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Experimental and theoretical evaluation of solidification cracking in weld metal

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ABSTRACT

Purpose: The main objective of this work is to compare the compatibility and reliability of the theoretical and experimental methodologies in the evaluation of the solidification cracking susceptibility of austenitic stainless steel weld metal, using three different electrodes.

Design/methodology/approach: The cracking susceptibility of welds is described here through an experimental procedure using the transvarestraint test, and a theoretical procedure developed as a function of the chemical composition and microstructure of the material. The theoretical procedure requires knowledge of the weld metal chemical composition and microstructure, which was taken from the literature.

Findings: Results obtained by means of tables, parameter evaluation and fitting, micrographs and macrographs indicate that the experimental and theoretical methodologies are consistent with one another, and are both reliable, regardless of the welding process employed

Practical implications: The results of our theoretical analysis were in complete agreement with those obtained from the transvarestraint test, thus indicating that, if correctly applied, either of these methods can be used to determine the susceptibility of austenitic stainless steels to form solidification cracks. The choice between the experimental or the theoretical method should depend only on the availability and ease of application for each specific case.

Originality/value: It is possible to make a theoretical assessment of the solidification cracking susceptibility of a given steel as a function of the: chemical composition, Creq/Nieq, ferrite number FN, microstructure, percentage of (S+P), and percentage of ferrite. Another way to measure the susceptibility of steel to solidification cracking is through experimental tests. The originality of this study is the numerical comparison made between the results provided by two different methods: the theoretical assessment and the practical technique, using the transvarestraint test.

Keywords: Welding; Solidification crack; Transvarestraint west; Stainless steel weld

1. Introduction

Austenitic stainless steels have become the most widely used stainless steels, and correspond to about 70% of all the stainless steel produced worldwide, thanks to their mechanical and metallurgical properties and their good weldability. However, these steels are susceptible to the solidification crack phenomenon [1, 2, 3, 4], and thus their welding process requires special attention.

Solidification cracking, also known as hot cracking, consists of fractures at the interdentritic and/or intergranular weld metal boundaries in the solidification process, during which the liquid phase of the mushy melt becomes rich in impurities, mainly sulfur (S) and phosphorus (P). [5, 6] This phenomenon reduces the mechanical strength at the grain and dendritic boundaries, rendering them susceptible to cracking. [1] The presence of 5% to 10% concentrations of ferrite-δ in solid weld metal makes austenitic weld metal less susceptible to solidification cracking. [2]

The assessment of the propensity for cracking susceptibility of austenitic stainless steels is based on the concentration of P + S and on the values of the Cr_{eq}/Ni_{eq} ratio, because the Cr_{eq} quantifies the influence of the ferritizing elements while the Ni_{eq} quantifies the austenizing compounds. [1] Brooks, et al. [1] also states that stainless steels with a value of $Cr_{eq}/Ni_{eq} \leq 1.5$ are susceptible to solidification cracking, while stainless steels with values of $Cr_{eq}/Ni_{eq} > 1.5$ are immune to solidification cracking, or nearly so.

The tolerance of S and P contents in solidification cracking susceptibility is influenced by the arbitrary unit values called the ferrite number (FN) [5, 7]. Stainless steel with a (P+S) ≤ 0.02% and with only an austenitic structure in the solid phase is not susceptible to cracking. Stainless steels with (P+S) ≤ 0.03% and FN ≥ 4, (P+S) ≤ 0.04% and FN ≥ 8, and (P+S) ≤ 0.05% and FN ≥ 12 are not susceptible to solidification cracking either.

Based on the above knowledge, it is possible to make a theoretical assessment of the solidification cracking susceptibility of a given steel as a function of the following parameters: chemical composition, $Cr_{eq}/Ni_{eq,}$ ferrite number FN, microstructure, percentage of (S+P), and percentage of ferrite.

Another way to measure the susceptibility of steel to solidification cracking is through experimental tests. There are a number of tests for measuring the solidification cracking susceptibility of weld, but the most recommended for assessing weld metal is the transvarestraint test.

The transvarestraint test is a variation of the varestraint test, whereby the required tangential strain is applied in the transversal direction on the weld bead at the instant of the extinction of the arc. The tangential strain is applied by means of matrices with curvature radii suitably calculated as a function of the test specimen thickness. This test is recommended by several authors, [2, 3, 5, 8] to evaluate the weld metal, because it promotes transversal bending of the weld bead.

The results of the transvarestraint test are usually interpreted in terms of two parameters: Maximum Crack Length (MCL), a measurement of the longest crack found in the weld line, and Total Crack Length (TCL), the sum of the lengths of all the cracks found in the weld line. According to Shankar (2000) [9], the MCL parameter is more advisable because it produces lower error levels than the TCL parameter.

The discussion above indicates that there are two ways to evaluate the susceptibility to solidification cracking of a given steel: theoretically, and by the transvarestraint test. The main objective of this work is to compare the compatibility and reliability of the theoretical and experimental methodologies in the evaluation of the solidification cracking susceptibility of austenitic stainless steel weld metal, using three different electrodes.

2. Materials and methods

In the present work, tubular AWS E316LT1-1 and AWS E316LT0-3 wires and the solid AWS ER316L wire were used, all with 1.6 mm diameter. The base metal of the test specimens used for the assessment of these electrodes was 316L austenitic stainless steel.

The shielding gases used for these electrodes, according to the AWS A5.22-95 specification, were carbon dioxide (100% CO_2) for the AWS E316LT1-1 wire, and Argon with 2% of oxygen (Ar + 2% O_2) for the ER316L wire. The AWS E316LT0-3 wire is self-shielded and does not require protection gas.

The test specimens were 260 mm x 160 mm rectangular plates, 9.5 mm thick, with a U-shaped groove (5 mm radius) cut into the center of the test specimen in the lamination direction of the plate. These test specimens are standard for the transvarestraint testing equipment used in this study. This device was built and calibrated in the Welding Laboratory of the Mechanical Engineering Faculty of the State University of Campinas. [10]

Because three distinct welding processes were employed to produce the weld, constant heat input was adopted as the control parameter. [7] The welds were automated and carried out in a flat position using a welding device with inverse polarity (CC+) coupled to a computational data acquisition system collecting data on arc voltage, welding current and travel speed. Welding parameters for each type of wire were optimized so that the groove would be completely filled in a single pass.

The welding parameters were optimized to obtain regular beads with full penetration and constant heat input (2000 J/mm). [11,12]

3. Results

In order to compare the compatibility and reliability of the experimental and theoretical methods in the evaluation of weld metal solidification cracking susceptibility, the results and discussion are presented separately according to the evaluation methodology.

3.1. Experimantal method

The experimental evaluation of the susceptibility to solidification cracking of the E316L stainless steel welded with three different electrodes was carried out using the transvarestraint test. Specimens were subjected to three levels of tangential strain, ε = 1%, 3% and 5%, which were applied with help of three matrices with appropriate curvature radii to cause these strains. The test initially consisted of welding and bending the lines.

The susceptibility of the electrodes to solidification cracking was evaluated by measuring the MCL (Maximum Crack Length) of the weld metal. The cracks were observed with a Carl Zeiss Jena model ZKM 01-250 C optical microscope with 10x magnification.

A Factorial Planning (3^2) with two influence variables (electrode type and degree of tangential strain) at three levels was adopted during the experiment to ensure repetitiveness and reduce possible experimental errors. [13] Thus, each of the tested electrodes generated 9 experiments, randomly carried out and repeated 3 times, totaling 27 tests.

Experimental tests started with the highest tangential strain rate (ε = 5%), which is the most severe condition. When solidification cracks began to appear under the most severe conditions, tests with milder strains (ε = 3% and 1%) were carried out to define the degree of crack susceptibility with the use of the different electrodes. Table 1 shows the results of the MCL measurements as a function of the three strains applied in the test with the three electrodes. Each testing condition shows the measured MCL of each repetition and the mean MCL value.

Table 1.
Maximum Crack Length (MCL) as a function of the strains

Tangential Strain (ε) (%)	E316LT1-1 (mm)		ER316L (mm)		E316LT0-3 (mm)	
	27.4		18.3		0	
5	23.3	26	15.9	17	0	0
	28.4		18.1		0	
	2.0		0		0	
3	1.6	2	0	0	0	0
	2.8		0		0	
	0		0		0	
1	0	0	0	0	0	0
	0		0		0	

Table 1 shows that the metal deposited from ER316L (solid wire) and E316LT1- 1 (gas-shielded flux-core electrode) exhibited cracking under a 5% tangential strain. The E316LT0-3 (self-shielded flux-core electrode), in contrast, showed no cracking in any of the three repetitions, even under careful examination by optical microscope (10x magnification).

The deposits from wires ER316L and E316LT1-1 which presented cracks under a tangential strain of 5% were subjected to the transvarestraint test under a strain of $\varepsilon = 3\%$. Under tangential strain $\varepsilon = 3\%$, only the weld of electrode E316LT1-1 showed small cracks in all the repetitions of the test, while the weld of electrode ER316L showed no cracking in any of the three repetitions.

The deposit of electrode E316LT1-1 which displayed cracking in the $\varepsilon = 3\%$ strain test was then subjected to a $\varepsilon = 1\%$ strain test, which produced no cracking in any of the three repetitions.

Table 1 clearly indicate that the weld metal of the gas-shielded flux-core wire (E316LT1-1) and the solid electrode (ER316L) fall into the transition area between susceptibility and non-susceptibility, for they showed practically no significant cracking below a 5% strain, while the weld metal of the self shielded electrode (E316LT0-3) was classified as insusceptible, displaying no cracking whatsoever, even under the most aggressive strain ($\varepsilon = 5\%$).

This variation in the susceptibility of the materials demonstrates that the transvarestraint test offers a high degree of sensitivity in determining the susceptibility to cracking of austenitic stainless steels welded with solid and gas shielded flux-cored electrodes.

3.2. Theoretical method

It is possible to make a theoretical analysis of the susceptibility to solidification cracking of a given steel as a function of the following parameters:

- Chromium Equivalen $Cr_{eq} = Cr + Mo + 0.7\ Nb$
- Nickel Equivalent $Ni_{eq} = Ni + 35C + 2N + 0.25Cu$
- % of phosphorus
- % of sulfur
- % of ferrite

The theoretical evaluation of the susceptibility of E316L stainless steel to form solidification cracking when welded with three different electrodes was based on the chemical composition and the microstructural analysis of the weld metal. Weld metals used for this were the same as in the experimental evaluation.

The chemical composition of the weld metal was determined by energy dispersive X-ray spectroscopy, and the results are given in Table 2.

The results of the chemical analysis enabled us to determine the Cr_{eq}, Ni_{eq}, Cr_{eq}/Ni_{eq} parameters and the (P+S) parameter. The Cr_{eq}/Ni_{eq} ratio is used to estimate the primary precipitation of ferrite-δ. Table 3 shows the values of Cr_{eq}, Ni_{eq}, Cr_{eq}/Ni_{eq} and P+S calculated from the chemical composition.

Table 2.
Chemical composition of the weld metal of the tested electrodes

Material	ER316L	E316LT1-1	E316LT0-3
Cr	17.7	16.6	17.3
Ni	11.8	11.4	11.3
Mo	2.7	2.7	2.9
Mn	2.00	1.65	1.70
Si	0.40	0.46	0.44
C	0.020	0.016	0.018
Cu	0.70	0.07	0.10
P	0.030	0.036	1,020
S	0.007	0.006	0.008

Table 3.
Values of Cr_{eq}, Ni_{eq}, Cr_{eq}/Ni_{eq} and P+S of the tested weld metal

Material	Cr_{eq}	Ni_{eq}	Cr_{eq}/Ni_{eq}	P+S
ER316L	20.4	12.7	1.6	0.037
E316LT1-1	19.3	12	1.6	0.042
E316LT0-3	20.2	12	1.7	0.028

Using the WRC-92 diagram, [14] with the Cr_{eq} and Ni_{eq} values presented in Table 3, the values of the ferrite number FN for the wires were determined. The presence and quantity of ferrite-δ were determined through measurements taken with an MP3 Magnetic Ferritoscope.

The existence of ferrite-δ was also confirmed by the qualitative evaluation of the microstructure. The micrographs were very similar, i.e., similar quantities of ferrite-δ were found in all test specimens.

Results of the susceptibility found through the theoretical evaluation are presented in Table 4. This table also shows (in italic, on the column name row) the limit values of parameters indicating susceptibility to solidification cracking, compiled and weighted from several published sources by other authors. [1, 2, 5,15]

Table 4 lists the FN values in the range of 6 to 10 and classified as primary precipitators of ferrite and austenite solidification. The P+S values were 0.03 and 0.04 and fall within the susceptibility limit. [5] The amount of ferrite-δ measured in the weld metal was the most significant parameter in the classification of susceptibility of these electrodes. The weld metal of the tubular E316LT1-1 and the solid ER316L electrodes exhibited ferrite-δ contents of 6.9% and 7.9%, respectively, classifying them in the transition zone of susceptibility to solidification cracking. [1] The tubular E316LT0-3 electrode, in contrast, showed a 10.9% ferrite-δ content, characterizing it as insusceptible to cracking.

Table 4.
Results of the susceptibility found through the theoretical evaluation

Material	Cr_{eq}/Ni_{eq} *(< 1,9)*	FN *(< 9)*	% (S+P) *($f \rightarrow FN$)*	% Ferrite δ *(< 8)*
ER 316L	1.6	8	0.037	7.9
E316LT1-1	1.6	6	0.042	6.9
E316LT0-3	1.7	10	0.028	10.9

These values indicate that the austenitic stainless steel electrodes tested here lie within the susceptibility transition limit. The ER316L and E316LT1- 1 are classified as having a low susceptibility, and E316LT0-3 does not have susceptibility to solidification cracking.

The results of our theoretical analysis were in complete agreement with those obtained from the transvarestraint test, thus indicating that, if correctly applied, either of these methods can be used to determine the susceptibility of austenitic stainless steels to form solidification cracks. The choice between the experimental or the theoretical method should depend only on the availability and ease of application for each specific case.

4. Conclusions

Based on the experimental and theoretical results discussed here, we can state that:

- The results of the theoretical method are in agreement with those obtained through the experimental method, in which the transvarestraint test was applied, thus confirming the reliability and compatibility of these two methods.
- The choice between the experimental or the theoretical method to evaluate the susceptibility to solidification cracking is only a matter of availability and ease of application for each specific case.
- Regardless of the evaluation method employed, the E316LT0-3 electrode proved insusceptible to solidification cracking, and the ER316L and E316LT1- 1 electrodes were classified as having a low propensity to solidification cracking.

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