Application of Leak-Before-Break concept in 316LN austenitic steel pipes welded using 316L

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ABSTRACT. The paper presents a study of the application of Leak-Before-Break (LBB) concept in a relatively small-diameter high energy reactor coolant line, where it is proposed type AISI 316LN to be used as base material welded with type AISI 316L coated electrode considering a pipe with diameter of 273 mm. The pipe material was characterized in terms of tensile test with Ramberg-Osgood analyses and fracture toughness tests with J-Resistance curve determination, considering base material, weld joint and heat affected zones. For the mechanical properties found in tensile tests and using the PICEP software, were determined the leak rate curves versus crack sizes, to determine the size of a detectable leakage crack, and the critical crack sizes, considering failure by plastic collapse. For the critical crack sizes found in weld, which presented the lowest toughness, J-Integral analysis was performed considering failure by tearing instability. Results show a well-defined mechanical behavior where base material has a high toughness, weld has a low toughness, and HAZ showed intermediate properties. For the load limit analysis, the lowest critical crack size was found for base material presenting circumferential cracks. For J- Integral analysis, it was demonstrated that failure by tearing instability will not occur.

KEYWORDS. Leak-Before-Break; 316LN; Weld 316L.

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INTRODUCTION

The LABGENE is a 48 MW thermal PWR prototype reactor under development in Brazil, that aims to develop and test the capability to design small and medium power reactors for electricity production and for nuclear propulsion. Leak-Before-Break (LBB) is a method used in design of nuclear power reactor coolant loop piping to eliminate consideration of the dynamic effects of pipe rupture. The exclusion of dynamic effects associated with pipe rupture from the design basis is allowed when analyses demonstrate that the probability of pipe rupture is extremely low for the applied loading resulting from normal conditions and a postulated safe shutdown earthquake (SSE). A deterministic LBB evaluation performed using guidance from NUREG-1061 Volume 3 [1] and SRP 3.6.3 [2] is usually used to demonstrate this low probability of pipe rupture. This examination is based on fracture mechanics analysis that is used to demonstrate that a crack leak, present in a pipe, can be detected by the plant leak detection systems, with a factor of 10 between the predicted leakage and the plant leakage detection capability. If the leakage crack size is smaller than the critical crack size by a factor of two, then LBB requirements are satisfied and the dynamic effects of pipe rupture need not be considered in the plant design basis [1].

For the critical flaw sizes determination, it can be used either limit load with net section collapse criterion or J-Integral and Tearing Modulus (J/T) analysis for tearing instability criterion. For the leak rate determination, a well know and extensively validated computer program called PICEP [3] is usually used for determination of leakage. This program contains a methodology for computing crack opening area based on elastic plastic fracture mechanics analysis and its flow rate equations are based on a modification of Henry's homogeneous non-equilibrium critical flow model.

Nonetheless, the small size of the reactor coolant piping, considered in LABGENE project, can makes it difficult to meet the same LBB standards that were developed for large commercial reactors, when NUREG-1061 Volume 3 [1] and NUREG-0800 Standard Review Plan 3.6.3 [2] were initially developed. Furthermore, the small pipe diameter makes the usual ferritic coolant pipe with inside austenitic cladding, impossible to be performed, then a fully austenitic pipe shall be used.

Austenitic stainless steels pipes made by material type AISI 316 and its variants have been chosen for applications in nuclear power plants owing of their good high temperature mechanical properties and creep and corrosion resistance. A low carbon choice alloyed with nitrogen of this steel, designated as AISI 316LN, is a possible chose for the LABGENE reactor coolant piping. Moreover, due to the need of connecting the pipes spools by use of weld, a shielded metal arc welds (SMAW) using AISI 316L coated electrode was select as the most appropriate commercial weld join material.

This proposal welded pipe is tested and analyzed as three-component composed of weld metal, base material and heat affected zone (HAZ). Inadequate mechanical properties in any of these three zones is a threat to the LBB analysis.

METHODOLOGY

Following is provided a summary of the methodology used for the LBB evaluation in the LABGENE's reactor coolant loop piping.

Determination of Loads and Stress

The loads to be used in LBB evaluations is considered as normal operating loads for leakage determination and normal plus seismic SSE loads for critical crack determination. The normal operating loads consist of pressure, dead weight, and thermal expansion loads. For calculation of critical flaw size, it was considered the maximum of SSE loads added to the normal operating loads.

The piping dimension is considered with an outside diameter of 273 mm and a thickness of 28.57 mm, the operating conditions for the LBB feasibility evaluation are considered as the usual one for a PWR plant, with operation temperature of 288 °C and internal pressure of 25.17 MPa in the reactor coolant line.

Determination of Material Properties

Material properties to be used in the LBB evaluation shall be evaluated by stress-strain curve determination using Ramberg-Osgood (RO) analysis, and material toughness is obtaining by resistance curve test method with the determination of material J-R curve.

The hot tensile tests were performed at temperature of 288 °C in according to the standard ASTM E8/E8M-13a and ASTM E21-09. The evaluation of the hot tensile tests includes the yield strength (σ_0) tensile strength (σ_R), flow stress (σ_f) and uniform elongation determination. The analysis includes also the determination of the Stress-Strain curve by means of the Ramberg-Osgood Eq. 1, as following:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \quad (1)$$

where:
σ = stress value;
ε = strain value;
σ_0 = reference stress;
ε_0 = reference strain (σ_o/E);
α = parameter from curve fitting of data; and
n = strain-hardening exponent.

The RO parameters were obtained using the engineering stress-strain curve, fitting the data in the range between 0.1 % strain and the strain corresponding to 80 % of the ultimate strength.

The fracture toughness tests were performed in accordance to the ASTM E1820-13 standard at temperature of 288 °C. The evaluation of the toughness tests includes the determination of the material resistance J-R curve, the initiation of stable crack growth J_{IC} and the material power law formula for the J-R data, obtained using a linear regression analysis, as following:

$$J_{mat} = C\left(\Delta a\right)^m \quad (2)$$

where:
$J_{mat} = J_{Deformation}$ in units of kJ.m^{-2};
Δa = crack extension in mm;
C = material constant; and
m = exponent.

The hot tensile and toughness tests were performed considering the three-component weld metal, base material and HAZ piping zones. Tested specimens quantity and orientation are showed in Tab. 1. Once only circumferential weld is used, it was considered that in the weld and HAZ zones only circumferential cracks could exists, so the transverse specimens orientation for the hot tensile test and C-L for the toughness test were considered only for the base material.

Test type	Specimen orientation	Pipe zone		
		Base Material AISI 316LN	HAZ	Weld AISI 316L
Hot tensile test	Longitudinal	3	3	3
	Transverse	3	--	--
Hot Toughness test	L-C	3	3	3
	C-L	3	--	--

Table 1: Quantity of specimens for hot tensile and toughness tests

Determination of the critical through-wall cracks size and the leakage cracks size

The sizes of critical through-wall cracks and the leakage crack were determined using net section collapse (limit load) analysis. For the critical cracks found in these analyses, it was verified if fail would occur by tearing collapse using elastic-plastic J-integral analysis.

The computer program PICEP [3] was used for the limit load analysis for determination both the size of critical cracks and the size of leakage cracks. For a given set of input conditions, including operation conditions, applied loads, crack morphology and material properties (obtained by hot tensile test), PICEP return as output the size of a critical crack and a curve of leakage flow rate versus crack size.

For the tearing collapse verification, the elastic-plastic J-Integral analysis is, in general, applied with the aid of finite element methods. For usual engineering cases, such as piping with a through-wall crack, solutions listed in manuals that are derived from numerical solutions are available. One of the most well-known and valid reference is the Ductile Fracture Handbook developed by Zahoor [4], that provides solutions for applied J and T, where each solution corresponds to a system of geometry, crack orientation, applied loading, and material properties. The applied J-Integral equation, proposed by Zahoor, for a circumferential through-wall crack present in a piping, considering bending moment loads, is the following:

$$J = J_{Elastic} + J_{Plastic} \tag{3}$$

$$J = \underbrace{\frac{f_b M^2}{R^3 t^2 E}}_{J_{Elastic}} + \underbrace{\alpha \sigma_0 \varepsilon_0 \pi \mathrm{R} \left(1 - \frac{\theta}{\pi}\right)^2 H_1 \left(\frac{M}{M_0}\right)^{n+1}}_{J_{Plastic}} \tag{4}$$

where:

M = Is the applied bending moment;

f_b and M_0 = Are parameters that depend on pipe dimensions, load conditions, crack size and orientation and material properties;

H_1 = Is based on finite element analyses, and can be found in reference [4];

R, t e θ = Are the pipe mean radius, wall thickness and crack half-angle, respectively; and

E, α, σ_0, ε_0 and n = Are constants in the RO stress-strain relation as showed in Eq. 1.

Determination of LBB viability

It shall be determinate the size of through-wall cracks that will result in a detectable leakage with a margin of 10 applied between the predicted leakage and the detectable leak, to cover various uncertainties associated with leakage prediction and leakage detection. Historically, a leakage detection capability of 1 gallon per minute (gpm) that presents 3.78 liters per minute in a PWR plant has been used for leakage detection capability [5]. Consequently, a 10 gpm leakage crack is considered in the LBB analysis.

LBB viability for an analyzing pipe system is demonstrated if a margin of at least two exists between the leakage crack size and the critical through-wall crack size.

RESULTS

Mechanical tests results

Hot tensile test results show a well-defined behavior among the three zones, where the base material has a high toughness behavior with relative low yield strength and high uniform elongation, the weld show a low toughness behavior with relative high yield strength and low uniform elongation, and the HAZ showed intermediate mechanical properties between the base material and the weld. Fig. 1 present typical stress x strain curves for the three different zones of the welded pipe.

Ramberg-Osgood analyses according Eq. 1 were performed for all specimen data, tested according to Tab. 1 for hot tensile test. The results of yield strength (σ_0) tensile strength (σ_R), flow stress (σ_f), elongation, Ramberg-Osgood parameter (α) and strain-hardening exponent (n) are presented in Tab. 2.

Fig. 2 present typical J-R curves obtained for the three different zones in the welded pipe. The results of all base material and HAZ are not valid according to ASTM E1820-13 because J_Q is much larger than the J_{limit} value. All J_Q results for the weld zone have met the criteria of validity of the standard and can be considered valid JIC values. For the power law analyses, according Eq. 2, only one weld specimen, CT2 of Tab. 3, fulfilled all the requirements to be validate.

Even though the results for the base material and HAZ did not present valid J_{IC} values, the tests demonstrated the high toughness of these zones of the welded pipe. Thus, for the elastic-plastic J-Integral analysis, only the weld zone will be considered, once that the analysis of the weld will bring the most conservative results. The results of J_{IC} and power law material constant (C) and exponent (m) obtained from the weld J-R curves and Eq. 2 are presented in Tab. 3.

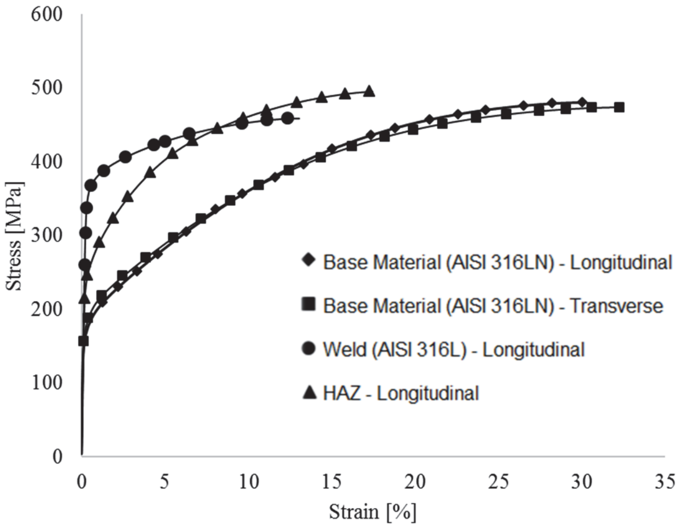

Figure 1: Typical Stress x Strain curves for different zones in the welded pipe.

Pipe Zone	Specimen	Orientation	σ_0 [MPa]	σ_R [MPa]	σ_f [MPa]	Elong. [%]	Ramberg-Osgood	
							α	n
Base Material AISI 316LN	BM1	Longitudinal	166	483	325	30.7	8.0	3.4
	BM2	Longitudinal	167	481	324	30.1	7.7	3.4
	BM3	Longitudinal	149	458	303	31.8	8.7	3.2
	BM4	Transverse	167	459	313	30.1	8.2	3.5
	BM5	Transverse	177	473	325	31.8	7.3	3.7
	BM6	Transverse	175	476	326	32.2	7.4	3.7
Weld AISI 316L	WM1	Longitudinal	360	463	412	9.0	1.3	9.9
	WM2	Longitudinal	358	454	406	11.7	1.2	9.2
	WM3	Longitudinal	354	455	405	16.7	1.3	11.4
HAZ	HZ1	Longitudinal	249	495	372	17.2	2.7	5.4
	HZ2	Longitudinal	249	486	368	14.7	2.4	5.5
	HZ3	Longitudinal	265	481	373	13.8	2.0	6.2

Table 2: Results of hot tensile tests.

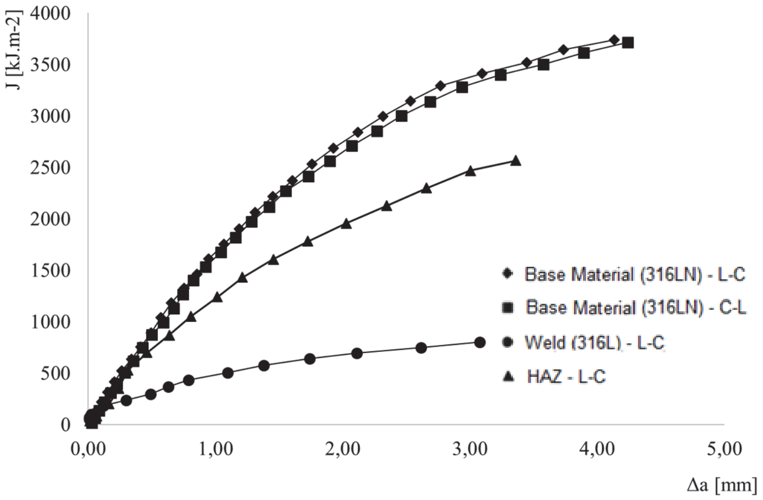

Figure 2: Typical J-R curves for different zones in the welded Pipe.

Specimen	Orientation	J_{limit} [kJ.m^{-2}]	J_{max} [kJ.m^{-2}]	J_{IC} [kJ.m^{-2}]	C	m
CT1	L-C	537	857	199	--	--
CT2	L-C	540	701	168	355	0.621
CT3	L-C	535	653	193	--	--

Table 3: Results of J-Integral tests for the weld AISI 316L

Fracture mechanics analyses

Applying the mechanical properties found in the tensile test and a specific load, that considers normal operation condition, in the leak calculation software PICEP, the leak rate curves versus crack size were determined. Fig. 3 present the typical leak flow rate versus crack length found for the three different zones in the welded pipe.

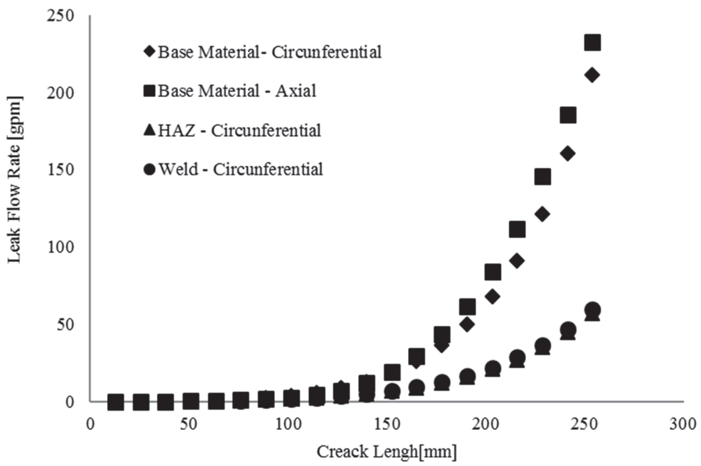

Figure 3: Typical Leak flow rate x crack length for different zones in welded pipe.

Considering that a typical detectable leakage capability of 1 gpm is considered for PWR plants and the margin of 10 shall be applied, it was possible to determinate the size of through-wall cracks that will result in detectable leakage of 10 gpm for each tested hot tensile specimen.

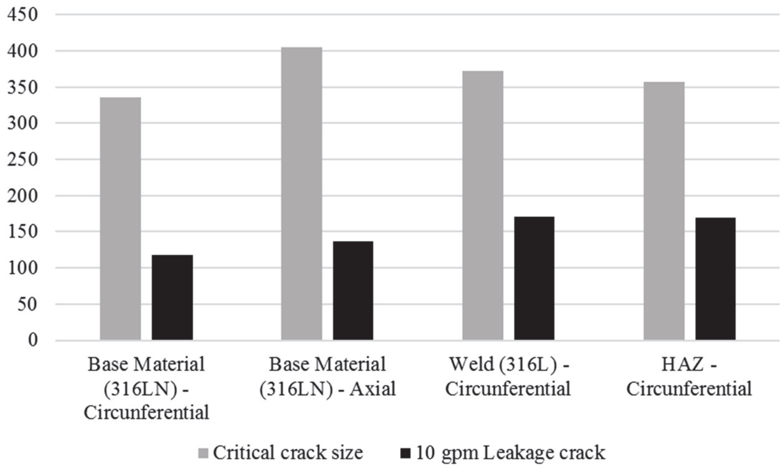

Figure 4: Average sizes for critical crack and 10 gpm leakage crack for different zones in welded pipe.

Using also the PICEP software, but considering normal plus seismic SSE loads conditions, size of critical through-wall cracks were found for all three zones of the welded pipe. Fig. 4 shows both the size of through-wall cracks that will result in leakage of 10 gpm and the size of critical cracks for all the three different zones and orientation in the welded pipe.

Fig. 4 shows that all the material zones and crack orientation fulfill the requirements for LBB application, since all critical cracks size considered are more than twice the size of the crack that would causes a 10gpm leak.
For the critical crack size found in the weld, which is the region that presented the lowest toughness, elastic-plastic J-Integral analysis was performed, to verify the possibility of tearing instability failure. In this analysis, two important consideration shall be taken, specifically, initiation or first extension of an existing crack denoted as J_{IC}, and stability or instability of a growing crack. If the material toughness J_{IC} is bigger than the applied value of J, the not occurrence of crack initiation or significant growth is guaranteed. When the J_{IC} is less than the applied J, the crack growth must be evaluated by a ductile instability analysis, e.g. Tearing Modulus analysis, to determine if the crack grows in a stable manner, or if the crack will grow unstably resulting in a structural collapse [6].
The applied J calculated using Eq. 4, considering the normal plus seismic SSE loads conditions, the size of critical through-wall crack found for the weld zone, and the material properties for the weld zone found in the hot tensile tests, was:

$$J_{aplied} = 164 \text{ kJ.m}^{-2}$$

This value is less than the lower J_{IC} value of 168 kJ.m^{-2} found in the toughness test performed in weld zone. This way, it was demonstrated that the failure by tearing instability will not occur under the considered conditions.

CONCLUSIONS

The lowest critical crack size was found for the base material presenting circumferential orientation crack. After a certain crack size, the leak rate in base material is much higher than for the HAZ and for the weld zones. For the critical crack size found in the weld, Integral-J analysis was performed, considering failure by tearing instability. It has been demonstrated that the failure by tearing instability will not occur under the considered conditions of this project.
All critical cracks size found for the three different zones and two different orientation, are more than twice the size of the crack that would causes a 10 gpm leak. Thereby, it can be concluded that the investigated 316LN austenitic steel pipes welded using 316L can be applied in the LABGENE reactor coolant loop considering LBB criterion.

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