FRACTURE TOUGHNESS PROPERTIES IN CORROSION RESISTANT WELDED STEEL JOINTS

Geraldo de Paula Martins
Center for Development of Nuclear Technology – CDTN/CNEN/MG. Rua Professor Mário Werneck, s/ nº. Pampulha. Belo Horizonte, 30123-970, MG, Brasil.
gpm@cdtn.br

Emerson Giovani Rabello
Center for Development of Nuclear Technology – CDTN/CNEN/MG. Rua Professor Mário Werneck, s/ nº. Pampulha. Belo Horizonte, 30123-970, MG, Brasil.
egr@cdtn.br

Carlos Alberto Cimini Jr
Department of Mechanical Engineering - UFMG, Pampulha. Belo Horizonte, 30123-970, MG, Brasil.
cimini@dedalus.lcc.ufmg.br

Leonardo Barbosa Godefroid
Department of Materials Science and Metallurgy Engineering– UFOP. Ouro Preto, MG, 35400-000 Mg, Brasil.
godefroid@barroco.com.br

Abstract. The growing use of steel in civil, mechanical and nuclear constructions is justified by the reduction of labor time and costs due to assembly simplicity. Almost all steel structures and components are manufactured using welding processes, which can introduce some defects (cracks, for instance) on the structure or component. These defects must be evaluated and controlled within allowed levels indicated by the existing codes. Crack propagation resistance of welded joints, one of the major concerns, can be assessed through fracture tests. On these cases, the region next to the melted zone, denominated heat affected zone, is more sensitive to crack initiation and growth, which, means that the crack propagation resistance of this region is a critical parameter to be evaluated. On this work, the crack propagation resistance of the heat affected zone of USI-SAC-50 welded joints is experimentally evaluated on the longitudinal and transversal directions with respect to the weld bead, using the Charpy impact energy and J Integral parameters.

Keywords. Fracture toughness, fatigue crack propagation, heat affected zone, J Integral, Charpy V Notch, mechanical testing.

1. Introduction

Steel use is growing on civil construction, mechanical and nuclear applications, mainly due to the simplicity on building procedures, weight savings and cost reduction. In general, these constructions are exposed to corrosive environment, which requires the selected material to present corrosion resistance. The USI-SAC-50 steel incorporates not only properties of corrosion resistance but also presents good welding characteristics and high strength. It has been used in different applications such as bridges, buildings, offshore platforms, etc.

The most adequate way to join members on the assemblage of grid structures using steel is the welding process. However, welded joints generally present defects that may (or not) affect the structure.

The base metal, during the process of welding, is affected by the thermal cycle imposed by the moving heat source, and will change not only the microstructure but also the mechanical properties in a region close to the weld bead. This region is known as heat affected zone. Generally, near the weld the following regions can be identified (Séferien,1965) as depicted in Fig. (1):

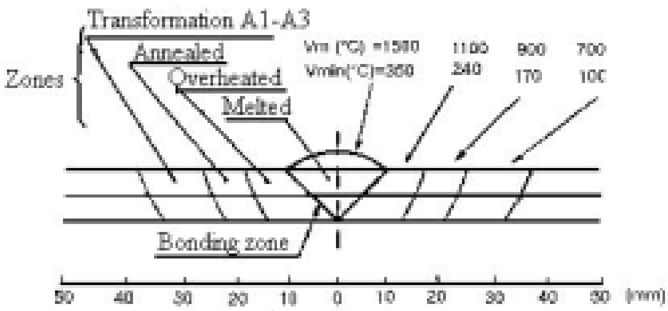

Figure 1. Different regions on a welded joint resultant from the imposed thermal cycle.

- overheated region on the vicinity of the fusion line, where grain growth is exaggerated;
- annealed region correspondent to the temperature range between 1173 K and 1273 K, where a finer grain structure is observed;

- transformation region with temperatures approximately between 993 K and 1183 K, where secondary phenomena occur depending on the chemical composition of the steel.
- region not affected by the heat, corresponding to the base metal with temperatures lower than 993 K.

Crack propagation resistance is evaluated from fracture toughness parameters obtained in fracture mechanics tests. These parameters are: K_{IC} obtained for plane strain conditions in materials presenting linear elastic behavior; CTOD (Crack Tip Opening Displacement) and J_{IC}, respectively crack tip opening displacement and J Integral, obtained for plane stress conditions materials presenting elasto-plastic behavior. Such parameters are obtained by means of standardized tests. Existing standards do not consider welded joints. However, it can be found in literature several works concerning the determination of fracture toughness parameters for welded joints, among them Barson & Rolfe (1998) and Kocak, Kim & Hornet (1998).

Anderson (1995), discussing the paper of Rice (1968), presents the J Integral as a characterization parameter of the stress field around the crack in non-linear materials. This characterization is done by means of a path integral on a trajectory around the crack, initiating and finishing on the crack surfaces and including the crack tip. Eq. (1) defines the J Integral:

$$J = \int_{\Gamma} \left(w dy - T_i \frac{\partial u_i}{\partial x} ds \right) \qquad (1)$$

where:

x, y – rectangular coordinates ahead of the crack;

w – strain energy density $w = \int \sigma_{ij} d\varepsilon_{ij}$;

T_i – traction vector on the contour;

u_i – displacement vector; and

ds – incremental line along the contour (Fig. (2)).

According to Anderson (1995) and Hertzberg (1995), Rice (1968) showed that the result of this integral is equal to the stress release rate for a non-linear body with a crack. Therefore, it may be concluded that the stress release rate for linear materials is the same as for non-linear materials. The relationship depicted on Eq. (2) is thus verified:

$$\mathrm{J} = \frac{\mathrm{K}_\mathrm{I}^2}{\mathrm{E}} = \frac{\pi \sigma^2 a}{\mathrm{E}} \qquad (2)$$

where:

σ – applied stress;
a – crack length;
E – Young's modulus;
K – stress intensity factor.

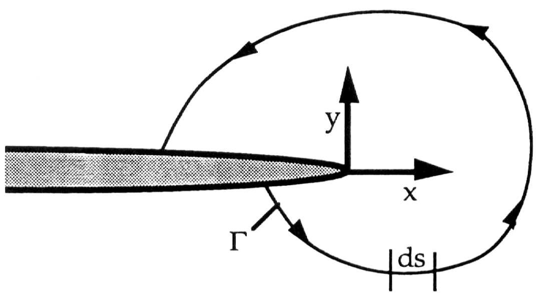

Figure 2. Arbitrary path around crack tip.

Failure occurs when J assumes a critical value. Tests on cracked specimens are used to establish the critical value for J, for this case represented by J_{IC}, as described on the standard ASTM E 1820 (2000). Since the majority of construction steels present a elasto-plastic behavior, i.e., admit a reasonable plastic deformation before failure in service, fracture mechanics tests indicated are CTOD tests and J Integral tests. These are specific tests to determine the crack propagation resistance for elasto-plastic materials. The methodology for experimentally obtaining the values for J Integral is described by the standard ASTM E 813 (2000), and ASTM E 1820 (2000) which defines:

$J_i = J_{el(i)} + J_{pl(i)}$ (3)

Equation (3) defines J Integral value at a point on the load-displacement curve, corresponding to the load P and the displacement δ_i . J Integral can be divided into an elastic part J_{el}, and a plastic part J_{pl}. For pure bending and for three-point bending, using a span-width ratio of 4 (Herzberg, 1995), J is given by:

$$J_i = \frac{K_i^2}{E}(1-\nu^2) + \frac{2A_i}{Bb} \quad (4)$$

where the first term of the right-hand side represents the elastic part of J (J_{el}) and the second term represents the plastic part of J (J_{pl}) as separated on Eq. (3). A_i is the area under the load-displacement curve on the load point, B is the specimen thickness and b is the remaining uncracked ligament length. Figure (3) shows the curves obtained for J Integral evaluation tests in two situations: (a) constant displacement and (b) constant load.

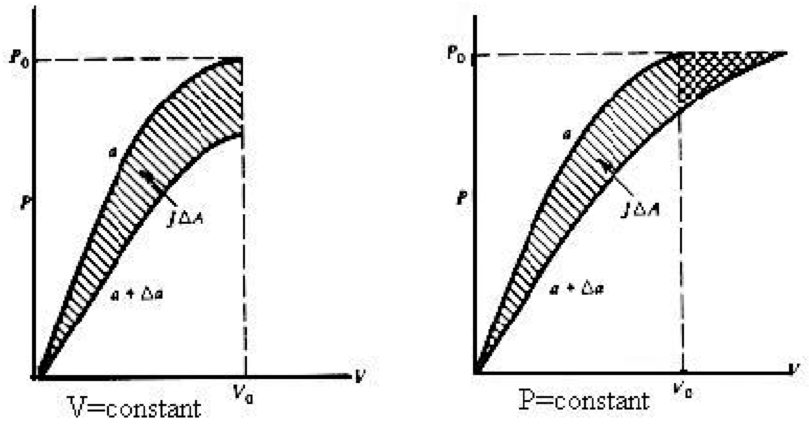

Figure 3. Graph for J Integral evaluation tests.

2. Materials and method

The steel employed in this study is the USI-SAC-50, presented on laminated sheets of 12 mm and 19 mm thickness. Chemical composition data given by the manufacturer is listed on Tab. (1). This steel is resistant to environment corrosion and thus indicated to be used in bridges and buildings exposed to atmospheric corrosion. Welded joints were prepared using shielded metal welding arc process with covered electrode. Weld beads were made aligned with the sheet lamination direction on ½V butt joints so that the heat affected region is the same through the thickness.

Weld parameters were used as follows: (i) 19 mm thickness sheet: 12 passes (20 V tension and 120 A current for the first two passes and 22 V and 230 A current for the others) using covered electrode E-7018 (3.25 mm diameter for the first two passes and 5 mm diameter for the others); and (ii) 12 mm thickness sheet: 6 passes at 20 V tension (110 A current first two passes and 220 A current for the others) using covered electrode E-7018 (3.25 mm diameter for the first two passes and 5 mm diameter for the others).

Reduced scale round specimens were prepared for tensile tests according to ASTM E 8M (ASTM, 2000) (3 transversal to the weld bead and 3 longitudinal to the weld bead). Specimens were machined with circular section along the sheet thickness. Gage section for tensile test specimens machined from 12 mm thickness sheet were 45 mm length and 6 mm diameter. For specimens machined from 19 mm thickness sheet, the gage section presented 60 mm length and 8.75 mm diameter. Charpy impact test specimens were manufactured according to ASTM E 23 (ASTM, 2000). J Integral specimens were produced according to ASTM E 813 (ASTM, 2000). Notches for Charpy impact test specimens and for J Integral test specimens were located on the heat affected zone according to T-L and T-S orientations, so that the effect of weld orientation on crack propagation could be inferred. Fatigue pre-cracking and J Integral tests were performed on an Instron universal load testing machine with capacity of 250 kN. J Integral tests for fracture toughness evaluation on elasto-plastic regime were conducted at room temperature (298 K). Specimen type used bar geometry with square cross section. Dimensions were (thickness B, width W and length L): B = 10 mm, W = 10 mm and L = 60 mm for 12 mm thickness sheet and B = 18 mm, W = 18 mm e L = 90 mm for 19 mm thickness sheet.

Table 1. Chemical composition of the USI-SAC 50 steel (12 mm and 19 mm thickness).

Chemical composition (%)											
Thickness (mm)	Element										
	C	Mn	Si	P	S	Cu	Al	Nb	Ti	Cr	Ni
12	0.12	1.13	0.34	0.024	0.013	0.26	0.037	0.022	0.009	0.44	0.20
19	0.12	1.14	0.29	0.021	0.012	0.30	0.033	0.024	0.014	0.47	0.17

3. Results and discussion

3.1 Tensile tests

Average values for the tensile tests are presented on Tab. (2). As it can be observed, values for tensile yield stress (σ_y) and for tensile ultimate stress (σ_u) for the longitudinal orientation along the weld bead are higher than the corresponding values for the transversal orientation. Failure occurred at the base metal for specimens with the transversal orientation, thus indicating that the strength of the weld is higher than the strength of the base metal.

Table 2. Tensile test results.

		Thickness			
		12 mm		19 mm	
Orientation	Transv	σ_y (MPa)	σ_u (MPa)	σ_y (MPa)	σ_u (MPa)
		480 ± 8	598 ± 8	403 ± 5	546 ± 6
	Longit	σ_y (MPa)	σ_u (MPa)	σ_y (MPa)	σ_u (MPa)
		534 ± 14	689 ± 8	583 ± 13	652 ± 12

3.2 Charpy impact tests

Charpy impact tests were performed in the temperature range between 77 K to 468 K, with notches located on the heat affected zone, with orientations T-L and T-S. Results (CVN – Charpy V-Notch) for room temperature (298 K), determined using the data adjust equation are presented on Tab. (3). It can be observed higher energy values for T-S orientation specimens when compared to T-L orientation specimens.

Table 3. Charpy impact test results.

CVN (J)		
	Thickness	
Orientation	12 mm	19 mm
Longitudinal (T-L)	63.4	67.4
Transversal (T-S)	83.1	76.4

3.3 J Integral tests

Table (4) shows the results from the J Integral test program. Tests were performed according to the standards ASTM E 1820 (ASTM, 2000) and ASTM E 813 (ASTM, 2000).

From Table (4) it can be observed that J Integral test results T-S orientation notched specimens are higher than for T-L orientation notched specimens for both 12 mm and 19 mm thickness sheets. Thickness was reduced from 12 mm to 10 mm and from 19 mm to 18 mm due to specimen machining, necessary to match the standard requirements.

Table 4. J Integral test results.

Thickness (mm)	Orientation	CP	J (kN/m)	Average ± Std. Deviation
10	T-L	G1	87.83	81.34 ± 4.89
		G2	80.35	
		G4	75.39	
10	T-S	G8	136.95	120.23 ± 11.89
		G9	113.36	
		G12	110.37	
18	T-L	F1	107.36	96.26 ± 871
		F2	99.08	
		F3	83.15	
		F4	95.43	
18	T-S	F6	167.09	176.34 ± 10.07
		F8	187.15	
		F9	165.51	
		F10	185.61	

Results for Charpy impact tests and J Integral tests presented coherence concerning specimen orientation. Comparing these results, it can be observed higher fracture toughness for T-S specimens when compared with T-L specimens indicating that a crack on the heat affected zone will grow easier on the longitudinal direction than through the thickness. Since the values of fracture toughness are high, compared with the results obtained by Araujo (2002), in SAC-50 base metal (99.4 kN/m) it can be inferred that the heat affected zone of welded joints of USI-SAC-50 steel are resistant to crack propagation for existent cracks on a structure made of this material. Araújo et al. (2002) conducted a crack propagation J Integral and CTOD test program on welded joints of USI-SAC-50 steel specimens prepared from a 12 mm thickness laminated sheet with notches on the base material, heat affected zone and weld metal, using minimum-to-maximum load ratios of 0.3 and 0.7 for fatigue crack propagation test. They concluded that the weld metal presented the highest crack propagation resistance followed by the heat affected zone and by the base material.

4. Conclusion

From the material previously exposed the following conclusions may be established:

1. Results obtained for J Integral tests are compatible with energy results obtained from the Charpy impact tests;
2. Both J Integral tests Charpy impact tests presented higher crack propagation resistance for cracks propagating through-the-thickness direction than for longitudinal direction;
3. An existing crack on a USI-SAC-50 steel structure tends to propagate along the longitudinal direction;
4. Higher values obtained for J_{IC} indicate that the studied material presents a considerable resistance to crack propagation.

5. References

American Society for Testing and Materials, Standard Test Method for Measurement of Fracture Toughness. ASTM E 1820-96, 1998.

American Society for Testing and Materials, Standard Test Method for J_{IC}, a Measure of Fracture Toughness. ASTM E 813-89, 1998.

American Society for Testing and Materials, Standard Test Method for Tension Testing of Metallic Materials. ASTM E 8 M-98, 1998.

American Society for Testing and Materials, Standard Methods For Notched Bar Impact Testing of Metallic Materials. ASTM E 23-81, 1998.

Anderson, T.L., *Fracture Mechanics: Fundamentals and Applications*, 2ª ed. CRC Press Inc., Boca Raton, 1995.

Araújo, J.G., Martins, G.P., Godefroid, L.B. and Cândido, L.C., "Tenacidade à Fratura e Resistência à Fadiga de Junta Soldada de Aço para Construção Civil", *Proc. 57th Annual Conference of the Brazilian Society of Metallurgy and Materials*, CD-ROM, , São Paulo, Brazil, 2002.

Barson, J.M. and Rolfe, S.T., *Fracture and Fatigue Control in Structures – Applications of Fracture Mechanics*, 3ª ed., ASTM (American Society for Testing and Materials), 1998.

Hertzberg, R.W., *Deformation and Fracture Mechanics of Engineering Materials*, 4ª ed. John Wiley and Sons, Inc., New York, 1995.

Kocak, M., Kim, Y. J. and Hornet, P., *Recommendations for J and CTOD Testing of Strength Mis-Matched Weldments*, GKSS and EDF View, France, 1998.

Rice, J.R., " A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks", *Journal of Applied Mechanics*, Vol. 35, 1968, pp. 379-386.

Séferien, D., *Métallurgie de la Soudure*, Dunod, Paris, 1965.

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