Creep-Fatigue crack growth of an axisymetric surface flaw in a welded junction under thermal loading

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ABSTRACT:

The aim of the present paper is to validate a creep-fatigue crack growth model, based on C* and ΔJ parameters, for life assessment of welded junctions containing flaws under thermal loading. For this, experimental results, coming from representative tests on a sodium loop device, are used. Experimental configuration of the TERFIS program is a thick tube made of 316L (N) austenitic stainless steel, with initial surface flaws located either in a circumferential welded joint or in base metal. The weld metal is an austeno-ferritic steel with 19% Cr, 12% Ni and 2% Mo. Cyclic loading is applied with a cold thermal sodium shock on the outer surface of the specimen, and creep loading with a 10 hour dwell period at 600°C after each shock. Experimental results show that under the same loading conditions flaws located in weldment give less propagation than those located in base metal.
A Finite Element analysis leads us to conclude that slower crack growth rate in welded specimen is mainly linked to a lower loading level. This phenomenon is observed for the Finite Element contour integral C(t) and the local bending stress in the ligament. Moreover, creep fatigue crack growth assessments, with the Finite Element contour integral C(t), are consistent with experimental results.

INTRODUCTION :

The industrial context of this study concerns life time assessment of austenitic stainless steel welded junctions in high temperature components. In the latter thermal loading can have a significant contribution to damage mechanisms. As creep-fatigue crack growth assessment models are often based on laboratory tests with mechanical loading specific studies are needed to validate the transposition to a representative thermo-mechanical loading. In the present study experimental results, coming from representative tests on a sodium loop device, are proposed. Experimental configuration is a thick tube made of 316L (N) austenitic stainless steel, with initial surface flaws located either in circumferential welded joint or base metal. The objective is to validate a creep-fatigue crack growth model, based on C* and ΔJ parameters, when propagation occurs either in base metal or weld metal. To analyse interaction phenomenon between the welded junction and the structure Finite Element computations are used. Base metal and weld metal behaviours are taken into account with a two potentials non linear isotropic and kinematic hardening model (D.D.I. : Two Inelastic strains Model). Transient viscous contour integral C(t) is computed with Finite Element results and a Creep Fatigue crack growth assessment is proposed with a da/dt-C* correlation identified on CT specimens under mechanical loading. Finally, C* simplified estimation under thermo-mechanical loading is discussed.

EXPERIMENTAL RESULTS :

TERFIS program :

In order to validate creep-fatigue crack growth models under representative thermo mechanical loading an experimental program, called TERFIS [1], was carried out at CEA Cadarache. The experimental test device is presented on Figure 1. Thermo-mechanical loading is a combination of a low tensile stress, applied with a pneumatic jack, and a local bending thermal stress through the thickness. The creep fatigue loading, representative of thermal transient stage, is generated with cold shocks from 600°C to 350°C on the outer surface and 10 hour dwell periods at 600°C. Compared to real loading conditions in a Fast Reactor component, the TERFIS creep-fatigue cycle has a higher magnitude and shorter dwell periods, in order to observe crack propagation in a reasonable time. Tested specimens are 12 mm thick tubes made of 316L (N) austenitic stainless steel, with initial surface flaws located either in circumferential welded joint or base metal as shown on Figure 1. The weld metal is a 316L type austeno-ferritic steel with 19% Cr, 12% Ni and 2% Mo. A destructive examination of the tested specimens after 400 creep-fatigue cycles of 10 hours is shown on Figure 1. According to these results we can conclude that a significant crack growth occurred in both specimens with an intergranular creep damage mechanism. However for the same loading conditions we can observe less propagation in the weld metal than in the base metal (Table 1).

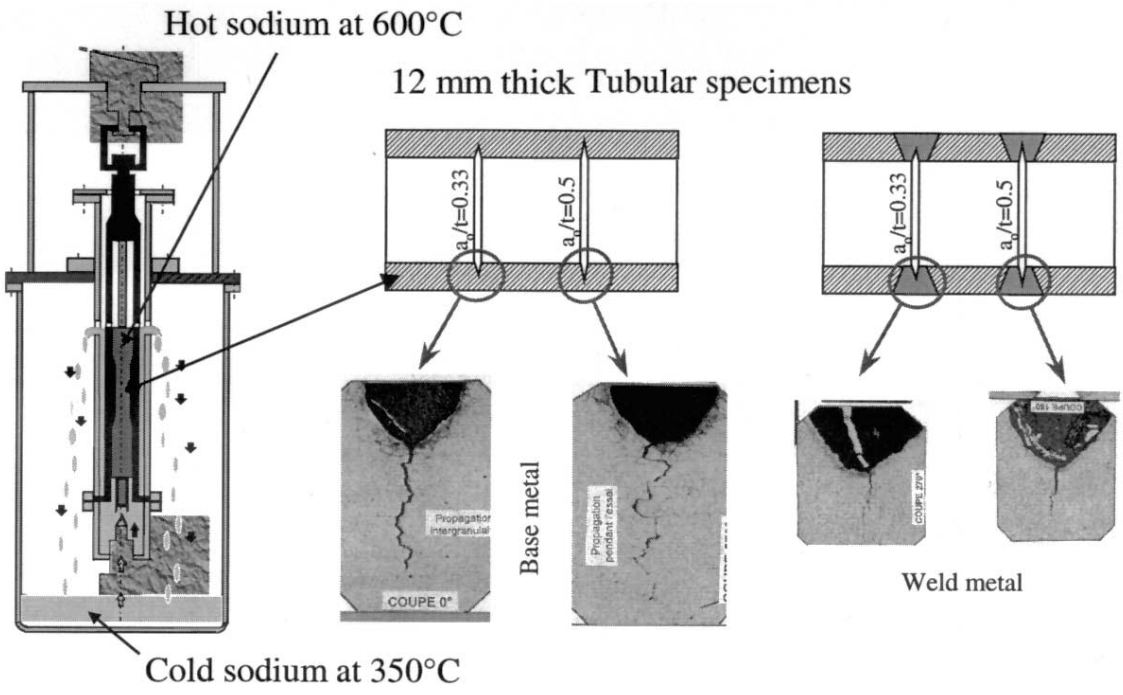

Figure 1: Creep-Fatigue crack propagation in base and weld metal

Table 1 : Experimental crack propagation

		Final crack depth in	
Specimen thickness (mm)	Initial notch depth (mm)	Base metal (mm)	Weld metal (mm)
12	4	4.86	4.18
12	6	6.98	6.3

Base and Weld metals mechanical properties :

In a welded junction there is a significant mismatch behaviour between weld and base metals as shown on Figure 2. On the latter curves are mean values extracted from a data base proposed in reference [2]. As presented on Figure 2 weld metal yield stress is much higher than base metal yield stress on the monotonic consolidation curve. However cyclic hardening in the base metal avoid this mismatch, and the stabilized consolidation curve of the base metal is above the weld metal one. Concerning creep strain rate, the weld metal creep law has an exponent approximately equal to 15 against 8 for the base metal. For stress levels encountered in structures, weld metal creep strain rate is smaller than the base metal one. In our study, specific tests have been carried out to characterise creep behaviour of base and weld metals used in TERFIS specimens.

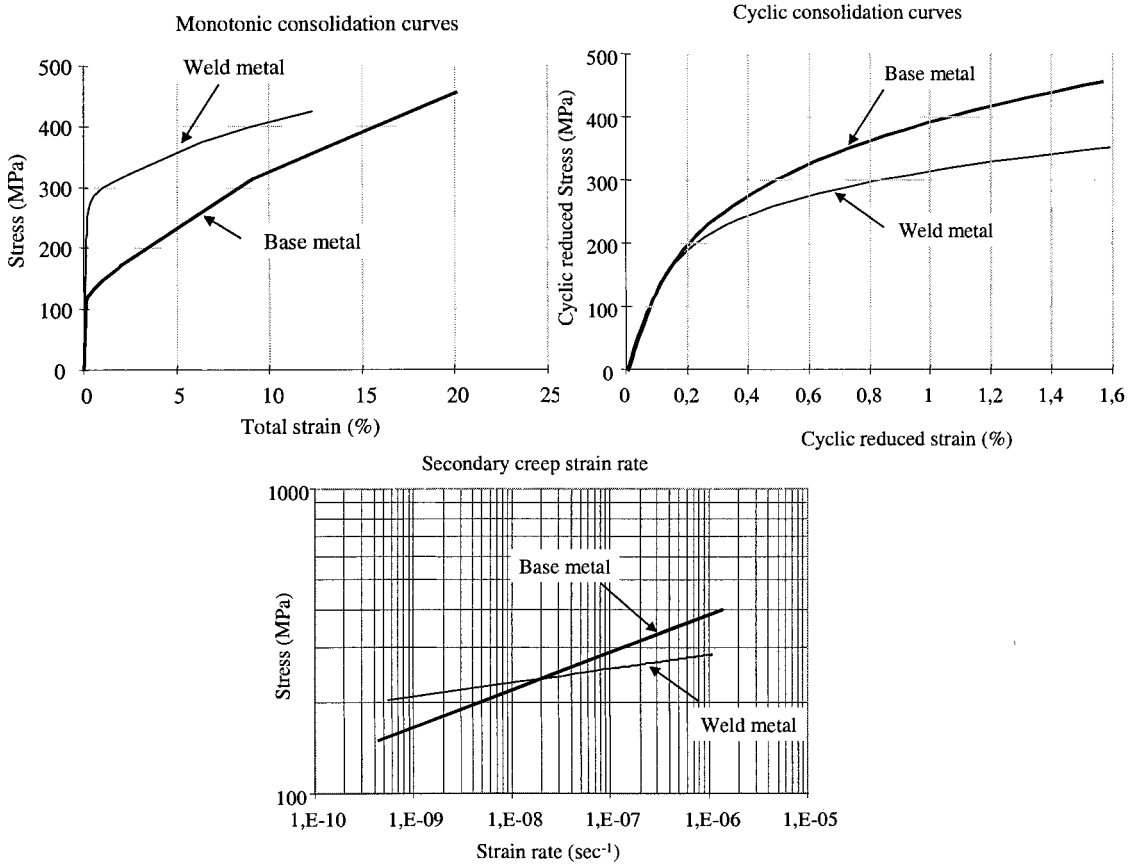

Figure 2 : Mismatch behaviour at 600°C between 316L(N) steel and 316L type weld metal.

Creep rupture data identified on base and weld metals are shown on Figure 3. According to these data, weld metal has a better resistance against creep crack initiation, when creep crack growth rate is smaller in the base metal. These results confirms that creep rupture properties mismatch between base and weld metals is not obvious to identify.

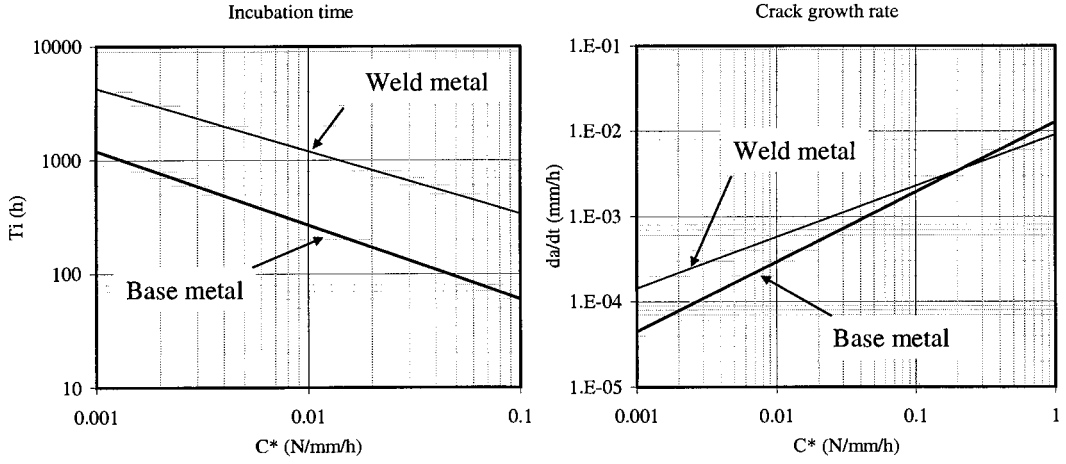

Figure 3 : Creep rupture properties at 600°C of 316L(N) steel and 316L type weld metal

FINITE ELEMENT SIMULATION

In order to analyse creep crack initiation and growth a Finite Element model has been used (Figure 4). A Two Inelastic Strain DDI model is used for constitutive equations of the material behaviour. The model identification, proposed in reference [2], enables to assess mismatch behaviour between base and weld metal as presented in paragraph 2.2.

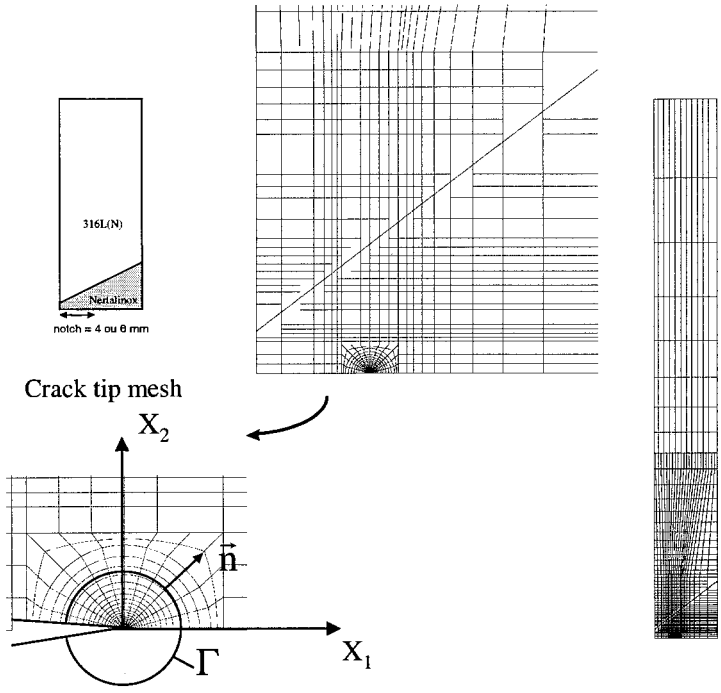

Figure 4 : Finite Element model of the TERFIS specimen

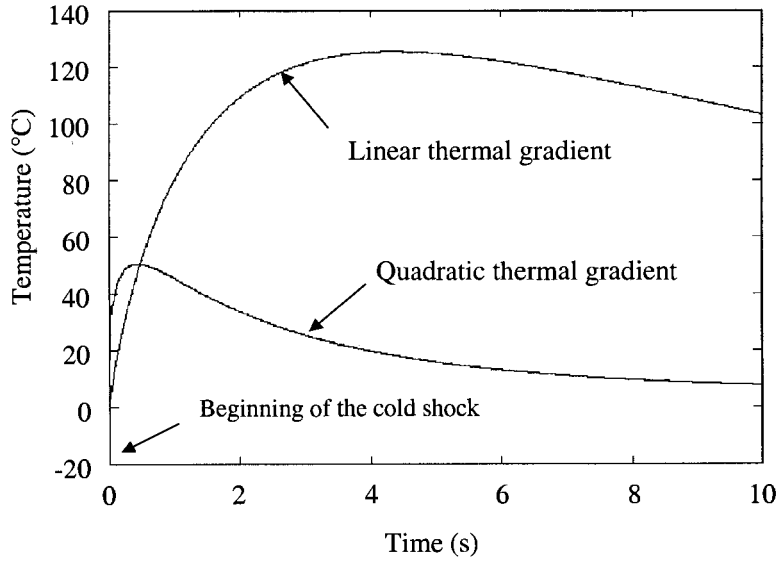

Figure 5 : Polynomial decomposition of the temperature through the thickness during the cold shock

In order to simplify the Finite Element analysis thermal loading is introduced as a linear temperature gradient through the thickness. This approach is based on the fact that at the maximum thermal loading point, temperature distribution through the thickness is approximately linear. Actually we can see on Figure 5 that the second order term, of the polynomial decomposition of temperatures through the thickness, is negligible when the linear gradient is maximum. Then the simplified thermal creep fatigue cycle is composed with the following sequence :

- a uniform temperature distribution of 600 °C at t=0
- a linear thermal gradient with a proportional variation up to 125 °C at t=4 s
- a proportional decreasing of the linear gradient up to a uniform temperature of 600°C at t=10 min
- a uniform temperature of 600 °C between t=10 min and 10 hours

In order to estimate crack tip loading during the 10 hour dwell period the visco-plastic transient C(t) contour integral of equation (1) is computed.

$$C(t) = \int_{\Gamma} \left[\dot{W}.n_1 - \left(\underline{\underline{\sigma}}.\vec{n}\right).\frac{\partial \dot{\vec{u}}}{\partial x_1} \right].ds \qquad (1)$$

Where Γ is a crack tip contour presented on Figure 4, $\dot{W}$ is the stress work rate density, $\underline{\underline{\sigma}}$ the Cauchy stress tensor and $\dot{\vec{u}}$ the visco-plastic velocity field.

The C(t) contour integral is computed with the G_THETA post processing method [4] using mechanical field assessment of the DDI model. As C(t) path independency is not demonstrated for constitutive equations of this model, it is checked with numerical results as shown on Figure 6.

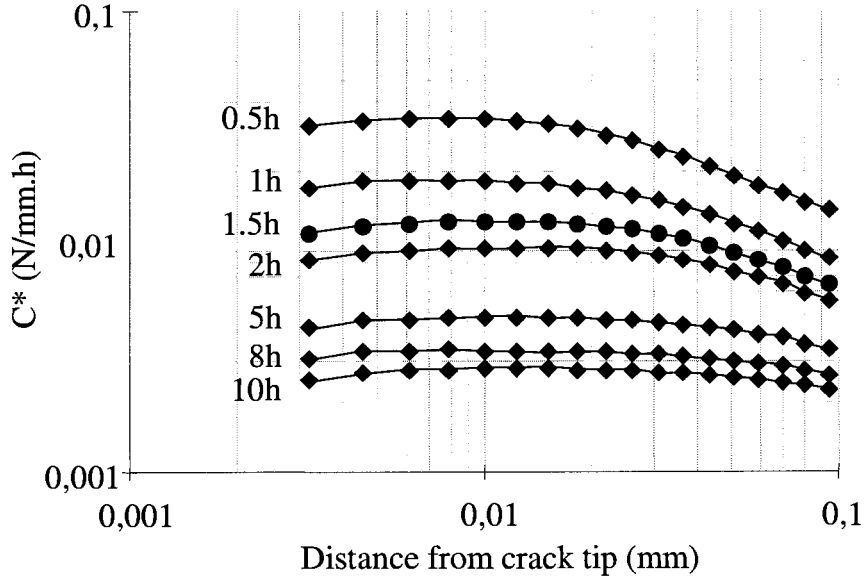

Figure 6 : Numerical stability of C(t) during the dwell period

Finite Element computation of C(t) during the 10^{th} dwell period is presented on Figure 7 for the 4 mm depth crack. These results lead us to conclude that for the same creep fatigue cycle crack tip loading is higher when the crack is located in the

base metal. The ratio between base metal and weld metal crack tip loading is approximately included between 1.2 and 1.8 during the dwell period.

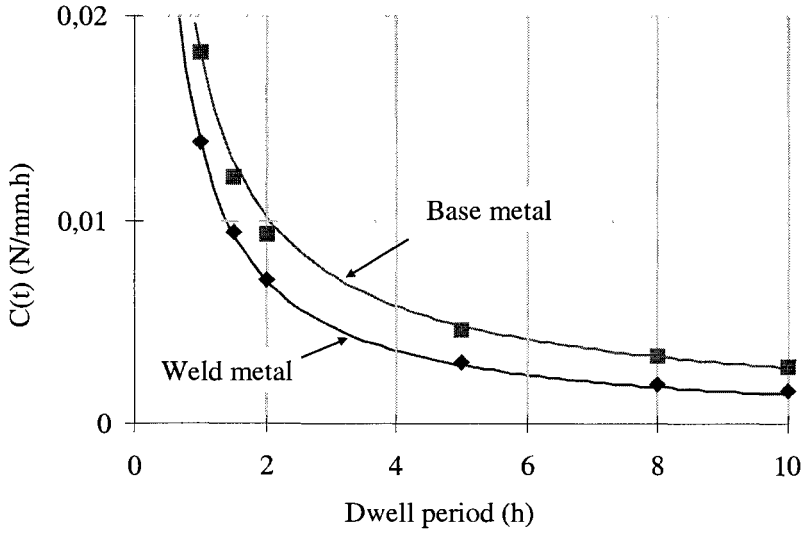

Figure 7 : Numerical computation of C(t) during the 10th dwell period

To understand the origin of a lower crack tip loading level in welded specimen the local bending stress through the ligament has been computed in both configurations and compared on Figure 8.

Creep crack growth estimation is derived from numerical values of C(t) as following :

- the C(t) mean value is used with the Ti-C* curve for incubation time assessment
- and the C(t) fitted function is used with the propagation law of Figure 3 for crack growth assessment.

Experimental and numerical results are compared in Table 2. For the base metal crack propagation assessments are in good agreement with experimental results. For the weld metal, crack propagation assessments overestimate experimental results with a ratio of approximately 3. When we compare crack propagation for the base metal and the weld metal we can see that numerical estimations are consistent with experimental results. Actually, the lower propagation level observed in the weld metal seems to be linked to a higher number of cycles for creep crack initiation. Concerning the sensitivity of crack propagation to initial crack depth, we can see that numerical results are consistent with experimental measurements for the base metal, when they are not consistent for the weld metal. This last point should be investigate in order to understand why crack propagation sensitivity to initial crack depth is not well assessed for the weld metal.

Table 2 : Creep crack growth assessment using the C(t) contour integral (BM : propagation in the base metal ; WM : propagation in the weld metal)

	Crack initiation assessment (nb of cycles)		Crack propagation assessment (mm)		Experimental crack propagation (mm)	
Initial crack depth	BM	WM	BM	WM	BM	WM
4 mm	40	200	0.98	0.84	0.86	0.18
6 mm	35	210	1.06	0.77	0.98	0.3

Concerning fatigue contribution to crack growth rate, a simplified estimation with the PARIS law leads us to conclude that fatigue damage is negligible in our case. Then the only acceleration factor due to cyclic loading in the simulation is linked to crack tip stress field actualisation every 10 hours.

To understand the origin of the low crack tip loading level observed for a notch located in the weld metal, Finite Element results have been post processed to compute the local bending through the ligament (see Figure 8) at the maximum loading point during the cold shock (negative values of local bending) and at the beginning of the dwell period (positive values of local bending). As we can see on Figure 8, the higher yield stress of the weld metal increases the closure local bending during

the cold shock. Then the residual opening local bending at the beginning of the next dwell period is smaller when the crack is located in the weld metal. This phenomenon leads to a ratio of 1.7 between dwell local bending values when the crack is located either in the base metal or in the weld metal. A simplified assessment of this residual dwell loading could be derived from the symetrization factor of the stabilised cycle.

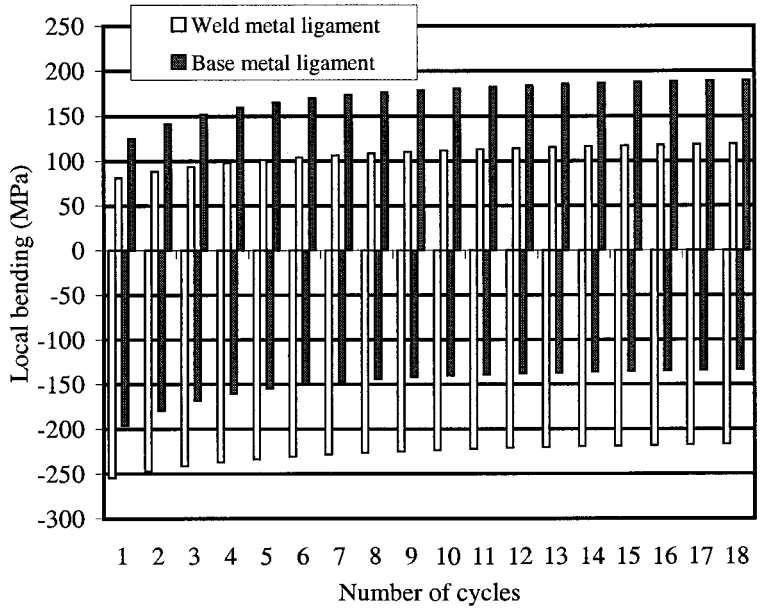

Figure 8 : Local bending in the ligament at the beginning of the dwell period

CONCLUSIONS

Creep-fatigue crack growth in weld and base metals under thermo-mechanical loading has been studied in this paper. Experimental results, on thick tube made of 316L (N) austenitic stainless steel and initial surface flaw located either in a circumferential welded joint or in base metal, lead us to conclude that less crack propagation is observed in the weld metal than in the base metal. To understand this results a detailed Finite Element analysis, taking into account the mismatch between mechanical properties of the weld and base metals, has been proposed. A qualitative analysis of Finite Element results leads us to conclude that crack tip loading is lower when the crack is located in the weld metal. Creep-fatigue crack growth assessments, derived from the C(t) contour integral, are in good agreement with experimental results for the base metal (with an error of approximately 10%). Concerning the weld metal, crack growth assessments are consistent with experimental results (with less propagation than in the base metal), but the latter are overestimated with a ratio of approximately 3.

REFERENCES :

1. MICHEL B. "Creep-Fatigue crack growth assessment under combined mechanical and thaermal loading with a simplified approach", SMIRT-14, Lyon, 1997.

2. A. ASSIRE "Amorçage et propagation de la fissuration dans les jonctions soudées à haute température", Ph-D thesis, 2000.

3. CONTESTI E. "Description of creep-plasticity interaction with non unified constitutive equations. application to an austenitic stainless steel", NED, 116, pp265-280,1989.

4. PARK D.M. "The virtual crack extension method for non linear material behaviour", Comp. Methods in Applied Mechanic and Eng., Vol. 12, 1977, pp 353-364.