

## 10. APPENDIX A

### Circular Patch Test

#### 1. Introduction

A Circular Patch Test (CPT), see Fig. 1, was selected to evaluate sensitivity to hot crack formation of the welds made with the materials used in the construction of the Research Reactor Pool Liner (RPL). The materials samples for evaluation were; 6 mm thick AISI 304L stainless steel plate, and a 2.4 mm diameter AWS A5.9 ER308LSi filler rod supplied by the Fabricator. Welding parameters used during welding of the CPT samples covered the range of parameters recommended in the welding procedure specifications; WPS C1/309 Rev 2, WPS C1/328 Rev 2 and WPS C1/331R. Potential delta ferrite content was predicted for the all materials used in construction of the research pool liner with use of the method recommended by WRC and is shown in Table 2.

#### 2. Sample preparation

A sample for CPT consists of a plate of 100 x 100 x 6 mm with a central hole of 50.8 mm diameter and clamping holes of 12 mm diameter at each corner of the plate as shown in Fig. 2. A disc of 49.8 mm diameter, of the same thickness, with a centre hole of 12 mm diameter fits into the plate hole (see Fig. 2). Both the plate and disc were made of the AISI 304L plate supplied for the testing. The edge of the hole in the sample plate and outer edge of the disc patch were prepared in such a way that square butt or single Vee welds could be completed.

#### 3. CPT Welding Procedure

The plate and disc were placed in a jig between the top and bottom copper plates and bolted firmly together with four bolts as shown in Fig. 1 Each bolt was tightened with a controlled torque of 35 ft-lbf (4.84 kgfm) to achieve the maximum restraint in the sample plate during welding. The amount of restraint in the CPT welds decreases with increased radius of a circular weld, root gap of the weld and decreased heat input<sup>1</sup>.

The test welds were welded with a gas tungsten arc welding (GTAW) method and the parameters shown in Table 1. The sample plate temperature was measured with a touch probe before and after welding. Technical grade Argon (99.99% Ar) was supplied to the welding torch and the CPT jig to shield the face and root of the weld during welding. Filler material was manually fed to the weld pool during welding. Both square butt and single Vee weld configuration welds were used in welding tests. In addition to these, a single Vee weld in the upside down position was used to simulate a penetration weld made from the other side of plate. This was thought to simulate the bottom part of the single Vee welds made during simultaneous welding from both sides, see WPS WPS C1/328 Rev 2. All the welds made in the CPT test were cleaned by pickling (in whata solution containing 10% of nitric and 1.2% of hydrofluoric acid) to remove surface oxides and were visually examined after welding.

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<sup>1</sup> Nelson T. W. et al: Evaluation of the Circular Patch Test for Assessing Weld Solidification Cracking, Part 1 – Development of a Test Method, *Welding Journal*, March 1993, pp. 110s-118s.

#### 4. Delta Ferrite Content

Potential delta ferrite content was predicted, see Table 2, for the all materials used in construction of the research pool liner with use of the method recommended by WRC<sup>2</sup>. Delta ferrite content in the welds made in the CPT weld samples was measured using a FERRITSCOPE MP30 tester of Helmut Fisher GMBH + Co, Germany.

#### 5. Metallographic Examination

Transverse sections of the CPT welds were extracted from the CPT welds; see Fig. 3 and Fig. 4, for metallographic examination to evaluate changes in the heat affected zone caused by welding. The conventional ASTM A262-02a<sup>3</sup> Practice A was used for detecting changes in the HAZ of the CPT welds. The test method consisted of polishing the sample to a final finish of 1  $\mu\text{m}$  and electrolytic etching in a 10 wt-% solution of oxalic acid for 1.5 minutes at a current density of 1  $\text{A}/\text{cm}^2$ . The etched surface was examined at a magnification of 620 times and resulting structure was classified depending upon the amount of intergranular etching that was observed.

These included:

- step structure; steps only between grains, no ditches at grain boundaries,
- dual structure; some ditches at grain boundaries, but no “single grain” completely surrounded by ditches,
- ditch structure; one or more grains “completely” surrounded by ditches<sup>3</sup>.

Photographs of the examined areas are shown in Figs. 5 to 10.

#### 6. Discussion

No cracks were detected in the CPT weld samples welded with the parameters shown in Table 1. This resulted from very high ferrite contents measured in the test welds, ranging from 6.1 FN to 8.5 FN. The highest ferrite content (8.5 FN, Sample 1, Table 1) was measured in the welds made with the lowest heat input of 1.62 kJ/mm and the lowest in the welds made with the highest of 2.04 kJ/mm (6.1 FN, Sample 8, Table). Similar trends were observed in the autogenous welds (Test 9 and 10 in Table 1) made on the base material (AISIA 304L). These contained 6.1 FN and 5.6 FN with 2.05 kJ/mm and 2.49 kJ/mm respectively. This indicates that increased heat input results in decreased ferrite content in the welds. This is in good agreement with similar observations made by Vitek et al<sup>4,5</sup>.

It has to noted that delta ferrite content depends also on the amount of the filler wire add to the weld. Therefore, the weld in Sample 4 (8 FN) and 5 (7.5 FN) made with more filler material added to the weld contain more delta ferrite even though the heat input was higher 3.23 kJ/mm

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<sup>2</sup> Kotecki D. J. and Sievert T. A.; WRC-1992 constitution diagram for stainless steels weld metals: a modification of the WRC-1988 diagram, *Welding Journal* 71, 1992, pp. 171s – 178s.

<sup>3</sup> ASTM A262 – 02a: Standard Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels, Published in 2002.

<sup>4</sup> Vitek J. M. et al; Improved ferrite Number Prediction Model that Accounts for Cooling Rate Effects – Part 1: Model development, *Welding Journal*, January 2003, pp. 10s – 17s.

<sup>5</sup> Vitek J. M. et al; Improved ferrite Number Prediction Model that Accounts for Cooling Rate Effects – Part 2: Model Results, *Welding Journal*, February 2003, pp. 43s – 50s.

Predicted ferrite content for base material used for construction of the RPL is also very high, ranging from 7.4 FN to 9.2 FN for AISI 304L 6 mm thick steel and 11.7 FN for 12 mm thick steel, and even higher for the filler materials 9.2 FN and 13.7 FN for ER308LSi (Lot No.29020) and ER308LSi (Lot No. 5225) respectively, see Table 2.

Various amount of intergranular etching, due to the oxalic acid attacking the chromium rich phases, was observed in the welds made with the heat inputs ranging from 1.8 kJ/mm to 3.23 kJ/mm. In the HAZ of the welds, made at 1.8, 2.05 and 3.23 kJ/mm, close to the weld fusion line (FL) only step structures were observed; see Figs. 5, 7 and 9. Further from the FL, however, step + dual or dual + step structures were observed, but no single grain was completely surrounded by ditches, see Figs. 6, 8 and 10. This indicates that both the high restraint applied to the weld in the CPT test, and the high heat input contributed to increased sensitivity of the grain boundaries to etching in certain areas in the HAZ. All of the samples prepared by etching in a 10% solution of oxalic acid as specified by ASTM A 262 – 02a Practice A, according to classifications given in Table 3, 4, 5 and 7, for Practices B, C, E and F, are acceptable without further testing.

However, it is assumed that a further increase in sensitivity to etching could be expected with multiple run welds as indicated in the relevant literature<sup>6</sup>. It is difficult at this stage to explain why these areas are more sensitive to etching. Possible explanations include:

- higher density of dislocations (higher stresses in these areas of HAZ) in the areas which are more easily attacked by etching solution,
- higher concentrations of chromium in these areas which are more prone to etching (This increased chromium could be due to carbide precipitation in these areas).

Similar observations of the base material in the as-received condition (see Fig. 11) and also after heavy deformation caused by hammering (see Fig. 12) showed no increased sensitivity to grain boundary etching. Further investigation (elemental mapping) is to be carried out to determine the reason for the observed sensitivity of grain boundaries to etching. All of these structures observed on the samples exposed to etching in 10% solution of oxalic acid as specified by ASTM A 262 – 02a, Table 3, 4, 5 and 7, are acceptable without further testing for intergranular corrosion.

## 7. Conclusions

The following conclusions can be drawn from the CPT weld tests:

1. No hot cracking was observed in the welds made with the heat input ranging from 1.62 to 3.23 kJ/mm.
2. Ferrite content in the welds decreased from 8.5 FN to 6.1 FN as the heat input was increased from 1.62 kJ/mm to 3.23 kJ/mm.

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<sup>6</sup> Lundin C. D. et al: Sensitization of Austenitic Stainless Steels; Effect of Welding Variables on HAZ Sensitization of AISI 304 and HAZ Behaviour of BWR Alternative Alloys 316NG and 347, WRC Bulletin 319, November 1986.

3. Various amounts of intergranular etching were observed in the HAZ of the CPT welds depending upon both the distance from the weld fusion line, and the heat input.
4. Increased sensitivity to grain boundary etching increased with increased heat input from 1.8 kJ/mm to 3.23 kJ/mm.

**Table 1 GTA Welding parameters used for CPT**

Test No.1	Current A	Voltage V	Edge Preparation	Ts/Tf °C	Travel Speed mm/min	Heat Input kJ/mm	Crack length, mm	Ferrite Content FN				Metallography
								FN (M)	Crater	Base Material	FN (C)	
1	110	10.8	SB	55/87	44.05	1.62	Nil	8.5	4.1	0.67	9.4	
2	110	12	SB	27	44.05	1.80	Nil	8.3	4.1	0.62	9	Y
3	110	12	SV	58/120	44.05	1.80	Nil	8.5	4.7	0.66	9	
4	190	12.5	SB	82.14	44.05	3.23	Nil	8.0	4.8	0.74	6.3	Y
5	190	12.5	SV	73/130	44.05	3.23	Nil	7.5	4.9	0.67	6.3	Y
6	120	12.5	SB	78/125	44.05	2.04	Nil	7.2	4	0.52	8.4	
7	120	12.5	SV^	70/130	44.05	2.04	Nil	6.9	4	0.60	8.4	
8	165	14	SV^	50/120	68.08	2.04	Nil	6.1	4	0.59	8.4	
9	165	14.1	BOP	20/130	68.08	2.05	-	6.1	3.9	0.59	8.4	Y
10	200	14.1	BOP	20/140	68.08	2.49	-	5.6	4.1	0.67	7.5	Y

SB - Square Butt

SV - Single Vee

SV^ - Single Vee upside down

BOP - Bead on Plate Weld

Ts – Sample temperature (Before welding)

Tf – Sample temperature (End of welding)

FN (M) – Measured Ferrite Number

FN (C) – Calculated Ferrite Number for the test heat input

**Table 2 Composition of materials used for the Reactor Pool Liner and predicted Ferrite Number**

Material Heat Number	C	Cr	Ni	Mo	N	Mn	Fe	Si	Cu	Nb	Co	FN (WRC)
AISI 304l (6 mm) 820045 L. 001	0.024	18.19	8.14	-	0.066	1.65	71.177	0.35	0.32	0.003	0.08	7.4
AISI 304l (6 mm) 820152 L. 003	0.022	18.20	8.12	-	0.07	1.72	71.126	0.35	0.2	0.002	0.19	7.6
AISI 304l (6 mm plate) 820586 L. 002 ***	0.019	18.19	8.29	-	0.068	1.68	71.061	0.32	0.25	0.002	0.12	7.4
AISI 304l (12 mm plate) 0037CT7570	0.019	18.6	8.25	-	0.04	1.62	70.961	0.51	-	-	-	11.7
AWS A5.9 ER308LSi 455960 L. 29020 ***	0.011	19.73	10.49	0.32	0.053	1.95	66.335	0.84	0.16	0.053	0.058	9.2
AWS A5.9 ER308LSi L. No. 5225 (2.4 mm diameter rod)	0.010	19.81	10.05	0.20	-	1.65	67.34	0.80	0.12			13.7

\*\*\* - Batches used for the CPT test