Experimental investigation on the fatigue life of 304L tubular welded joints

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Abstract

In the nuclear energy industry, the use of components made of austenitic stainless steel is widely spread, because of its specific thermal properties. The assembly of these pressure vessels and piping by welding processes often requires surface mechanical treatments such as grinding or polishing before or after welding. The objective of these operations is to prepare surfaces for improving their state, because it is known that hardened surfaces and lower roughness ensure better fatigue resistance.

This study aims at having a better knowledge of the high cycle fatigue behaviour of 304L tubular welded structures with different surface finish, at ambient temperature. We focus on the influence of operations such as welding and grinding.

In this goal, some experiments are performed on AISI 304L austenitic stainless steel half-rings. By submitting such specimen to high cycle mechanical fatigue (10^6 cycles aimed) we intend to reproduce stress gradient that can be achieved by in service thermal cyclic loading. More precisely, the tests are conducted under a uniaxial strain control mode.

The objective is to compare the results to design curves used to assess nuclear components fatigue life, resulting from low cycle fatigue tests realized on cylindrical specimens.

1 INTRODUCTION

The ageing of PWR nuclear power plant is a very important issue, as well for the utilities as for the safety authorities. Among the most important phenomena inducing age-related degradation, we find thermomechanical fatigue and, more particularly, high-cycle fatigue.

Some authors have studied the influence of many parameters such as temperature, environment and residual stresses on the fatigue behaviour of austenitic stainless steels, widely used for nuclear pressure components. In this study we focus on the influence of mechanical operations, such as grinding or polishing, on high cycle fatigue behaviour of 304L tubular welded structures, in air environment at room temperature.

For this purpose a specific half-ring specimen closer to the in-service geometry has been developed. Some of them are base metal rings (which stand as reference), the rest presents a longitudinal and symmetrical Y-weld joint, with or without grinding.

All these steps are necessary to identify the influence of each process separately, which will be useful to numerical simulations.

2 TEST METHOD

2.1 Test specimen

The specimens are manufactured from a stainless steel AISI 304L pipe, of 168.5 mm external diameter and 18.5 mm wall thickness, in a solution annealed state (solution treated for 1h at 1050°C and then water quenched). This type of pipe is used for Reactor Heat Removal System of PWR nuclear power plants. The chemical composition and the mechanical properties are listed in Tables I and II respectively.

Table I. Chemical average content (wt%).

Element	Base metal (pipe) AISI 304L	Weld metal AISI 308L
C	0.008	0.007
Cr	18.35	19.00
Ni	9.75	9.25
Cu	0.175	0.035
Mn	1.83	1.59
Si	0.30	0.50
Ti	0.022	0.002
V	0.09	0.095

Table II. Mechanical properties.

	$R_{p0.2\%}$	R_m	A	H_{v30}		
Base metal	266 MPa	591 MPa	53%		160	
Weld metal	390 MPa	579 MPa	52%	Weld metal 205	HAZ 187	Base metal 160

The experiments are run on three kinds of specimens :
- base-metal specimens (no weld joint),
- as-welded specimens,
- ground-welded specimens.

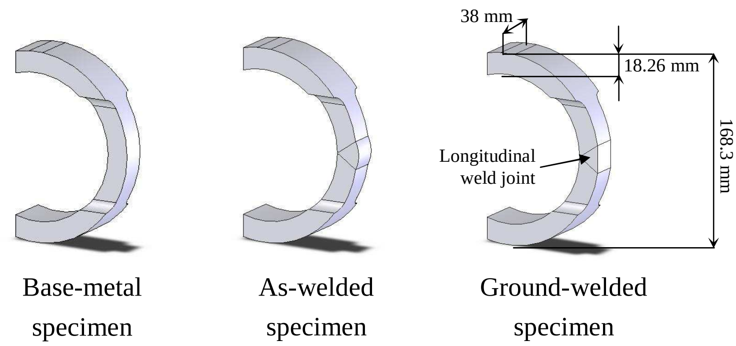

Figure 1 : Geometry of the specimens.

The specimen's geometry is presented in Figure 1. It is a half-ring of 38 mm width. The welded specimen presents a longitudinal Y-weld joint. The specimen's width is thinned around the weld joint in order to favour the damaging in this zone during the fatigue tests.

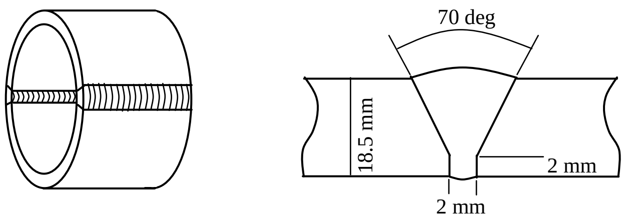

Figure 2 : Geometry of the weld joints.

The weld joint geometry is presented in Figure 2 : it is a single Y-groove joint geometry with a root face and a root gap of 2 mm, and a 70 deg included angle.

The half-pipes were joined along the length direction using a multipass welding process. The first pass was obtained by the Tungsten Inert Gas process. Then the weld joint was fulfilled using the shielded arc welding process with type 316 basic coated electrodes of 3.2 mm diameter.

As for the ground-welded specimens, the setting up of a test bench (Figure 3) has been essential in order to control as many parameters as possible and to reproduce the grinding operations. Therefore the test bench is composed of a portable disk grinder (power of 2000 Watts) and uses a grinding disk of 230 mm in diameter. The fixed parameters are the type of grinding disk and its rotation speed (6500 rpm).

Figure 3 : Grinding test bench.

The test bench enables control of :
- the down speed of the grinding wheel on the specimen,
- the pass depth,
- the parallelism of the grinding wheel to the specimen,
- the number of passes (a pass is a return passage of the grinding wheel at the surface of the specimen).

The grinding has been defined as light, which means a pass depth of 0.2 mm maximum, as mentioned in the reference [1]. The specimen surface temperature reached during this operation has been assessed by infrared camera at approximately 350°C.

The grounded surface presents a roughness parameter Ra of 5.7 µm.

2.2 Test condition

As thermomechanical fatigue tests are difficult to set up and control, mechanical tests have been run in order to reproduce the stress gradient that can be achieved by in service thermomechanical cyclic loading. It means that the half-ring specimen associated with a uniaxial loading presents a stress gradient in the studied zone thickness, with a maximum tensile stress on the external surface, as could be obtained with a thermomechanical loading.

The studied zone is located in the symmetry plane, where stands the weld joint of welded specimens (Figure 4). The width thinning around the position of the weld joint enables neither to insure the damaging in this zone, nor to emphasize and control the stress concentration on external and internal surfaces.

The fatigue test programme was performed in air, at ambient temperature, with a purely compressive loading (R_σ=0) and a frequency of 1 Hz. The tests were strain-controlled, thanks to a strain gauge in the studied zone (the most loaded of the specimen) and the displacement of the machine plate (both are linearly linked).

Regular stops were made at given numbers of cycles in order to determine the relaxation of surface residual stresses.

The stop criterion is otherwise based on a 25% drop of the stabilized force loading, or 10^6 cycles if no failure occurs.

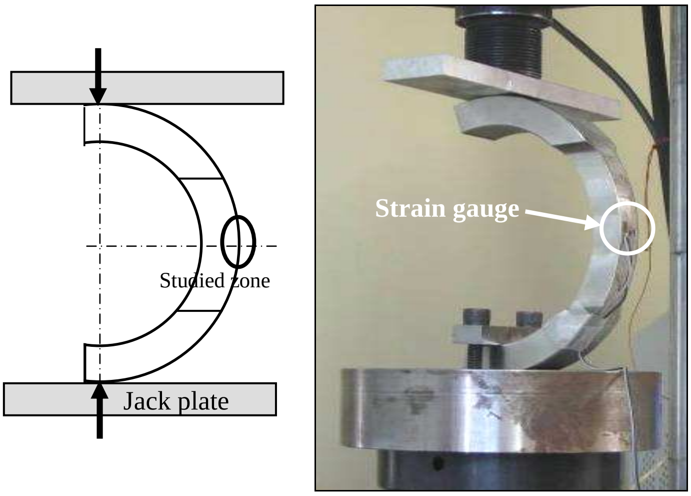

Figure 4 : Fatigue test conditions and bench.

The test conditions are presented in Table III : U_a is the machine plate displacement amplitude and ε_a is the strain amplitude.

Table III. Fatigue test parameters.

Type of specimen						
	Base metal	Reference	B6	B1	B4	B2
		U_a (mm)	±0.47	±0.7	±0.8	±0.9
		ε_a (%)	±0.052	±0.092	±0.093	±0.095
		ε_m (%)	0.099	0.41	0.55	0.64
	As-welded	Reference	S3	S2	S1	S4
		U_a (mm)	±0.6	±1.07	±0.8	±0.9
		ε_a (%)	±0.07	±0.121	±0.085	±0.094
		ε_m (%)	0.081	0.38	0.128	0.99
	Ground-welded	Reference	SA6	SA2	SA3	SA5
		U_a (mm)	±0.63	±0.96	±0.9	±1.08
		ε_a (%)	±0.07	±0.108	±0.094	±0.11
		ε_m (%)	0.08	0.35	0.137	0.15

3 TEST RESULTS

3.1 Base-metal specimen

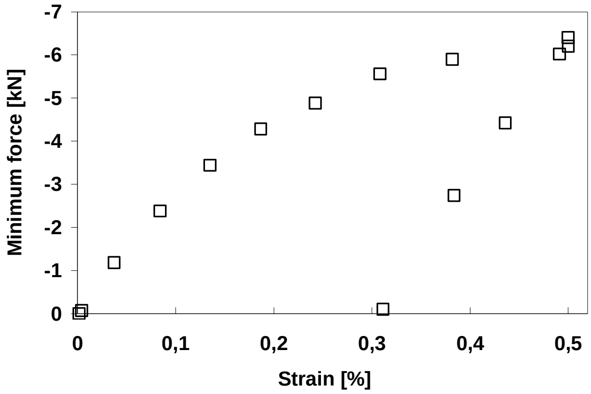

Figure 5 : Cyclic loading and strain of base-metal specimen B1.

Figure 4 shows the cyclic force and local strain on the studied zone of the B1 specimen, during the very first cycles. The loading reaches constant amplitude very rapidly, the elastic shakedown requires only a few cycles.

Whatever the strain amplitude, it remained under the fatigue strength since tests performed on base-metal specimens were stopped at 10^6 cycle lifetime, with no damage observed.

3.2 Ground-welded specimen

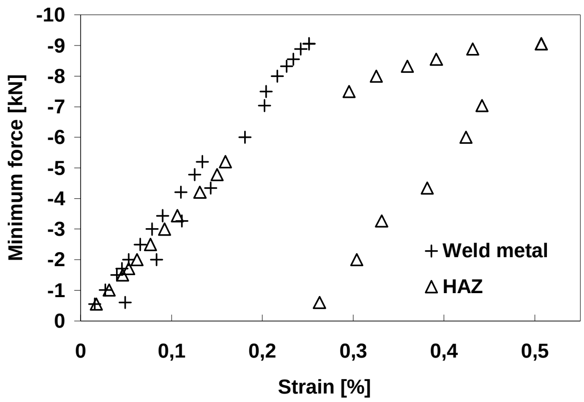

Figure 6 : Cyclic loading and strain of ground-welded specimen SA2.

As for as-welded and ground-welded specimens, strain was locally measured in the weld metal zone and the Heat Affected Zone (HAZ).

Figure 5 shows the force and local strain for the SA2 specimen. In both cases, the elastic shakedown requires only a few cycles. Nevertheless we can observe that the weld metal is stronger than the HAZ material (mismatch effect [2]) which behaves like the base metal of Figure 1.

Table IV. Fatigue lifetime of ground-welded specimens.

Reference	SA6	SA2	SA3	SA5
U_a (mm)	±0.63	±0.96	±0.9	±1.08
ε_a (%)	±0.07	±0.108	±0.094	±0.11
ε_m (%)	0.08	0.35	0.137	0.15
N (cycles)	$10^6 \rightarrow$	512 000	$10^6 \rightarrow$	291 300

Fatigue lifetimes of ground-welded specimens are presented in Table IV. The strain amplitude $\boldsymbol{\varepsilon_a}$ corresponds to the HAZ strain gauge measurements, since the values in this zone were higher and more detrimental than in the weld metal.

Two specimens failed before 10^6 cycles : many cracks initiated over the specimen largeness, in the base-metal zone. Fatigue striations were enlightened by MEB observations, as shown in Figure 6.

Thus the fatigue limit of a ground-welded structure (for R_σ=0) is around $\boldsymbol{\varepsilon_a}$ **=** 0.09 %.

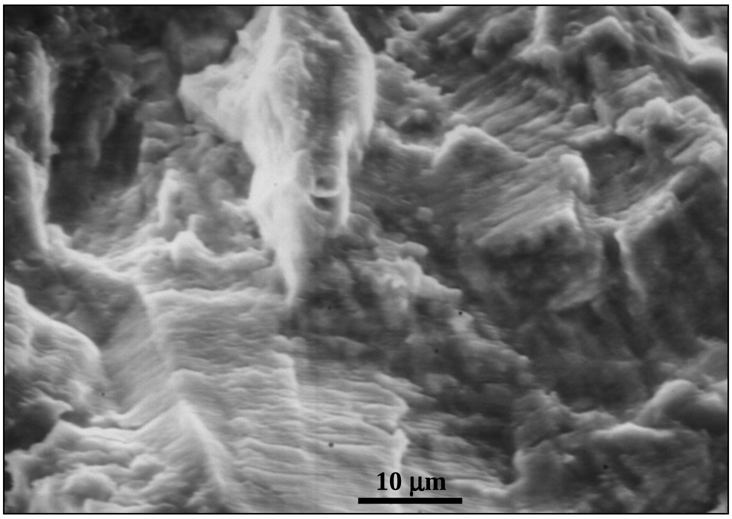

Figure 7 : Fatigue striations on S2 specimen.

3.3 As-welded specimen

Figure 7 shows the force and local strain for the S2 as-welded specimen. We can observe the same behaviour of the weld metal and the HAZ as for the ground-welded specimens : a few-cycle elastic shakedown and the weld metal stronger than the HAZ material.

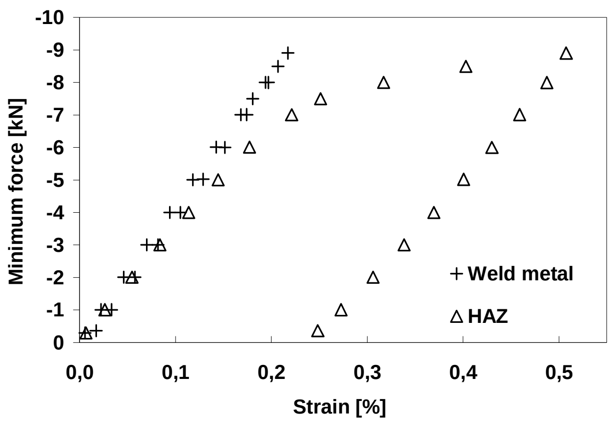

Figure 8 : Cyclic loading and strain of as-welded specimen.

Every as-welded specimen failed before 10^6 cycles (Table V) : cracks initiated over the specimen largeness, in the weld toe (Figure 8). Though the cracks initiated at the surface limit between weld metal and base metal, it did not propagate along this way and went straight through the width of the specimen. The same fatigue striations as for failed ground-welded specimens were enlightened by MEB observations (Figure 6).

The fatigue limit of an as-welded structure (for R_σ=0) is beneath $\boldsymbol{\varepsilon_a}$ **=** 0.07 %.

Table V. Fatigue lifetime of as-welded specimens.

Reference	S3	S2	S1	S4
U_a (mm)	±0.6	±1.07	±0.8	±0.9
ε_a (%)	±0.07	±0.121	±0.085	±0.094
ε_m (%)	0.081	0.38	0.128	0.99
N (cycles)	375 000	53 000	150 000	95 000

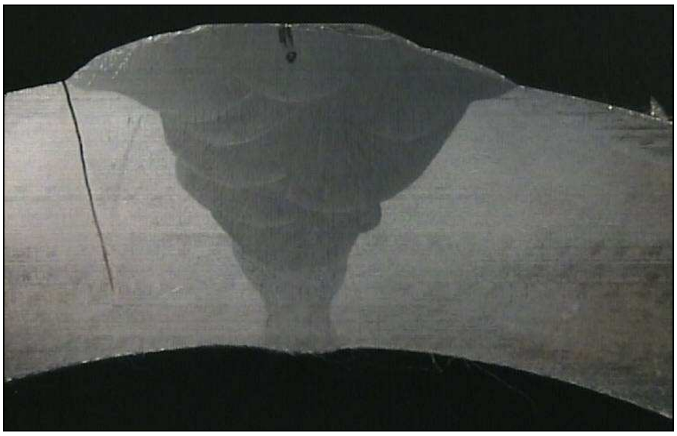

Figure 9 : Fracture of as-welded specimen S3.

4 DISCUSSION

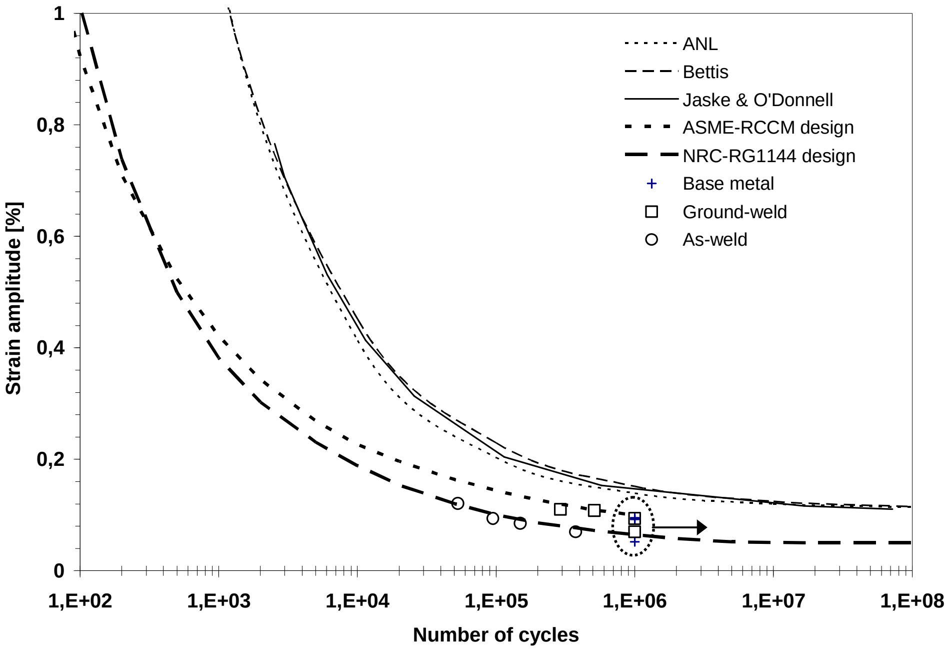

Figure 10 : Comparison of fatigue tests results with S-N curves (R_σ=-1).

Figure 9 gives a comparison between fatigue tests results obtained and best-fit mean S-N curves and design curves (including safety margins) proposed for austenitic stainless steels by different authors or scientific committees (the Argonne National Laboratory [3], the Bettis Atomic Power Laboratory [4], Jaske & O'Donnell [5], the ASME-RCCM [6] and the NRC Regulatory Guide 1144 [7]). The symbols with arrows denote run-out data.

The results of our fatigue tests performed on structural specimens are located below the mean curves, especially those of as-welded specimens. These curves were established from cylindrical specimens, with a polished surface finish. Thus it shows the necessity to have the best knowledge of the influence of specimen geometry and operations such as welding and grinding, in order to assess the structure lifetime.

As-welded specimen results follow quite tightly the NRC design curve, whereas none of the base metal specimens failed. The presence of a weld joint undoubtedly weakened the structure, seemingly because of the stress concentration at the weld toe. Nevertheless grinding the weld joint enabled to improve significantly the lifetime, as it removes the weld toe.

5 CONCLUSION

This study confirms that presence of weld roots has a detrimental effect on austenitic stainless steel components fatigue damage. Manufacturing operation such as grinding improved the fatigue lifetime results with improving the surface geometry of the specimen. This study will enable the determination of correction factors on S-N curves characterizing the effect of each operation, so that the component designing remains precise and safe.

Eventually it will be necessary to synthesize the influence of such operations performed on pressure structures. They have non negligible effects on their mechanical states, especially as for residual stress [8][9] and fatigue behaviour.

It is finally essential to know the influence of each operation for a good estimation of the durability of the pressure pipes.

6 REFERENCES

1. H. Bléhaut, D. Gognau, P. Flahaut, L. Khouchaf and S. Hariri, Characterisation of the effects of grinding on residual stresses, Proceedings 6th European Conference on Residual Stresses, A. M. Dias, J. Pina, A. C. Batista, E. Diogo, eds., Trans Tech Publications, 2002.

2. Y. Madi, Comportement et durée de vie d'une jonction tubulaire soudée en 316L à 600°C, PhD thesis, université Blaise Pascal – Clermont II, 2001.

3. O. K. Chopra, Effect of LWR coolant environments on fatigue design curves of austenitic stainless steels, NUREG/CR-5704, ANL, april 1999.

4. T. R. Leax, Statistical models of mean stress and water environment effects on the fatigue behaviour of 304 stainless steel, PVP, Vol. 386, ASME 1999, 229.

5. C.E. Jaske, W. J. O'Donnell, Discussions : fatigue design criteria for pressure vessel alloys, Transactions of ASME, Journal of Pressure Vessel Technology, vol. 99, 1977, 584-592.

6. ASME Boiler & Pressure Vessel Code, Section III, Rules for Construction of Nuclear Power Plant Components, American Society of Mechanical Engineers, 2007.

7. Regulatory Guide 1144, Guidelines for evaluating fatigue analyses incorporating the life reduction of metal components due to the effects of the light-water reactor environment for new reactors, US Nuclear Regulatory Commission, July 2006.

8. L. Monin, S. Panier, S. Hariri and C. Faidy, Influence of surface finish and method of manufacture on residual stresses in welded pipes, ASME PVP 2006/ICPVT-11, Vancouver, Canada , Vol. 7, 23-27 July 2006, 335-342.

9. L. Monin, S. Panier, S. Hariri, D. Zakrzewski and C. Faidy, Caractérisation des contraintes résiduelles sur assemblages soudés tubulaires en acier 304L, Conférence ESOPE 2007, Paris France, 9-11 octobre 2007, submitted text.