fracture
R	Stress ratio
α	Coefficient of linear thermal expansion
ΔK_{th}	Threshold stress intensity factor range
ΔT	Temperature difference across the wall thickness
$\Delta\varepsilon$	Cyclic strain range
$\Delta\varepsilon_n$	Nominal cyclic strain range
$\Delta\sigma$	Cyclic stress range
$\Delta\sigma_n$	Nominal cyclic stress range
ν	Poisson's ratio
ξ	Ratio of inner to outer radii ($= R_i/R_o$)
σ_{max}	Peak stress
σ_t	Thermal stress
σ_y	Yield stress

INTRODUCTION

Since the first failures occurred in 1977 in the ATUCHA-1 PHWR moderator circuit branch piping, which is made of stainless steel to DIN 1.4550 specification (similar to AISI 347), it has been shown that mechanical fatigue was not the only mechanism that caused crack propagation.¹⁻³ From those early investigations it was concluded that the pressurized heavy water environment itself also had some influence on crack propagation, since there was agreement between the nature of the

fracture surfaces examined and those reported in some other relevant works.^{4,5}

More recent experimental work⁶ has confirmed the presence of fluctuations in a coolant zone where stratified temperature layers occurred, these fluctuations being associated with variation in moderator flow, so allowing thermal fatigue to be induced. The stratification process is due to the ingress of relatively cold heavy water at 140°C into the primary cooling circuit, which is at 280°C, as shown in Fig. 1. The cold water is derived from the moderator circuit and a cold plug condition is produced in some emergency shut-down and periodic valve testing situations.

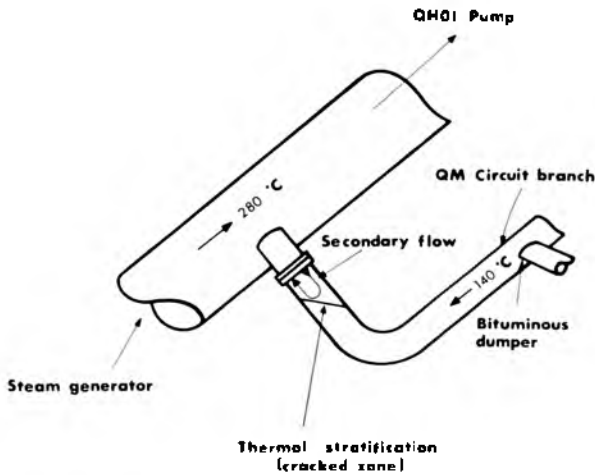


Fig. 1. Moderator circuit branch piping scheme showing the stratified layer location.

Although a considerable amount of work on thermal fatigue has been done in the past and part of it shows that the appearance of the fracture surface is transgranular brittle,⁷ there is not much published evidence on this aspect.

The first section of the present paper evaluates the possibility of cracking due to thermal fatigue phenomena. The following section describes a test which simulated the thermomechanical conditions to which the moderator circuit branch piping is subject, in order to clarify whether an environmental effect interacts with thermal fatigue phenomena. The resulting fracture surfaces under different rupture conditions are compared.

POSSIBILITY OF THERMAL FATIGUE CRACKING

As indicated above, the thermal fatigue process is considered to originate in the fluctuation of a stratified coolant layer; the related conditions are that the temperature of the inner surface of the pipe is 280 °C and every 20 s a 'strip' of water at 140 °C moves cyclically on this surface. This implies a quasi-stationary process governing the phenomenon in which a thermal shock condition appears to be of minor relevance, involving only a very thin layer of material thickness; nevertheless, such a thermal shock effect is of particular concern for a stationary regime because stresses produced by this effect reinforce stresses coming from fluctuations of the stratified layer.

Stationary thermal stresses were given by Zudans and Yen⁸ as a function of pipe radius, r ($R_i \leq r \leq R_o$), where the internal surface hoop stresses are tensile and the external surface hoop stresses are compressive:

$$\sigma_t = \frac{E\alpha \Delta T}{2(1-\nu)\ln \xi} \left[1 + \ln\left(\frac{r}{R_o}\right) + \frac{\xi^2 \ln \xi}{1-\xi^2} \left(1 + \frac{R_o^2}{r^2}\right) \right] \quad (1)$$

These pseudo-elastic stresses, which also include the hoop stresses due to pressure through the wall thickness, are shown in Fig. 2. The solid lines represent these stresses once they have been transformed into

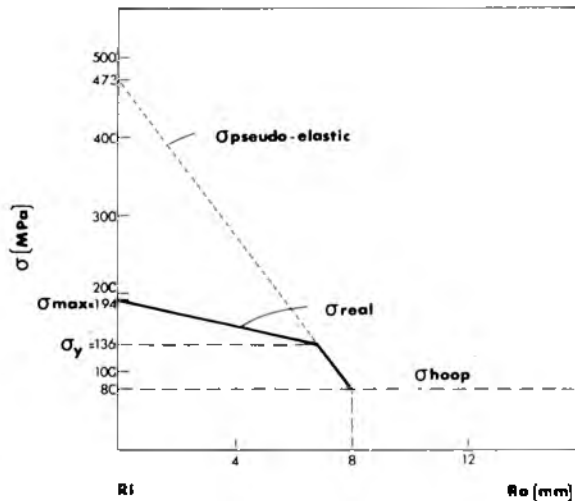


Fig. 2. Stress levels through the pipe wall thickness due to thermal fatigue plus hoop stresses.

elastic-plastic stresses. As can be seen in Fig. 2, up to 7 mm depth from the internal radius the stresses are higher than the material yield stress.

Using the values of these cumulative stresses in conjunction with the fatigue design curves from ASME Code, Section III, it can be predicted that a fatigue crack will develop in about 10^4 cycles. Considering that in low-cycle fatigue the number of cycles for crack initiation is about 10-20% of the number of cycles for fracture, then in the present case such initiation should occur after 1000-2000 cycles.

The fatigue crack propagation rate is governed by the effective stress intensity factor, K_{eff} , which is given by the following expression:⁹

$$K_{eff} = K_{max}(1 - R)^m \quad (2)$$

where K_{max} has been estimated from the following relationship:¹⁰

$$K_{max} = (\sigma_{max}\sqrt{\pi a})F(a/b; R_i/R_o) \quad (3)$$

where $F(a/b; R_i/R_o)$ is a non-dimensional function.

Figure 3 shows the profile of K_{eff} through the wall thickness, calculated with pseudo-elastic stresses after eqn (1). An elastic-plastic criterion would be more appropriate for the first 6-7 mm of wall thickness but it was considered that the elastic solution used should bring a conservative result. The inflection point shown in Fig. 3 indicates a change in the crack growth process, since at that point the cyclic stress frequency varies from seconds (due to the thermal fatigue phenomenon) to months (due to

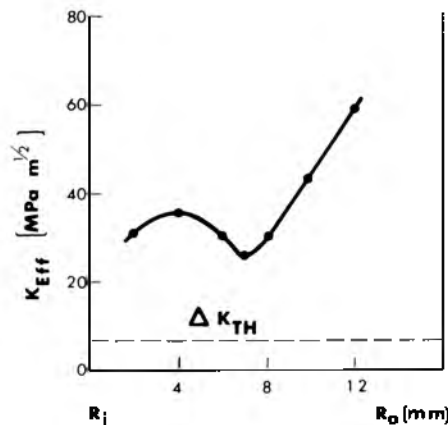


Fig. 3. K_{eff} profile through the pipe wall thickness.

variation of internal pressure produced by reactor start-ups and shut-downs). It follows that at such a point the crack will not grow by a fatigue process. The conditions are then especially set up for stress corrosion cracking to drive the crack growth process because the length of the crack may produce a stagnant environment with a high stress intensity factor at the crack tip.

EXPERIMENTAL PROCEDURE

A notched modified standard fatigue specimen was designed, which is shown in Fig. 4. Specimens were machined from the failed wall pipe, the specimen axis following the longitudinal axis of the tube.

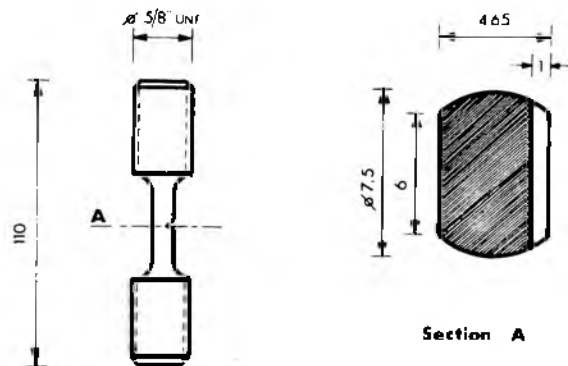


Fig. 4. Notched modified standard fatigue specimen.

The chemical composition of the steel agreed with the standard specification for DIN 1.4550 (AISI 347) and its microstructure in the transverse section is shown in Fig. 5.

The distribution of the inclusions was normal but a few large inclusions (up to $10^3 \mu\text{m}$ long) were aligned in the longitudinal direction of the tube.

The temperature cycle was achieved by means of a 10 kW (450 kHz) induction heating furnace, using 30 s for increasing the temperature from 100°C to 300°C and 17 s for cooling it down to 100°C. The total thermal cycle was accomplished in 47 s.

The cooling process was carried out by means of copper blocks fixed to the specimen with an internal injection of cold water flow. Simultaneously



Fig. 5. DIN 1.4550: austenitic stainless steel microstructure with partial recrystallization ($\times 100$).

a jet of cold air was applied in order to accelerate the cooling. Before the heating cycle was reinstated the cooling was stopped and the copper chamber emptied. The temperature loop system was closed by a 0.3 mm diameter Chromel–Alumel thermocouple located directly at the specimen notch root.

By keeping the stroke constant, stiff restraints were imposed on the specimen by means of a servohydraulic universal testing machine

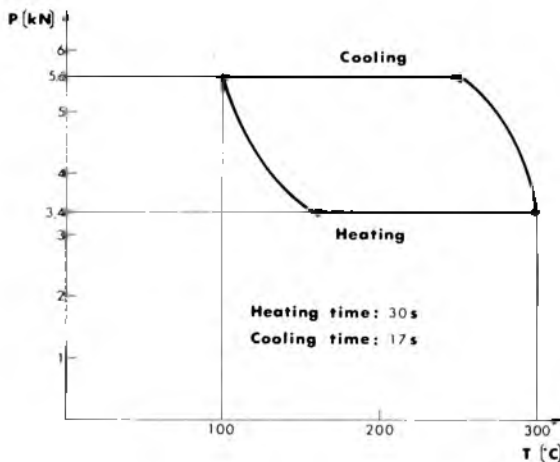


Fig. 6. Experimental thermomechanical cycle imposed on the specimen.

(100 kN). The stress resulting from this restraint was increased by an additional monotonic tensile stress. The applied net stress at 100°C was then 210 MPa, which was the stress estimated to cause crack initiation in approximately 10^3 cycles.

The complete thermomechanical cycle is shown in Fig. 6. Due to the stress relaxation dependence¹¹ a semi-continuous adjustment was made to the applied load in order to maintain a constant stress on the specimen during the complete cycle.

CRACK INITIATION PREDICTION

In order to predict the number of cycles required to initiate a crack about 0.2 mm long it is necessary to know the stress and strain fields at the notch tip. This requires the local strain at the notch tip to be related to the cyclic behaviour of a specimen without notch which is subject to the same cyclic strain.¹² It is assumed that the number of cycles for crack initiation is the same for similar strain values in both specimen types.

The notch tip material can be characterized by the stationary cyclic stress-strain response. This relationship was derived from data obtained by Kanazawa and Yoshida¹³ for stainless steel type AISI 347 at 450°C and strain rate $\dot{\phi} = 6.7 \times 10^{-3} \text{ s}^{-1}$:

$$\Delta\sigma = K'(\Delta\varepsilon)^{n'} \quad (4)$$

where K' and n' had the values 6000 MPa and 0.542 respectively.

Furthermore, the Neuber rule¹⁴ was considered to apply in order to obtain the relationship between the notch tip stress and strain concentration factors:

$$K_\sigma K_\varepsilon = K_T^2 \quad (5)$$

where $K_T = 2.74$.¹⁵ Substituting in eqn (5):

$$\frac{\Delta\sigma}{\Delta\sigma_n} \cdot \frac{\Delta\varepsilon}{\Delta\varepsilon_n} = K_T^2 \quad (6)$$

Combining eqns (4) and (6):

$$(\Delta\varepsilon)^{1+n'} = \frac{K_T^2 \Delta\sigma_n \Delta\varepsilon_n}{K'} \quad (7)$$

With $K' = 6000$ MPa, $n' = 0.542$, $K_T = 2.74$, $\Delta\sigma_n = 210$ MPa and $\Delta\varepsilon_n = 0.2\%$, eqn (7) gives $\Delta\varepsilon = 0.76\%$.

At the notch tip eqn (7) gives the value of the calculated strain which, if it is assumed to match that homogeneously distributed strain for an unnotched specimen, allows the determination, through the $\varepsilon-N$ curve of the material, of the number of cycles to fracture. Using data from Kanazawa and Yoshida¹³ for such an $\varepsilon-N$ curve, the result is $N_f = 10^4$ cycles. It is also known that in low-cycle fatigue conditions the number of cycles to initiate a crack is about 10–20% of N_f , i.e. in this case about 1000–2000 cycles.

EXPERIMENTAL RESULTS

Under established experimental conditions, with stiff restraints imposed by the application of a 210 MPa stress and a heating-cooling cycle of 47 s between 100°C and 300°C, the number of cycles required for crack initiation (0.2 mm crack length) was about 10^3 . This value agrees with the crack initiation prediction, so that the isothermal cyclic curves can be

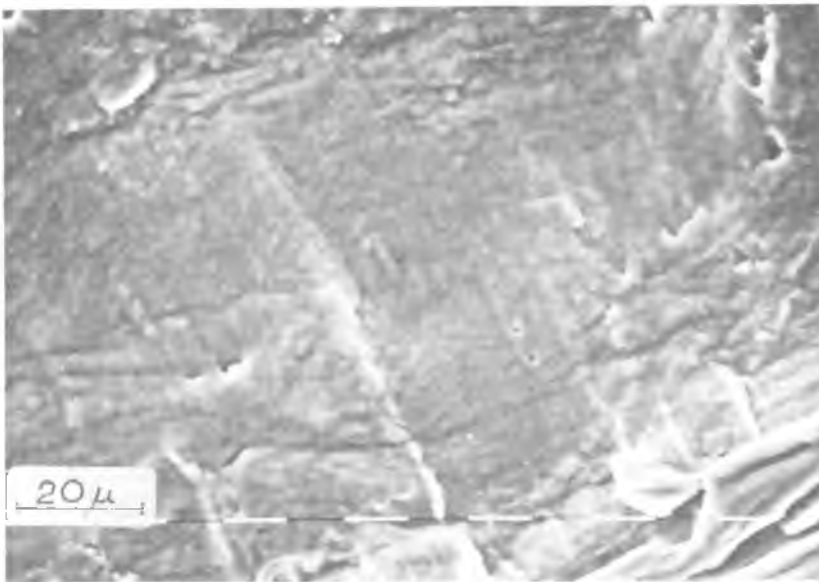


Fig. 7. DIN 1.4550: fracture surface of a thermal fatigue crack.



Fig. 8. DIN 1.4550: fracture surface of a low-cycle mechanical fatigue crack.

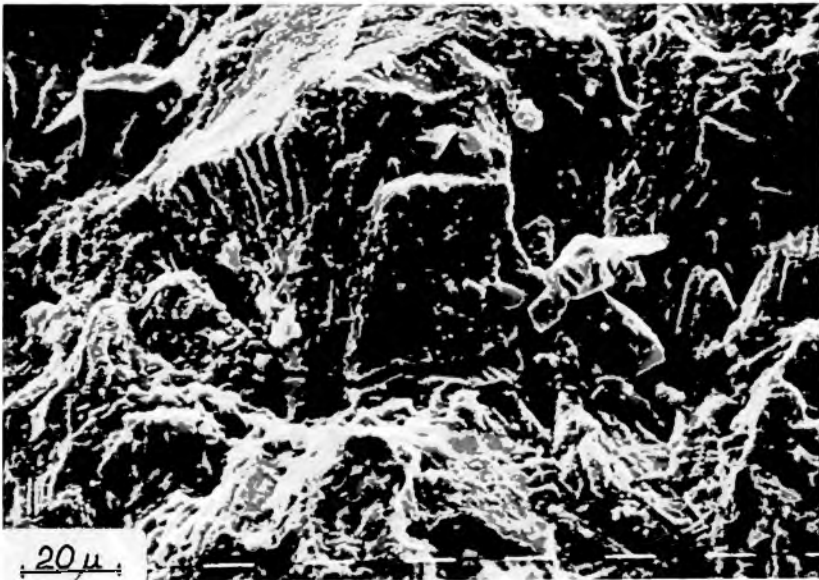


Fig. 9. DIN 1.4550: brittle transgranular type of fracture surface crack as produced by in-service failure.

used to predict the number of cycles for crack initiation of a notched test specimen under thermal fatigue conditions.

Figure 7 shows the fracture surface of specimens tested in thermal fatigue where the rupture is of ductile transgranular type with clear indications of fatigue striations.

For comparison purposes, Figs 8 and 9 show the fracture surfaces of the same material under mechanical fatigue² and service conditions respectively. As can be seen in Fig. 9 this fracture surface presents brittle characteristics which agree with the previous conclusions about stress corrosion cracking as a phenomenon driving the crack propagation process.

DISCUSSION AND CONCLUSIONS

From the foregoing evaluation it is predicted that a thermal fatigue crack can be initiated in the ATUCHA-1 PHWR moderator circuit branch piping under normal service conditions. This prediction does not take into account thermal shock stresses, thermal stripping¹⁶ or stresses due to mechanical restraints in the pipe different from those applied in the tests. These may reduce the calculated life for crack initiation.

Nevertheless, it is considered that the prevailing process is quasi-stationary, in agreement with the results obtained by Braschel *et al.*¹⁷ The prediction of the number of cycles to failure is ratified by the failure frequency of the component.

In laboratory tests, the number of thermal cycles necessary for crack initiation in a notched modified standard fatigue specimen under simulated conditions of thermomechanical fatigue was about 10^3 . This can be used to predict conservatively the number of thermal cycles for crack initiation in actual branch pipes, including those subject to the cold plug condition which is produced in some emergency shut-down and valve test situations.

It was also demonstrated that thermal fatigue is capable of propagating the crack only up to 7 mm depth in the tube wall; beyond that depth it grows mainly by stress corrosion cracking. This prediction was confirmed by comparison of crack fracture surfaces caused by thermal and mechanical fatigue with microfractographic observations of in-service tube failures which revealed the presence of an interacting environmental effect driving the crack until leakage occurred.

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