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Creep-Fatigue Initiation of a Weldment Joint Singularity in 316L Stainless Steel under Mixed Mode Loading I and II

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ABSTRACT:

In the present paper mixed mode loading creep fatigue crack initiation assessment methods are compared to experimental results. The latter are coming from creep fatigue experiments carried out on a sodium test device at C.E.A. Cadarache. Initial flaw is a design singularity located in a weldment joint between two thick tubes made of 316 L (N) stainless steel. Assessment methods tested are the σ_d approach, as proposed in the A16 document [1], and intergranular creep damage model of the Ecole des Mines de Paris [2]. In both methods the number of cycles needed for crack initiation is lower than experimental results, and sensitivity to the mode II loading is close.

1. INTRODUCTION :

Weldment joint design in Fast Reactor's components can lead to geometrical singularities. Design rules for such joints have to take account stress intensification around the singularity, considered as an initial flaw. More over mixed mode loading conditions can often occur because of an initial flaw not linked to loading direction. Then a high temperature defect assessment method under mixed mode loading is needed to study creep-fatigue initiation of such flaws.

A simplified approach, called the σ_d method, has been developed at C.E.A. in order to assess creep-fatigue crack initiation. Further more a physical approach is proposed by the Ecole des Mines de Paris for intergranular creep damage, where creep crack initiation can be assessed with a critical value of the scalar damage field.

In order to study creep fatigue crack initiation under mixed mode loading, experiments have been carried out at C.E.A. Cadarache. Specimens are representative of a weldment joint singularity in 316 L stainless steel, and are tested on a sodium test device.

In the present paper the σ_d method and the intergranular creep damage model assessments are compared to experimental results. For the simplified approach stress intensity factors are derived from Finite Element computations and the σ_d rule is applied as defined in A16 document. Concerning intergranular damage approach, inelastic mechanical fields (stresses and viscoplastic strain) are computed with a Finite Element model and CHABOCHE's unified visco-plastic constitutive equation. Finite Element calculations are performed on CASTEM2000 computation code.

2. EXPERIMENTAL RESULTS :

Experimental program is carried out on a sodium test device. The aim is to give quantitative estimations of initiation times for a weldment joint design singularity under representative Fast Reactor's creep-fatigue loading conditions (i.e. low primary loading and high secondary loading). Specimens are defined on figure 1 and are designed in order to give different ratio between mode I and II.

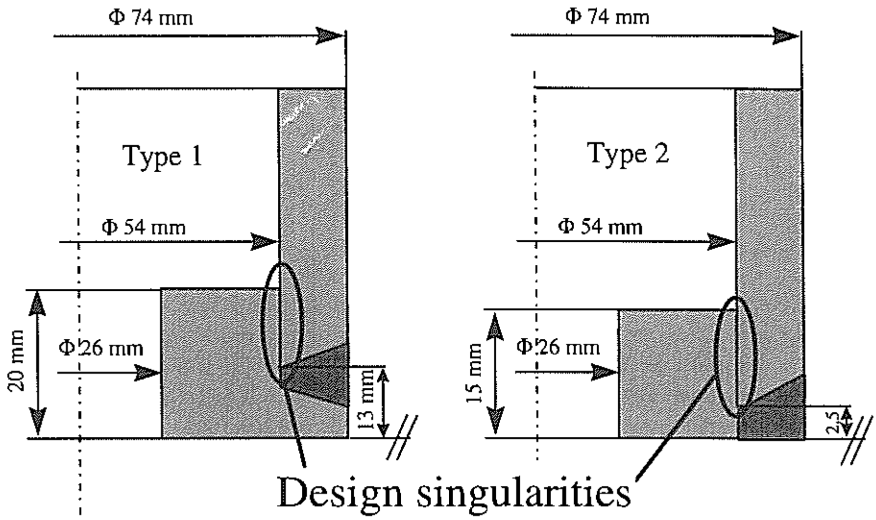

Figure 1 : Geometrical characteristics of test specimens type 1 and 2.

In both cases the influence of a gap between base metal parts has been tested. The creep fatigue loading is composed with a cyclic cold thermal shock on the outer surface and a 4 hour dwell period at 600°C. The residual stress state consecutive to transient thermal stage lead to creep damage during dwell periods. Main characteristics of the loading and experimental results are given in table 1.

Table 1 : Experimental results

Specimen type	test number	gap	Thermal shock (°C)	Number of cycle	Crack growth (µm)
1	1	no	600/350	150	210
	2	yes	600/350	150	120
2	3	no	600/350	150	0
	4	yes	600/350	360	0

On figure 2 we can see a metallographic examination of the design singularity after 150 creep-fatigue cycles. Crack growth from the tip of design singularity is approximately 300 μm, and is located in the weld metal.

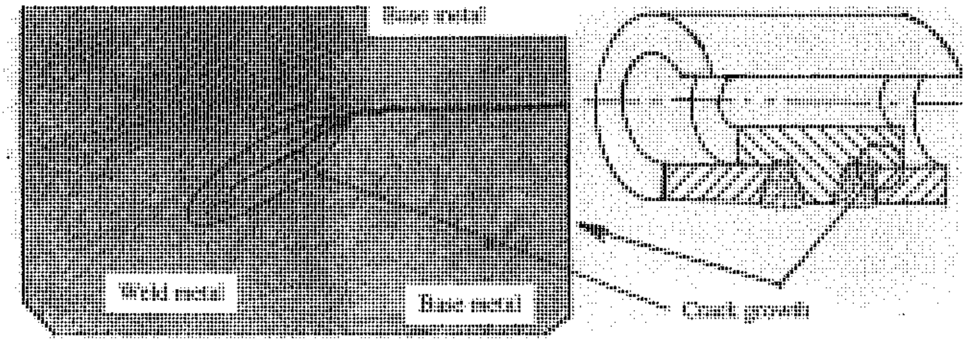

Figure 2 : Metallographic examination after creep fatigue test.

3. THERMAL LOADING :

Thermal loading is derived from the FINITE ELEMENT computation code CASTEM2000, using the mesh shown on figure 3. Initial temperature is 600 °C, the cold thermal shock is applied on the outer surface of the specimen with a sodium flow at 350°C.

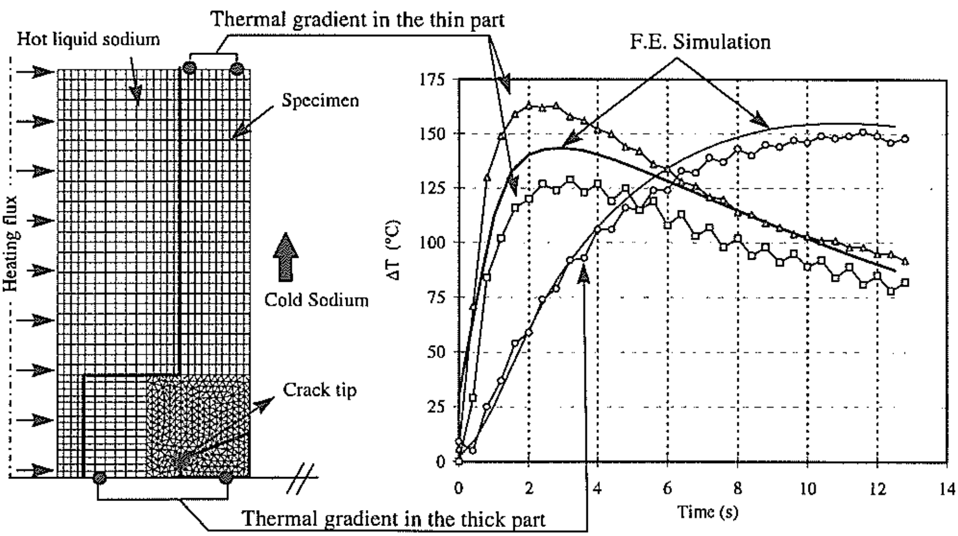

Figure 3 : Finite Element simulation for thermal loading

Convection exchange ratio on the outer surface of the specimen is fitted with experimental temperature gradients during the thermal transient stage (figure 3).

4. σ_d DEFECT ASSESSMENT METHOD

The σ_d method as presented in [1] is a simplified approach for creep-fatigue crack initiation assessment. It is based on the RCC-MR creep fatigue interaction diagram, and use rupture properties of uncracked specimens under a stress magnitude computed at a distance d from the crack tip in order to avoid singularity. σ_d defect assessment method has been validated in [3], for CT specimens under mode I creep-fatigue loading, and in [4] for notched tubular specimens under mode I thermal creep-fatigue loading. However few results are available for mixed mode loading I and II.

4.1 σ_d Simplified method

The influence of mode II stress intensity factor is introduced in elastic estimation of σ_d stress with an equivalent stress intensity factor given in equation (1).

$$\Delta\sigma_d^{elastic} = \frac{\Delta K_{eq}}{\sqrt{2.\pi.d}} = \frac{\sqrt{\Delta K_I^2 + \Delta K_{II}^2}}{\sqrt{2.\pi.d}} \quad (1)$$

Where ΔK_I and ΔK_{II} are stress intensity factor ranges in mode I and II during the cyclic loading, d is a characteristic distance approximately equal to the grain size average (50 µm in austenitic stainless steels).

According A16 simplified approach an elasto-plastic estimation of the strain range at distance d is given by :

$$\Delta\varepsilon^{ep} = \Delta\varepsilon_1 + \Delta\varepsilon_2 + \Delta\varepsilon_3 + \Delta\varepsilon_4 + \Delta\varepsilon^{cr} \quad (2)$$

Where $\Delta\varepsilon_1$ is elastic strain range due to $\Delta\sigma_d^{elastic}$, $\Delta\varepsilon_2$ is plastic strain range due to primary cyclic loading, $\Delta\varepsilon_3$ is plastic strain range due to secondary cyclic loading (derived from the Neuber's rule in the A16 method), $\Delta\varepsilon_4$ is plastic strain range used to take into account fatigue remaining life reduction factor due to triaxality and $\Delta\varepsilon^{cr}$ is creep strain range due to dwell stress state (see below).

The dwell stress at a distance d is derived from the elasto-plastic stress range, itself associated to $\Delta\varepsilon^{ep}$ via the cyclic consolidation curve, assuming that the stress cycle is symmetric :

$$\sigma_{kd} = 0,5.\Delta\sigma^{ep}(\Delta\varepsilon^{ep}) \quad (4)$$

Table 2 : Main parameters of the σ_d method for mixed mode loading creep-fatigue tests

Specimen type	ΔK_I ($MPa.\sqrt{m}$)	ΔK_{II} ($MPa.\sqrt{m}$)	$\Delta\varepsilon^{ep}$ (%)	σ_{kd} (MPa)
1	21,5	20,5	3	380
2	19	13	2,1	338

In table 2 the σ_d method is applied to creep-fatigue tests described in paragraph 2. In this table stress intensity factor ranges in mode I and II are derived from Finite Element results, computed with the G_THETA method, during the cold thermal shock.

4.2 Creep-fatigue crack initiation

Fatigue damage V is derived from fatigue failure assessment diagram based on the Manson Coffin criteria :

$$V=N/N_R \tag{3}$$

Where N_R is the number of cycles to rupture under $\Delta\varepsilon^{ep}$ and N the number of creep-fatigue cycles.

Creep damage W is derived from the creep time to failure under stress σ_{kd}, computed on a creep failure assessment curve based on Katchanov criteria :

$$W = N.\int_0^{t^{cycle}} \frac{dt}{T_R(\sigma_{kd}(t))} \tag{5}$$

Where t^{cycle} is the length of the dwell period. Stress relaxation can be applied on σ_{kd} by using the strain hardening creep law and an elastic follow up ratio consistent with loading and geometry.

Number of cycles for creep-fatigue crack initiation is derived from RCC-MR creep-fatigue interaction diagram. Creep and fatigue damages for mixed mode loading tests described in paragraph 2 have been computed in table 3.

Table 3 : Creep-Fatigue crack initiation assessment

			Minimal properties			Mean properties		
Specimen type	test number	Number of cycles	V	W	Initiation Nb of cycles	V	W	Initiation Nb of cycles
1	1	150	7,2	32,3	3	0,36	3,1	38
	2	150						
2	3	150	3,4	17,8	6	0,17	1,8	69
	4	360	8,2	42,7		0,41	4,3	

5. INTERGRANULAR CREEP DAMAGE ASSESSMENT METHOD

For intergranular creep damage, occurring at high temperature in austenitic stainless steels, a physical approach has been developed at the Ecole des Mines de Paris [2]. In the last reference a model is proposed to compute a scalar damage field describing intergranular creep damage D :

$$dD = A \cdot \langle \sigma_1 \rangle^2 \cdot \frac{1}{\sqrt{\varepsilon_{eq}}} \cdot d\,\varepsilon_{eq} \qquad (6)$$

Where A is a material parameter ($A=2.10^{-5}$ in [2]), σ_1 maximal principal stress, ε_{eq} cumulated creep strain and <x> positive par of x.

In this model intergranular damage doesn't occurred under a compressive stress state, and dD represents the ratio of damaged grain boundaries. The whole grain boundary is broken when intergranular creep damage D reach a critical value Dc, set at 2,5% in [2]. For a thin crack initiation is defined as the rupture of the first grain boundary, more over damage scalar field is not computed for distance lower than the grain size average in order to avoid unrealistic values.

In the present study mechanical fields (stress and strain) are computed versus time with Finite Element code CASTEM2000 for creep fatigue loading given in paragraph 2. Material behaviour is described with CHABOCHE's unified visco-plastic model [5], identified for the base metal 316L (N) at 600°C. For this study anisothermal behaviour of the material during cold shock is not taking into account, and weldment joint has the same behaviour than base metal. The aim of this study was to quantify the influence of mode II loading on creep-fatigue crack initiation, in order to be compared to the simplified approach.

Figure 4 give the maximal principal stress and creep strain around the crack tip at the end of the 10^{th} dwell period. Residual stress field during the dwell period tend to open the crack tip as expected. Mode II loading lead to a tensile stress state on the right hand side of the singularity, where intergranular creep damage is maximum as shown on figure5.

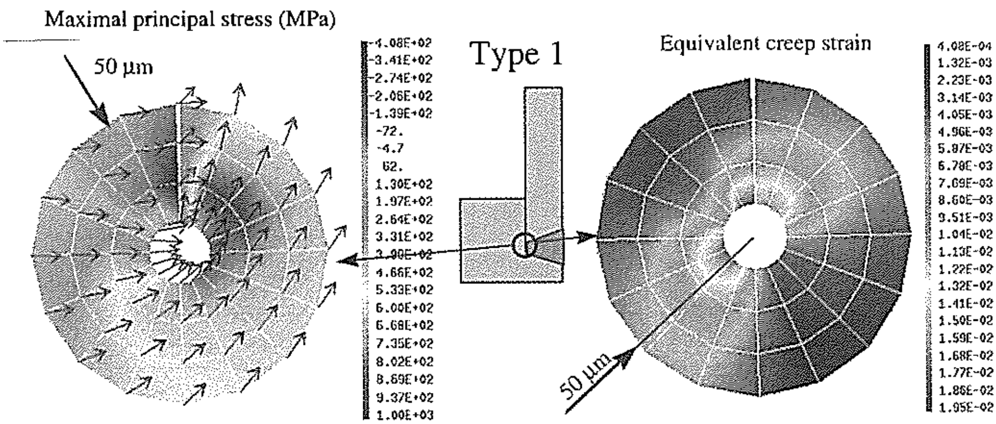

Figure 4 : Mechanical fields around crack tip at the end of 10^{th} dwell period.

Scalar damage field is integrated with Finite Element results according equation (6) and is shown on figure 5 at the end of 10^{th} cycle.

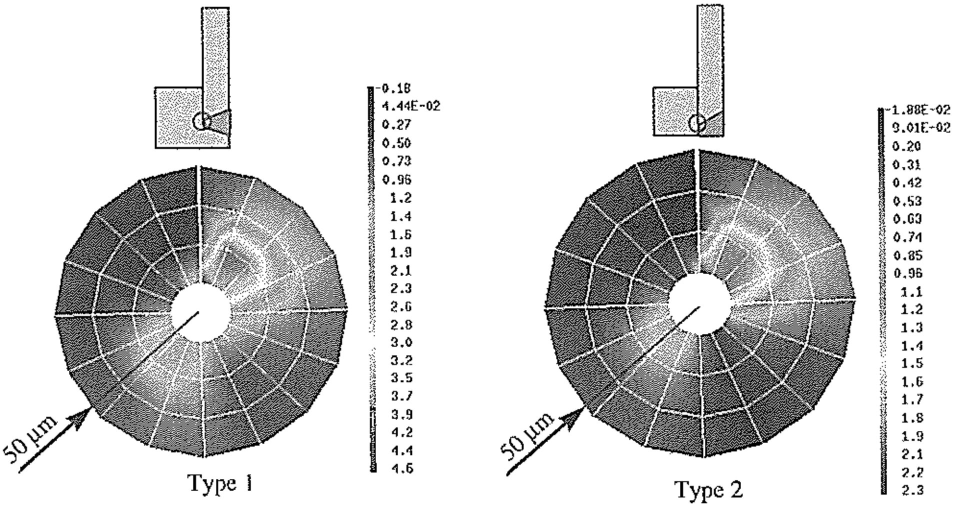

Figure 5 : Intergranular creep damage field at the end of 10^{th} creep-fatigue cycle (%)

Creep fatigue crack initiation number of cycles is assessed with maximum value of damage scalar field at 50 µm from the crack tip. Maximum damage evolution versus number of cycles is given on figure 6. Creep-fatigue crack initiation number of cycles, derived from a linear extrapolation on figure 6 and a critical damage of 2,5%, is 27 for specimen type 1 and 45 for specimen type 2.

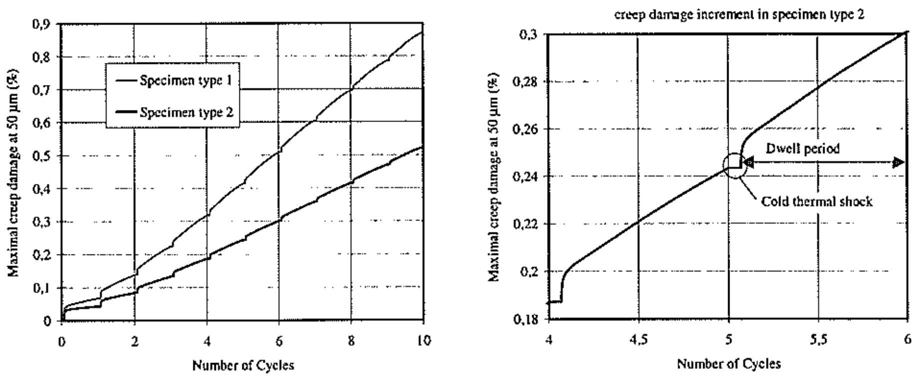

Figure 6 : Maximum creep damage at 50 µm versus number of cycles.

6. DISCUSSION

According experimental results presented in table 1 a significant crack initiation appears in specimen type 1, and no crack initiation appears in specimen type 2 although a higher number of creep fatigue cycles for test number 4. Mode II stress intensity factor in specimen type 2 is 13 MPa.$\sqrt{m}$ against 20,5 MPa.$\sqrt{m}$ in specimen type 1, however loading level doesn't seem enough to explain a much smaller crack initiation number of cycles in specimen type 1 than in specimen type 2. Actually both defect assessment methods, σ_d and intergranular creep damage model, give approximately a ratio of two between crack initiation number of cycles of each specimen type. A more realistic hypothesis to explain higher nocivity of geometrical singularity in specimen type 1 is a lack of penetration of weld metal at the crack tip observed mainly in test specimens type 1.

σ_d crack initiation assessments are very conservative, even compared specimen type 1 results, when using minimal properties for fatigue and creep rupture criteria. For mean properties crack initiation number of cycles given by σ_d method is in good agreement with experimental results of specimen type 1, and is steel very conservative for specimen type 2 as discussed above.

Intergranular creep damage model crack initiation assessments are close to results given by σ_d method when it is used with mean properties. Localisation of creep damage given by the intergranular model (6) is consistent with experimental results on figure 2. However experimental crack growth path is not correctly assessed with the scalar damage field on figure 5. It worthwhile to notice that mechanical properties of the weld metal have not been introduced in the present study, a complete model with specific behaviour and damage law for base metal and weld metal would probably improve crack growth path assessment.

6. CONCLUSIONS

Creep Fatigue crack initiation tests under mixed mode loading have been performed on a sodium test device. Initial flaw is a geometrical singularity due to the design of the weldment joint. Significant crack initiation was observed in one specimen type, where a lack of penetration seems to explain a higher nocivity of the geometrical singularity.

Mixed mode loading I and II is introduced in σ_d crack initiation assessment method as an equivalent stress intensity factor range. σ_d crack initiation assessments are conservative for all specimens when using minimal properties for fatigue and creep rupture criteria.

Intergranular creep damage field has been computed with a Finite Element code and the CHABOCHE's unified visco-plastic constitutive model. Crack initiation number of cycles given by intergranular creep damage model are close to mean assessments of the σ_d method, and are in good agreement with most unfavourable experimental results.

REFERENCES :

1. A16 : "GUIDE for DEFECT ASSESSMENT and LEAK BEFORE BREAK ANALASIS", Rapport DMT 95/659, third draft, 1995.
2. PIQUES R. "Mécanique et mécanismes de l'amorçage et de la propagation des fissures en visco-plasticité dans un acier inoxydable austénitique". Thèse soutenue à l'Ecole Nationale Supérieure des Mines de Paris, 1989
3. L. LAIARINANDRASANA : "Amorçage de fissure à haute temperature dans un acier inoxydable austenitique", Thèse soutenue à l'Ecole Nationale Supérieure des Mines de Paris, 1995
4. B. MICHEL "Creep-Fatigue crack initiation assessment on thick 316L tubes under cyclic thermal shocks with the σ_d approach", Creep fatigue damage rules for advanced FR design, Proceedings of technical comittee, 1996.
5. J.L. CHABOCHE, "Constitutive Equations for cyclic plasticity and cyclic viscoplasticity" Int. J. of Plasticity, Vol 5, 1989.