Mechanical Cyclic Behavior of 316L Pipe Weldment for Fatigue Analysis

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ABSTRACT

To take into account the reduced fatigue strength of welded joints, a reduction factor on fatigue curves (J_f value) was introduced into the RCC-MR French nuclear design and construction code. To better assess this factor, previous work on large plates showed that mechanical behavior of a welded assembly is influenced by the geometry of the weld and by the interaction of the different cyclic plastic behavior of the two materials: base metal (BM) and weld metal (WM). A new campaign (named FFAST) was performed on welded joint specimens extracted from butt welded pipe connections (uniaxial tensile-compressive load). An innovative experimental approach is proposed to study the local mechanical behaviour of the welded joint specimens and then determine the J_f parameter. The main advantage of the method is to avoid problems due to relative stiffness of weld part versus base metal part of the specimen : a continuous recording of the stress and strain in the weld allows the estimation of mechanical behavior and finally the fatigue life of the joint. Observations of crack surface show two different crack initiations near the weld and depending on the load level. Calculations of the tests and comparison with experimental results are presented. These studies allow to assess in a practical way the J_f design method. It appears that J_f value can not be considered as an single value but it is influenced by several factors depending on the weldment, and the load level.

INTRODUCTION

As a result of their size, fast breeder reactor vessels are not made of a single material but of many parts welded together. The welds frequently represent a weak point, particularly because the fatigue resistance of welded joints depends on the surrounding geometry and loading to which they are subjected, but also the discontinuity resulting from their presence. The discontinuity is both geometrical (surface finish and welding defects) but also associated with the presence of two materials with different mechanical properties.

The lower fatigue resistance of welded structures is provided for in the French RCC-MR codes [1], for the design and construction of fast breeder reactors, by applying reduction factor Jf to the fatigue curve of the parent metal. For 316L(N), Jf is equal to 1.25 [2].

The purpose of this initiative (FFAST program) is to experimentally and numerically study the behavior of specimens taken from a butt-welded annular joint to determine coefficient Jf [3].

PROPERTIES OF MATERIALS

Composition

The parent metal (PM) used in the FFAST program is austenitic stainless steel of AFNOR grade: Z2 CND 17-12 (316L). The joint was made by manual welding with a coated electrode (MMA). The composition of the weld metal (WM) is similar to that of the parent metal (Table 1) . It corresponds to grade (16%Cr – 8%Ni – 2%Mo) as used for making welded joints in the primary and secondary systems of fast breeder reactor plants.

Table 1

Chemical composition (% by weight)											
	C	Mn	Si	Cr	Ni	Mo	S	P	Co	B	Cu
Weld metal	0.051	2.14	0.39	16.13	8.10	2.23	0.010	0.015	0.013		
Parent metal	0.011	1.70	0.42	16.85	11.21	2.14	0.006	0.023	0.099	0.0008	0.099

Cyclic Behaviour

Specimens were machined (figure 1) from the parent metal and from a welded joint made for the purpose. A symmetrical load with imposed strain was applied to the specimens (strain variation 0.4 to 1.4%).

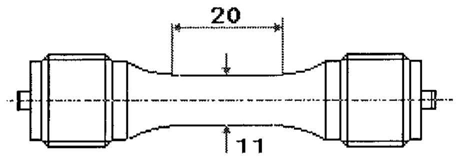


figure 1 : Shape of the specimen for metal caracterisation

Cyclic hardening of the parent metal was observed during the first loading cycles, followed by stabilization after a few tens of cycles (Figure 2).

For the weld metal, the consolidation phase was rapid (first 20 cycles). It was followed by a deconsolidation phase which continued until the specimen failed (Figure 2).

On the basis of the variation in stress and strain measured at half the lifetime, it is possible to plot the reduced cycle work hardening curve, comparable to the tensile curve. That of the parent metal is representative of the stable phase of cyclic response. That of the weld metal is more conventional, as the metal is in the deconsolidation phase (Figure 3)

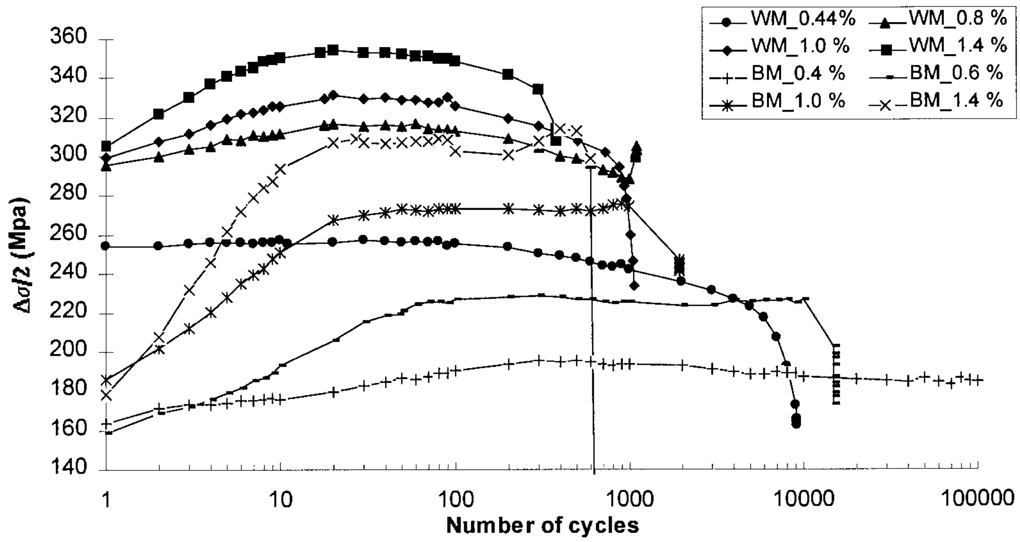


Figure 2 : Variation of stress amplitude as a function of the number of cycles

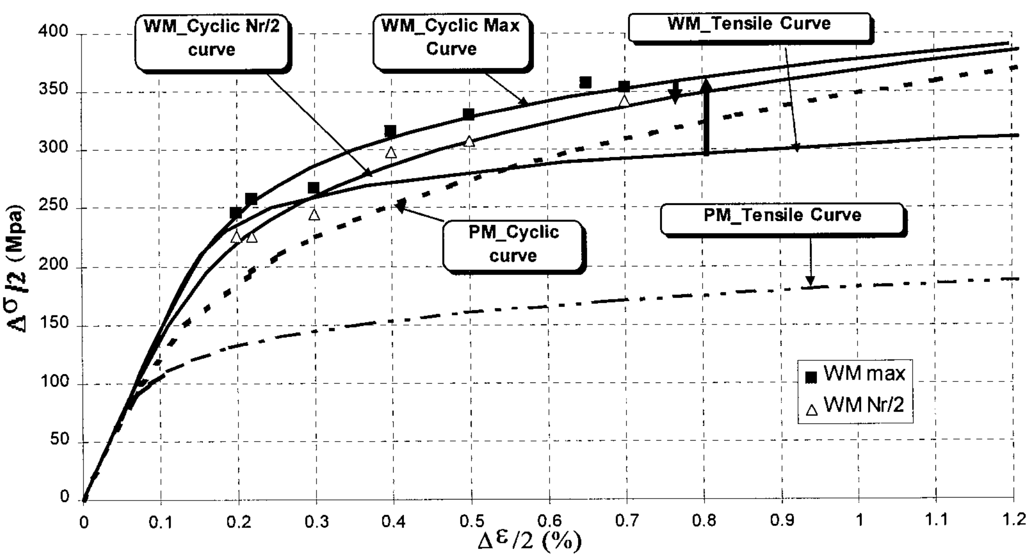


Figure 3 : Monotonic and Cyclic Curves of Type 316 L stainless steel and 16-8-2 weld metal –at 600°C

Fatigue

By means of the same tests, continued to the point of fracture, the fatigue curve of the materials can be determined (Figure 4).

In the high strain range, the fatigue resistance of the parent metal is consistent with the average values indicated for 316 L in RCC-MR (Appendix A3-3S). In the range corresponding to a large number of cycles, it is similar to that of grade 316L(N) (Appendix A3-1S).

The fatigue resistance of the parent metal is greater than that of the weld metal.

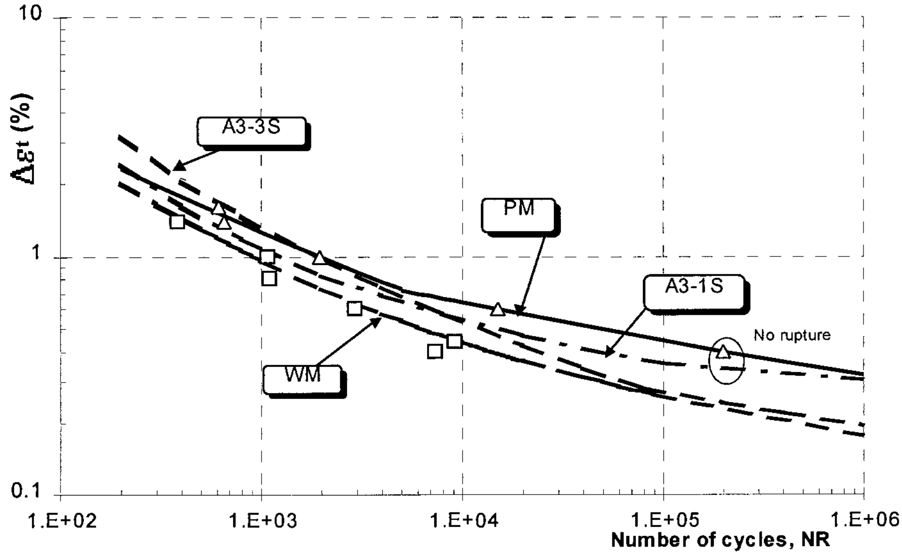


Figure 4 – Fatigue curves of Type 316 L stainless steel and 16-8-2 weld metal

MAKING WELDED JOINTS

Welded joints between two sections of tube are made in successive passes.

A double chamfered joint was chosen for making dissimilar metal specimens (Figure 5), taken from the annular weld (Figure 5), to obtain near-symmetrical response.

Specimens with X-shaped geometry were machined from the welded tube (Figure 6)

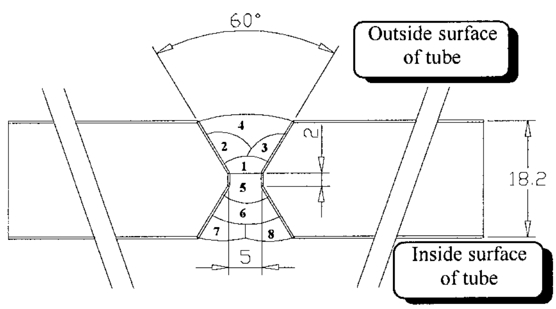


Figure 5 – Double-chamber joint for making dissimilar metal specimens

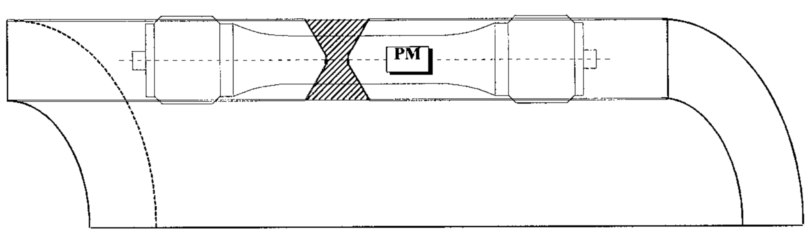


Figure 6 – Specimen position

STUDY OF LOCAL RESPONSE WITH DISSIMILAR METAL SPECIMENS

Method:

In practice, the volume of the welded joint is small compared to the dimensions of the surrounding structure. If the rigidity of the two materials is similar, overall response is not disturbed by the presence of the weld. Strain in the parent metal resulting from loading remains the same, whether there is a welded joint or not.

This being the case, it can be deduced that it is the remainder of the structure which imposes the loading on the welded joint. An approach is then devised using parent metal strain for reference purposes. This involves taking dissimilar metal specimens representative of the actual welded joint and its surroundings (including the heat-affected zone). The parent metal is subjected to controlled strain, and weld strain is measured with an additional extensometer. By this means, involving two extensometers (Figure 7), it is possible to gain a better picture of the response of an actual welded joint than by tests on welded specimens with a single strain measurement covering a weld metal section.

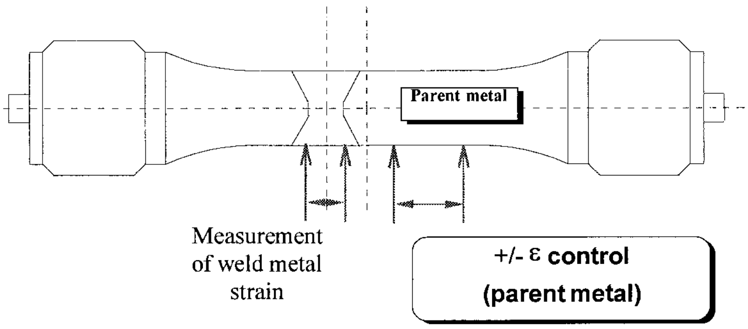


Figure 7 – Control of dissimilar metal specimen tests

Recording of Strain

Measurement of weld metal strain, made after stabilization of the parent metal, indicates that there is a phase characterized by increase at a relatively constant rate (Figure 8). This corresponds to cyclic deconsolidation of the weld metal.

This is followed by the final phase. The manner in which strain develops in the weld metal depends on where initiation begins. When cracking occurs outside the region measured by the extensometer, strain tends to diminish, and vice versa.

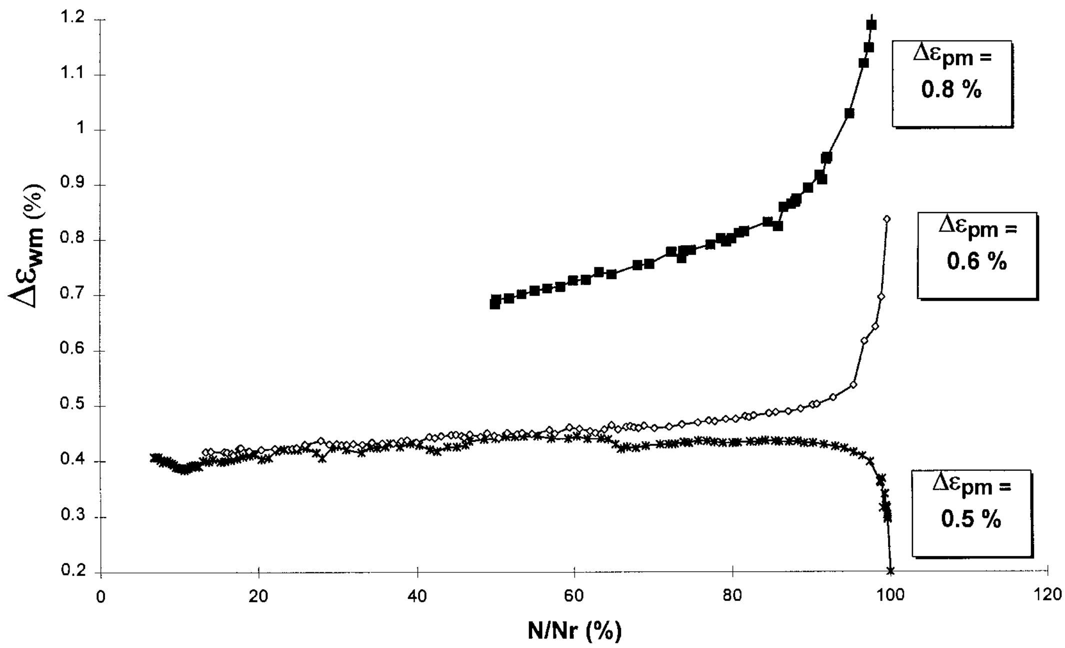


Figure 8 – Strain variation in the weld metal

Location and Mode of Fracture

Observation after testing confirms that the location depends on the degree of loading (Figure 9). At low strain, fracture occurs at the surface, in the parent metal or the weld metal (Figure 10). At greater strain, initiation begins internally, at the welded face (Figure 11). Propagation in two opposite directions then follows.

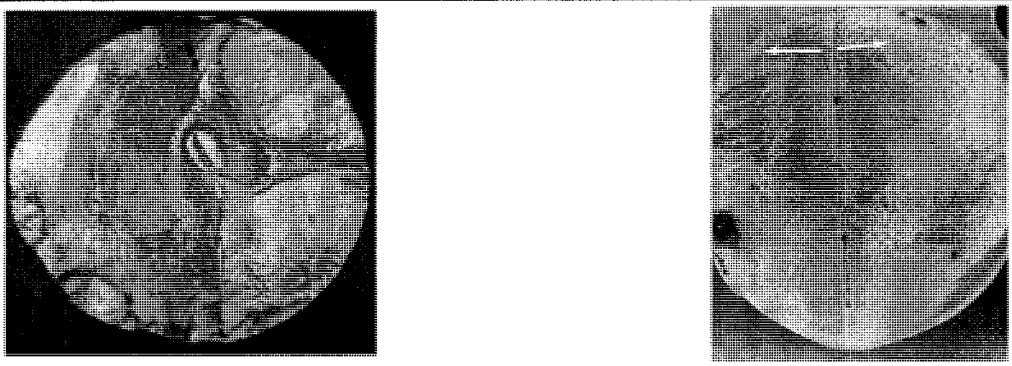


Figure 9 – Fracture face

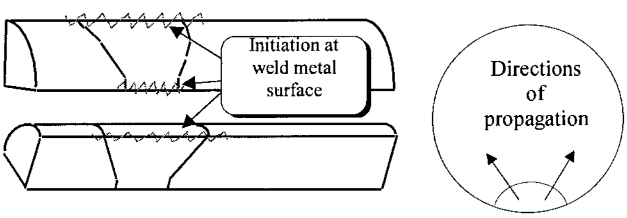


Figure 10 – Type I fracture mode

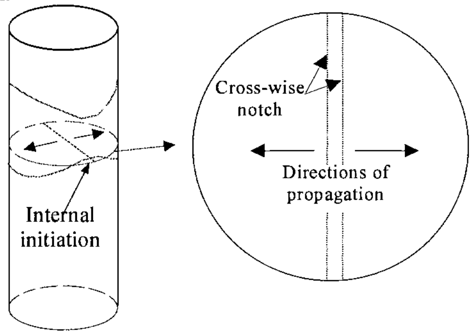


Figure 11 – Type II fracture mode

Determination of the Number of Cycles

In each test, the number of cycles to fracture is determined on the basis of the fatigue curves of the parent metal and weld metal, using calculated strain variations with the cyclic behavior curves corresponding to the imposed stress variations. The description is satisfactory for tests at low levels of loading, but not for tests at higher levels (Figure 12). This show that there is a strain concentration created by the X-shape geometry of the welded joint. This is not allowed for in the simplified calculation made.

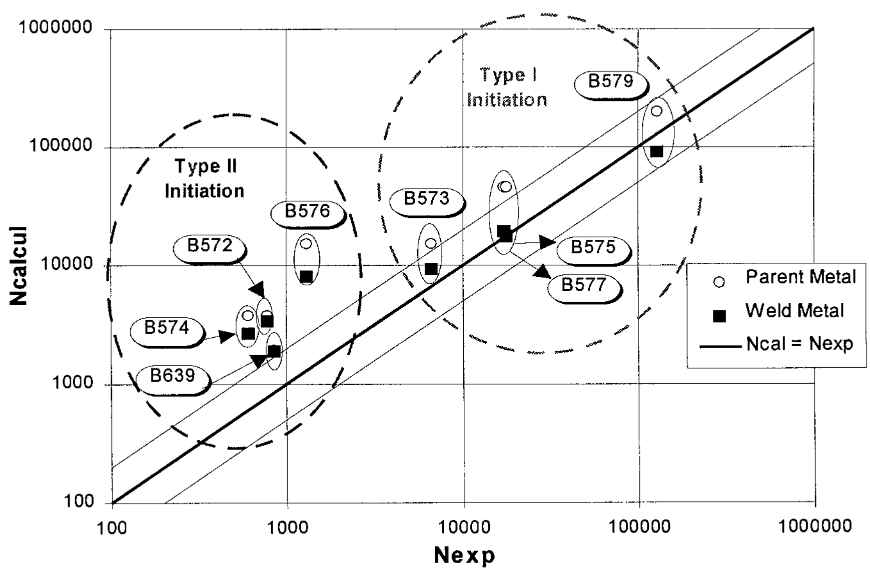


Figure 12 – Calculation of the number of cycles

Finite Element Calculation

3D finite element calculations were carried out using the reduced cyclic curves attained at half-lifetime as the response law. The material model is an isotropic elastoplastic one of the Ramberg-Osgood type. The calculations indicate the points where the loading is the highest (Figure 13). These agree with the experimental observations. They show strain concentration. In this approach, no allowance can be made for history and hence usage factor accumulation because the time-related aspect of cyclic consolidation is not modeled.

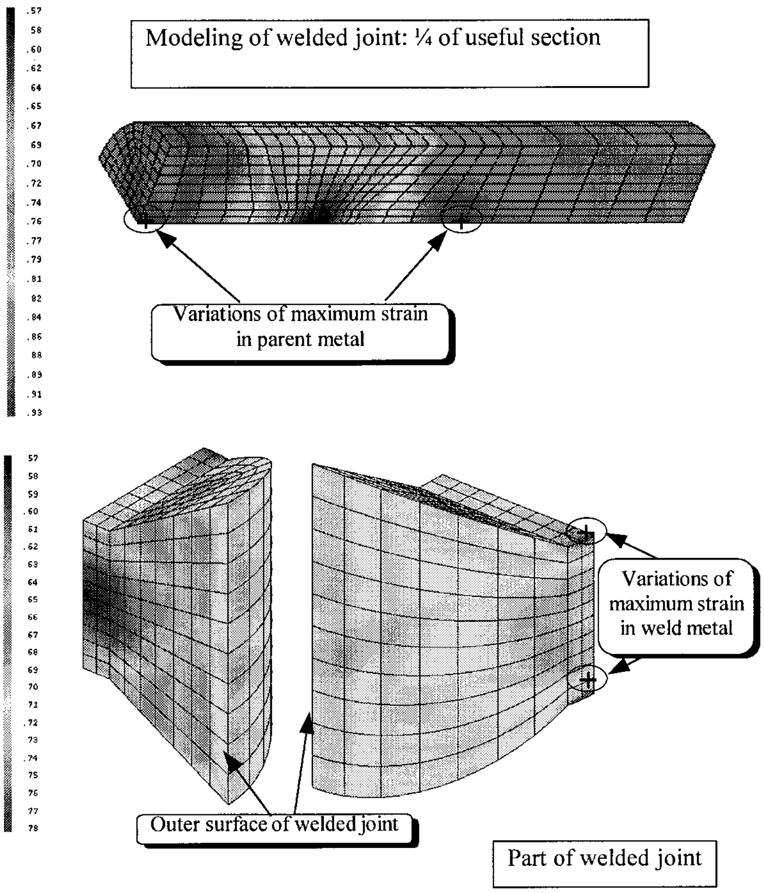
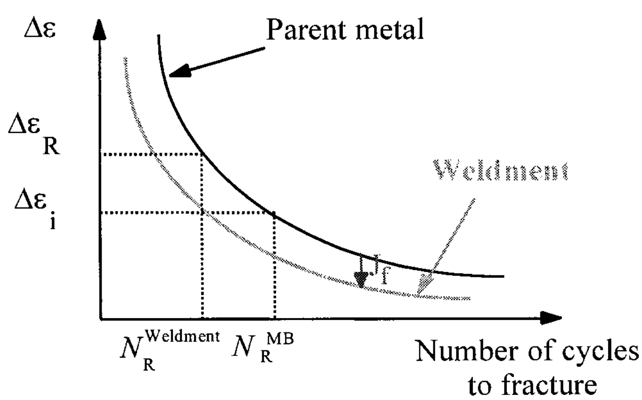


Figure 13 – Location of maximum equivalent strain in the welded joint, $\Delta\sigma/2 = 270$ MPa

Experimental Joint Coefficient J_f

Coefficient Jf expresses the amplification to be applied to the strain variation occurring in a uniform tube (here, the imposed strain variation in the parent metal $\Delta\varepsilon_i$) to obtain that corresponding to the number of cycles to fracture N_R of the weldment, $\Delta\varepsilon_R$, taken from the parent metal fatigue curve (Figure 14).



$$J_f = \frac{\Delta\varepsilon_R}{\Delta\varepsilon_i}$$

Figure 14 – Definition of Jf

The results of the dissimilar metal tests are shown in Table 2.

At low strain loading, representative of loading in service, Jf values are below the value given in RCC-MR (1.25), which is conservative at such loading.

At higher loading, corresponding to Type II fracture, the Jf values are greater than 1.25. These loading levels need to be carefully considered. It is important to note that these results are specific to the X-shaped geometry which results in internal strain concentration. It is anticipated that the results would be better with the V-shaped geometry used for tube joints.

The method using joint coefficient Jf is not appropriate for describing tests in which the fracture mode is of Type II. In this fracture mode, the location of higher stresses and the probable presence of micro-cracks cause the propagation phase to predominate over the initiation phase [3].

Table 2

	$\Delta\varepsilon_{mb}$ (%)	Number of cycles to fracture	$\Delta\varepsilon_R$ (%)	J_f	Type of fracture
B575	0.5	17,556	0.584	1.17	I
B577	0.5	17,015	0.587	1.17	I
B573	0.6	6,670	0.688	1.15	I
B576	0.6	1,305	1.151	1.92	II
B572	0.8	773	1.392	1.74	II
B574	0.8	610	1.520	1.90	II
B639	1.0	1,907	1.341	1.34	II

CONCLUSION

The value of coefficient Jf characterizing the weld for fatigue indicated in RCC-MR is 1.25 for 316L.

Here we propose a systematic experimental approach for characterizing the value of the coefficient as a function of the type of welded joint. This approach is based on study of the behavior of a weld when subjected to loading in the proximity of the welded joint.

For an X-geometry joint, of the type studied, Jf depends on the degree of loading. The value given in the code is only conservative for imposed strain variations of less than 0.6%.

It would appear to be necessary to make a study of different types of welded joints using the experimental approach proposed.

Cyclic bending tests on tubes at 0.6% strain failed to accurately indicate the value of Jf for the welded joint in question.

REFERENCES

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