LOW CYCLE FATIGUE STRENGTH OF HIGH TEMPERATURE WELDED JOINTS: AN EFFICIENT METHOD TO PREDICT LIFE OF AUSTENITIC 316L(N) WELDMENTS.

LE BER L.*, SAINTE CATHERINE* C., WAECKEL N.**, TURBAT M.***,

High temperature reverse bending tests on 316L(N) large welded plates have been performed within an European program. Varying applied displacements, weld geometry, plate thickness have been studied. The reduced life of welded structure is not related to a lower fatigue endurance of weld metal but to a strain enhancement in cyclic plasticity due to dissimilar materials. In order to get a better description of the phenomena involved in this cyclic enhancement, elasto-plastic calculations have been carried out using a non-linear isotropic and kinematic hardening constitutive equations in finite element, coupled with a simple damage rule.

INTRODUCTION

Welded joints are generally considered to be a life limiting feature of structures due to their observed inferior high temperature performances under fatigue and creep fatigue loading conditions. For low cycle fatigue analysis of welded joints, the French RCC-MR (1) design code for fast breeder nuclear reactors makes use of a reduction factor (J_f) on the strain variation of the Manson-Coffin fatigue curve of the base metal. This reduction factor is fixed at 1.25 and based on preliminary tests performed within a European program.

Studies have been carried out both experimental and analytical, in order to have a better understanding of the phenomena involved in these fatigue life reduction factors.

* CEA DRN/DMT/SEMT, SACLAY, France.
** EDF SEPTEN, LYON, France.
*** NOVATOME, LYON, France.

TESTS PRESENTATION

Bending tests have been performed in AEA/Risley on butt 316L(N) austenitic steel welded plates (Figure 1), with varying applied displacements ($\Delta\varepsilon$: from 0.3 to 1%), weld geometry (simple V or double V), plate's thickness (10 mm, 25 mm), and weld direction (longitudinal or transverse). Test temperature was 550°C.

AEA has carried out a first tests campaign of 9 fatigue tests :

- 5 fatigue tests on 10 mm thick plates
- 4 fatigue tests on 25 mm thick plates

An additional testing matrix (see TABLE 1) has been performed by AEA under a CEA contract ((2) and (3) « SOUFFLE » program) :

- 2 tests on 10 mm thick plates
- 2 tests on 25 mm thick plates:

An accompanying characterisation program has been performed by CEA (4) in order to evaluate the cyclic and fatigue behaviour of both base metal and MMA weld. It has been found that MMA metal shows a very slight cyclic hardening (Figure 2). As a consequence the over-matching between weld and base metal on the first cycle turns to an under-matching after some cycling, especially for high strain levels. Fatigue tests have shown that fatigue life is very similar for 316L(N) base metal and 316L(N) MMA weld (Figure 3).

TESTS INTERPRETATION

In the French RCC-MR (1), rules for weldment are proposed in the paragraph relative to *shell design rules* and reduction coefficients due to material properties are given in Appendix A9. For fatigue analysis, last version of RCC-MR (1993) has proposed a reduction factor on fatigue curves (J_f value) equal to 1.25 for 316L(N) autenitic steel.

Effectively, SOUFFLE tests have shown fatigue life reduction and a so-called $(J_f)_{exp}$ factor can be determined by:

$$(J_f)_{exp} = \frac{\Delta\varepsilon(N_r)}{\Delta\varepsilon_{ap}} \qquad (1)$$

where $\Delta\varepsilon_{ap}$ is the applied strain range, and $\Delta\varepsilon(N_r)$ is the strain range corresponding to the experimental number of cycle to rupture N_r and is derived from the base metal fatigue curve. The Jf values of the tests are proposed on TABLE 1.

TABLE 1 : SOUFFLE fatigue tests results

Plate	Weld			strain	Rupture	
(mm)	Orientation	Type		(%)	N_r (cycles)	$(J_f)_{exp}$
10	*Transverse*	Single Vee	MMA + TIG	0.983	1295	1.14
10	*Transverse*	Single Vee	MMA + TIG	0.6	3932	1.34
25	*Transverse*	Double Vee	MMA	0.3	114670	1.39
25	*Longitudinal*	Double Vee	MMA	0.6	8480	1.10

The $(J_f)_{exp}$ factor is varying quite a lot from one test to another. As a matter of fact, longitudinal weld endurance is much larger than the transverse weld one. But it is also very important to notice that there is a non negligible influence of the strain amplitude. We can so assume that the experimental $(J_f)_{exp}$ factor should not be linked to a reduction in endurance (reduction in the abscissa of the fatigue curve) but represent a strain enhancement (co-ordinate of the fatigue curve).

From the experimental program, we can so conclude that there is a strain concentration due to different cyclic plasticity between the two materials. In order to validate this latest assumption, we carried out elasto-plastic calculations that allow to estimate strain enhancement in the structure.

<u>ELASTOPLASTIC CALCULATIONS</u>

Finite Elements calculations have been conducted on a 25 mm thick plate, butt welded (single V, dressed weld) and for 3 strain variation level ($\Delta\varepsilon$=0.4, 0.6 and 1%). The 2D Finite Elements mesh is shown on Figure 4.

All the bending tests and the characterisations have been performed at the same total strain rate (1.10^{-3}%/s). So, we could use a cyclic non-linear isotropic and kinematic plastic model (6) :

The scale yielding equation is :

$$f = J_2(\underline{\underline{\sigma}} - \underline{\underline{X}}_1 - \underline{\underline{X}}_2) - R_P - R_{P0} \tag{3}$$

The Hill plastic flow rule is :

$$d\underline{\underline{\varepsilon}}_p = \frac{3}{2} d\lambda \frac{\underline{\underline{\sigma}}' - \underline{\underline{X}}_1' - \underline{\underline{X}}_2'}{J_2(\underline{\underline{\sigma}} - \underline{\underline{X}}_1' - \underline{\underline{X}}_2')} \tag{4}$$

The non linear kinematic and isotropic hardening functions are :

$$d\underline{\underline{X}}_i = \frac{2}{3} C_i d\underline{\underline{\varepsilon}}_p - d_i \underline{\underline{X}}_i dp \tag{5}$$

$$dR_P = b_P(Q_P - R_P)dp \tag{6}$$

The 7 parameters (C_1, d_1, C_2, d_2, R_{P0}, Q_P and b_P) have been both identified for base metal and weld, on the hysteresis loops of the characterisation tests for 3 strain variations (0.4, 0.6 and 1%) by using Ident1D software (7)

<u>Cyclic calculation of an homogeneous plate (without weld) :</u>

A constant displacement variation Δd (approximately associated to 1% strain variation at the 1st cycle) is imposed on an homogeneous plate. The associated strain variation per cycle $\Delta\varepsilon_{eq}$ (see Figure 5) is calculated on points D0 (centre of the plate) and PR (in the joint between large part of the plate and thin part see Figure 7). Instead of being constant, these strain variations varies. This phenomena can be related to the fact that, the point D0 is more loaded, and there, the base metal cyclically harden « faster » than in point PR. As point PR less hardens, it concentrates strain until it reaches material stabilisation (cycle 200).

As the strain variation per cycle has been calculated, it can be associated to a life fraction per cycle estimation with this simple rule :

$$\tau_C = \frac{1}{N_a(\Delta\varepsilon_{eq})} \tag{7}$$

Where N_a means the number of cycles to initiation given by the fatigue curve of the base material. This life fraction is then summed with the Minner's rule in order to predict the homogeneous plate's initiation. The calculated number of cycles to plate's initiation is 2392.

Cyclic calculation of a welded plate :

A welded plate is now subjected to the same imposed displacement variation previously calculated for the homogeneous plate. The associated strain variation is then shown on Figure 6.

One can see here two phenomena : the first has been already described for the homogeneous plate and is related to the differential cyclic hardening of the base metal at point D2 and PR. The other phenomenon is the differential cyclic hardening of weld and base metal. During 30 cycles, the weld is harder than the base metal that's why it does not concentrate strain variation. After the 30th cycle, the base metal is harder than the weld and the weld concentrates strain. A life fraction estimation can be calculated and the number of cycle to plate's initiation is 1635.

The same calculations have also been conducted for global strain variations of 0.4 and 0.6% on homogeneous plates and welded ones. The results are summarised in TABLE 2 and compared with the mean experimental $(J_f)_{exp}$.

TABLE 2 : Calculated J_f values and comparison with the mean experimental one

Global strain variation	$\Delta\varepsilon = 1\%$	$\Delta\varepsilon=0.6\%$	$\Delta\varepsilon=0.4\%$
Number of cycle to initiation (homogeneous plate)	**2392**	**28657**	**673339**
Associated $\Delta\varepsilon(N_a)$ (homogeneous plate)	0.9375	0.525	0.3735
Number of cycle to initiation N_a (welded plate)	**1635**	**7366**	**77522**
Associated $\Delta\varepsilon(N_a)$ (welded plate)	1.0525	0.672	0.438
calculatedJ_f Coefficient	**1.12**	**1.28**	**1.17**
Mean experimental $(J_f)_{exp}$:	**1.09**	**1.19**	**1.28**

There is a good agreement between calculated J_f values and experimental ones except for the global strain variation of 0.4%. In that case, the number of cycles that need to be calculated to reach structure stabilisation is more important than those calculated. But, we were not yet able to conduct such heavy simulations without efficient cycles jumping methods.

CONCLUSIONS :

A full comprehensive program on low cycle fatigue behaviour has been carried out on 316L(N) austenitic welded joints. Various plate's thickness, weld geometry and loading have been tested. Many factors have an influence on plate's fatigue life. But the reduced fatigue life of 316L(N) welded structure at 550°C is not related to a lower fatigue endurance of weld metal but to a strain enhancement in cyclic plasticity due to dissimilar materials cyclic behaviour.

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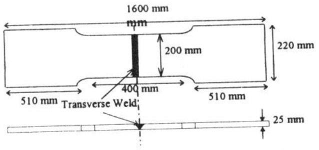

Figure 1 : *schematic of a 25 mm thick plate with transverse butt weld*

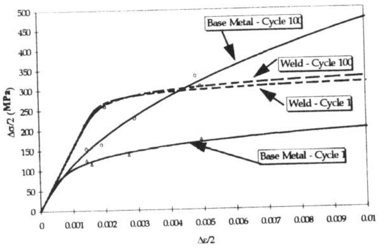

Figure 2 : *Cyclic stress - strain curves for both base metal and MMA weld*

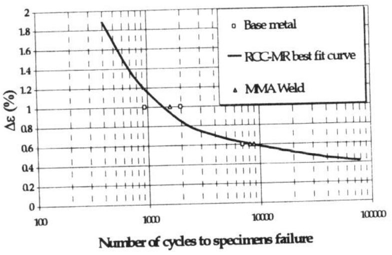

Figure 3 : *fatigue curve of base metal and MMA weld*

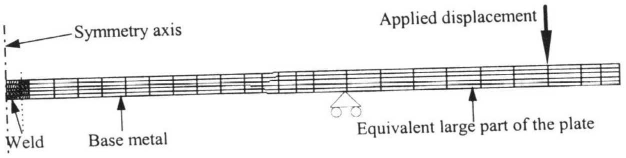

Figure 4 : *2D Mesh of the 25 mm plate*

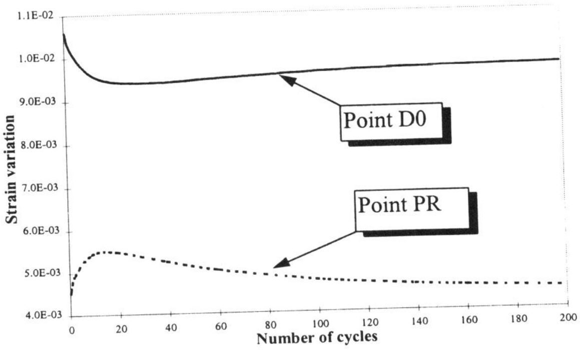

Figure 5 : *Evolution of the strain variation during cycling of an homogeneous plate*

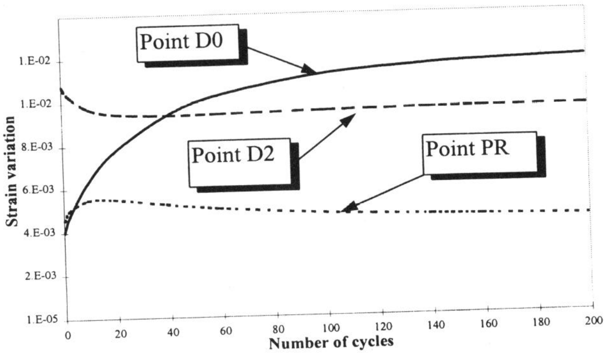

Figure 6 : *Evolution of the strain variation during cycling of a welded plate*

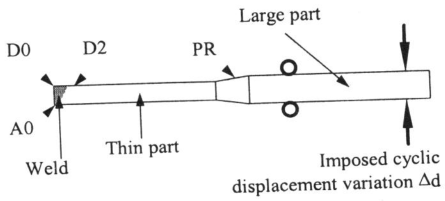

Figure 7 : *schematic of a plate D0, D2 and PR positions*