Effect of Welding Variables on Cooling Rate and Pitting Corrosion Resistance in Super Duplex Stainless Weldments

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This work was carried out to investigate the effect of welding variables (includes wire feeding techniques, wire feeding rates and heat inputs) on the cooling rate, $\Delta t_{8/5}$ (cooling time from 800 to 500°C), in the weld and heat affected zone (HAZ) areas of multi-pass weldments in a super duplex stainless steel. Furthermore, changes in thermal condition caused by welding variables can affect the microstructure and consequently the material properties. Therefore, supporting tests, including pitting corrosion resistance and microstructure analysis were investigated.

To establish the effect of welding variables on the cooling rate, a series of weldments using a semi-automatic welding process which is enable the control of welding variables such that one parameter can be varied at a time were completed. The method used for pitting resistance tests was the basic ASTM G48-76 standard, with reference to the ASTM A923-94 standard and recommended practice for pitting corrosion tests for duplex stainless steel weldments by the use of ferric chloride solution from The Welding Institute (TWI). Microstructure Analysis was carried out using a Buehler Omnimet Image Analysis System and a manual point counting technique with reference to ASTM E562-89 (Standard test method for determining volume fraction by systematic manual point count).

From these tests results, various empirical correlations have been proposed to relate the cooling rates and pitting corrosion resistance to the welding variables.

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1. Introduction

The so-called Duplex Stainless Steels (DSS's) consist essentially of ferrite and austenite with an approximately 50/50 mixture of the two phases.^{1,2)} A new class of DSS, the super duplex stainless steel (SDSS, contains around 25% Cr and has pitting resistance equivalent numbers greater than 40), has also been developed with a better corrosion resistance than the conventional DSS.

Over the past decade, the use of super duplex stainless steels has increased rapidly for demanding applications because of their combination of corrosion resistance, strength and toughness. This increased use of super duplex steels has led to the concern of welded joints with acceptable corrosion resistance and mechanical properties.³⁾ Understanding that controlling phase balance becomes crucial to achieve the goals.

To control the phase balance, in the past, procedures for welding super duplex stainless steels have emphasized the importance of controlling heat input to the weld. Recent experience has shown that a more important parameter for controlling the phase balance in weldments is the cooling rate.⁴⁻⁶⁾ This in turn dictates the heat input range to be used.

In practice, the cooling rate depends on a number of variables,⁷⁻¹¹⁾ for example heat input, process efficiency, material properties, preheat temperature, material thickness and wire feeding rate.

Rosenthal developed an equation^{2,3)} for predicting cooling rates and peak temperatures in heat affected zones (HAZ) of a weldment. Based on Rosenthal's equation, many computer programs and simulation models have been developed to investigate the effect of welding variables on the thermal characteristics in the HAZ.¹¹⁾ However, there are potential inaccuracies within these methods. The most significant

potential inaccuracy is the arc efficiency, *i.e.* the amount of heat transferred into the weldment as compared to the theoretical heat input available.¹¹⁾ Many investigations¹²⁻¹⁸⁾ indicate that the value of arc efficiency is variable and can depend on a number of factors *e.g.* welding process,¹²⁾ welding current,¹⁶⁾ welding speed,¹⁷⁾ arc length¹⁸⁾ and polarity.⁸⁾

Therefore, to eliminate the potential accuracies, this study has been carried out to experimentally investigate the effect of the welding variables (includes heat inputs, wire feeding techniques and wire feeding rates) on the thermal characteristics in the weldment. To enable the control of welding variables such that one parameter can be varied at a time to establish its effect on the thermal characteristics, a series of weldments using a semi-automatic welding process were completed. The critical pitting temperatures (CPT's) of the weldments were then determined in 10% FeCl₃.6H₂O solution, essentially following the ASTM Standard G48-76,¹⁹⁾ ASTM standard A923-94²⁰⁾ and recommended practice for pitting corrosion tests for duplex stainless steel weldments by the use of ferric chloride solution from The Welding Institute (TWI).²¹⁾ From these results, various empirical correlations were proposed to relate the pitting corrosion to the welding thermal cycles.

2. Equipment and Experimental Method

2.1 The choice of materials

2.1.1 Parent materials

Zeron100 super duplex stainless steel containing 25% Cr and pitting resistance equivalent (PREN) value greater than 40, are available in many product forms and are extensively utilized in the oil and gas industry for a wide range of applications because of their very good corrosion resistance,

Table 1 Chemical composition which has been classified in Zeron 100 pipe.

Chemical Compositions of Zeron 100 pipes												
	C	Si	Mn	S	P	Cr	Ni	Mo	W	Cu	N	Fe
Min.						24	6.0	3.0	0.5	0.5	0.2	
Max.	0.03	1.0	1.0	0.01	0.03	26	8.0	4.0	1.0	1.0	0.3	Bal.

Table 2 Chemical composition specified for Zeron 100X.

Chemical Composition of Zeron 100X											
	C	Mn	Si	S	P	Cr	Ni	Mo	W	Cu	N
Min.	—	—	—	—	—	24	9.0	3.0	0.5	0.5	0.2
Max.	0.03	1.0	1.0	0.01	0.03	26	10.0	4.0	1.0	1.0	0.3

high strength and good strength to weight ratio.^{1–5}) In this study, an 88.9 mm (3") O/D pipe with a wall thickness of 7.5 mm was used for this study. Table 1 shows the chemical compositions which have been classified in Zeron 100 pipe.

2.1.2 Welding consumable

Over the years, experience has shown that Zeron 100x is the most suitable consumable for welding super duplex stainless steels (SDSS). Table 2 is a summary of chemical composition specified for this type of consumable.

2.2 Parameters for welding processes

In this study, the pulsed TIG welding process, using pure argon shielding gas with a constant flow rate of 20 cubic feet per hour (cfh), is employed to study the effect of welding variables on the SDSS weldments. Detailed information related to the welding variables is described as follows:

2.2.1 Heat inputs

Using the single pass welding process, repeated tests were carried out to obtain a possible range of heat inputs which would allow higher peak temperatures in the HAZ, without over penetration in the weldment. Test results have shown that a possible range of heat inputs from 1.1–1.8 kJ/mm would be suitable for the joint geometry design for the welding measurement. Three selected heat inputs, 1.1, 1.4, and 1.8 kJ/mm, were therefore employed in the study. Table 3 presents the applied heat inputs and their parameters (voltage, current, and welding speed) which are used to the heat input calculation.

2.2.2 Wire feeding rate

In the past, the wire feeding rate was not viewed as a welding variable for the fusion welding process. Recent experience^{4,22}) suggests that this may actually affect micro-structure, mechanical properties and corrosion resistance of

Table 3 Applied heat inputs and their parameters used to the heat input calculation.

Current I/A	Voltage V/V	Welding Speed v/mm.min. ⁻¹	Heat Input q/kJ.mm ⁻¹
80	9.0	39	1.1
95	9.7	39	1.4
116	10.4	39	1.8

the welded metal. It has also been reported by Dorsch²²) that cooling rates can be affected by wire feeding rate, which may attribute to the better heating efficiency of the parent material. Therefore, the effects of wire feeding rate on the thermal characteristics were investigated in this study.

In this study, the wire feeding rate was controlled by the various wire feeding techniques and rotating equipment (this also control of the welding travel speed). To more easily control the wire feeding rate, the welding speed was fixed at 39 mm/min and weld wire feeding rates were varied directly by means of the wire feeder.

However, the real wire feeding rates, which were obtained by measuring the weight difference between the welded pipe and un-welded pipe, are shown in Table 4.

2.2.3 Wire feeding techniques

From earlier studies, various empirical correlations^{23,24}) were proposed using the weld bead area to determine the cooling rate. This poses the question as to whether the welding cooling rate was affected by the wire feeding technique or not. Therefore in the study, three wire feeding techniques which demonstrated the different mechanisms for the formation of the weld were applied to investigate their effect on cooling rate, they are:

1. Weld completed without using consumable.
2. Filler wire feed into the front of the weld pool.
3. Filler wire feed into the back of the weld pool and oscillated.

2.3 HAZ thermal cycle measurement procedures

To satisfy the requirements of quasi-stationary state heat flow, the welding arc must continue to move at constant velocity as weld solidification and temperature changes are being measured.⁸) Apparatus was designed and built to accomplish this requirement which is shown as Fig. 1. In this design, the pipe was rotated by an A & N Plant GP 150-6 Rotating & Positioning Equipment, which maintains a constant rotating and welding speed and a fixed welding head in down-hand position, which maintains a constant weld heat input. In order to correctly calibrate the current and voltage, it is required to evaluate the heat input during the

Table 4 Range of wire feeding rates and wire feeding techniques.

Set No.	H.I at 1.1 kJ mm ⁻¹				H.I at 1.4 kJ mm ⁻¹						H.I. at 1.8 kJ mm ⁻¹				
	11a	11b	11c	11d	14a	14b	14c	14d	14e	14f	18a	18b	18c	18d	18f
Feeding method	N	F	OB	OB	N	F	F	OB	OB	OB	N	F	F	OB	OB
Depos. rate W/g.h ⁻¹	0	32	38	130	0	79	97	143	181	214	0	52	184	221	228

H.I—Heat Input, N—None filler wire was applied, F—Filler wire fed into the front of the weld pool, OB—Filler wire fed into back of weld pool and oscillated.

Fig. 1 The equipment configuration for weld HAZ thermal cycle measurement.

welding process. The PAMSII system, with an optional extra to accept AC and DC TIG welding processes was used. To allow a repeatable quantity of filler material to be placed between the faces of the two pipes during the multi-pass process, a wire feeder was applied. The oscillator is employed to distribute the heat and help to obtain better edge fusion. By selection of appropriate parameters, oscillation speed, oscillation width, and dwell period used at the each end of oscillation, higher allowable wire feeding rates can be achieved.⁸⁾ In this study, a simple U butt joint (see Fig. 2) was used. The thickness of root face was machined to 4 mm which allows a wide range of heat inputs to be applied for the first pass weld without over penetration and keeps the weld above the root of the pipe. In recent years, there has been a great increase in the number of data gathering systems available which can be easily interfaced with computer based equipment.²⁵⁾ A modified design, with an innovative data logger system and software, was developed and applied.

To establish the effect of welding variables on the cooling rate, thermal cycle measurements were conducted on various multi-pass welds with different wire feeding rates, wire feeding techniques and heat inputs. The parameters used for this study are all shown in Tables 3. The first run was made with a range of different heat inputs, without any filler and at room temperature (25°C). This heated up the weld area. The second pass was started when the temperature had dropped to an acceptable interpass temperature, 100°C using the same heat input as the first pass. Figure 3 shows an example of the thermal cycles collected from a weld with a heat input of

Fig. 3 An example of measured welding thermal cycle.

Fig. 4 The positions and size of holes for the thermocouples.

1.4 kJ/mm and a 79 g/h wire feeding rate. Four holes were drilled at the 3 O'clock position shown in Fig. 4 to embed the thermocouples. These were drilled half the depth (4 mm deep for 7.5 mm thick pipe) of the plate. Thermocouples were installed at various locations expected to be just outside the fusion pool boundary. These studies support the experimental findings of earlier research that $\Delta t_{8/5}$ (cooling time from 800 to 500°C) is independent of the distance from the weld centre line,¹²⁾ and confirm further studies²⁶⁾ suggesting that $\Delta t_{8/5}$ readings only varied within 5% in all individual tests when all three thermocouples were recording.

2.4 Method used for pitting resistance tests

The method used for pitting resistance tests was the basic ASTM G48-761⁹⁾ standard (Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels

Fig. 2 Joint geometry design for multi-pass welding measurement.

Fig. 5 (a) samples cut from pipe using appropriate radial cuts. (b) test specimens machined with a test face size of 50 mm × 25 mm.

and Related Alloys by the Use of Ferric Chloride Solution), with reference to the ASTM A923-94²⁰⁾ standard (Standard Test Methods for Detecting Detrimental Intermetallic Phase in Wrought Duplex Austenitic/Ferritic Stainless Steels) and recommended practice for pitting corrosion tests for duplex stainless steel weldments by the use of ferric chloride solution from TWI.²¹⁾

Following the completion of the welding process, two samples were cut from pipe using appropriate radial cuts (see Fig. 5a). The test specimens were machined with a test face size of 50 mm × 25 mm (see Fig. 5b). The sides and ends of the specimens were then ground to remove any machining marks using a 1200 grit finish. The specimens were then weighed using a balance capable of ±1 mg accuracy.

The tests were performed using ferric-chloride solution (made up from 100 g of FeCl₃·6H₂O and 20 g of Na₂EDTA·2H₂O per 99 mL of distilled water) with a volume based on the larger (20 L/m²) of the specimen surface areas. Each specimen and solution was contained in a tall-form glass beaker with a capacity of 1 L. The beaker and solution were covered with a watchglass and placed in a water bath pre-heated to within ±0.5°C of the specified test temperature. The specimen was placed in the glass cradle at an angle of approximately 45° to the vertical and immersed in the test solution for 24 hours.

At the end of the 24-h test period, the specimens were removed from the solution, rinsed with water, scrubbed with a soft bristle brush under running water to remove corrosion products, dipped in acetone and dried in air. With reference to the recommended practice from TWI,²¹⁾ if the specimen has gained weight or lost ≤20 mg it was considered to have passed the test.

In this study, the initial test temperature was 40°C subsequent temperatures being at 2.5°C intervals. The critical pitting temperatures were established by holding samples in the solution for 24 h periods at progressively higher temperatures until samples failed to conform to acceptance values of pitting resistance.

3. Experimental Results and Discussions

3.1 Cooling rate measurement

As indicated previously, the welding variables, heat input, wire feeding rate and wire feeding technique, which may

Fig. 6 Effect of filler addition and heat input on the cooling time, $\Delta t_{8/5}$ (The 2nd pass weldment).

contribute to alternations to the cooling rate of the weld were incorporated into the experimental measurements. The effects of welding parameters are thus illustrated as follows:

3.1.1 Effect of wire feeding rate

From Fig. 6, for a given wire feeding technique, the cooling time, $\Delta t_{8/5}$ was not significantly affected by the wire feeding rate. This may be caused by the similarity of thermal properties between the parent material and consumable. The only difference between the chemical composition of the consumable and the base material is an increase of approximately 2% Nickel, with all other elements being similar.

3.1.2 Effect of wire feeding technique

There were essentially three wire feeding techniques used in this study:

1. Weld completed without using consumable.
2. Filler wire fed into the front of weld pool.
3. Filler wire fed into back of weld pool and oscillated.

The third wire feeding technique displays a different flow pattern, (see Fig. 7) in comparison to the conventional wire feeding technique. When the wire is fed into the back of the weld pool the pool becomes shorter as it is undercooled by the filler wire. With a combination of wire feed and oscillation, an obvious increase in wire feeding rate was obtained, especially when a higher heat input was applied. The phase balance of the weld was significantly affected by this welding mechanism.

As shown in Fig. 8, a macrophotograph of the longitudinal centre line cross section from Sample 18d (a heat input of 1.8 kJ/mm and a wire feeding rate of 221 g/h applied), the weld cap area was undercooled thermally by the feeding wire. The surface of the weld cap is mainly molten consumable with a very small amount of dilution from the parent material. This is evidenced by a higher content of austenite (around 48%, see Table 3) in the weld cap area, more than is usually obtained with normal wire feeding arrangements. This technique improves austenite reformation to a level that is near optimum when compared to the high levels of ferrite found in the weld cap with conventional wire feed rates.

From the experimental measurements, the cooling time was not significantly affected, although the weld cap area was

Fig. 7 The flow pattern in the TIG welding pool when wire fed into the back of weld pool.

Fig. 8 A macrograph of longitudinal centre line cross-section from the Sample 18d.

undercooled. However, in order to analyze the two dimensional heat flow, the location of the holes for the thermocouples were drilled to half the depth of the pipe. Therefore, the undercooled area was small and significantly above this position. Consequently the thermocouples did not respond to the higher cooling rates achieved during these conditions.

3.1.3 Effect of heat input and preheat temperature

Since no filler addition was applied to the first pass in every welded pipe, Fig. 9 shows only three test results from a variety of heat inputs. Compiled from the second run of thermal cycle measurements, the experimental results of $\Delta t_{8/5}$ with a constant interpass temperature (100°C) are also shown in this figure. From the figure, it can be observed that heat input is an important variable which plays a key role in governing the cooling time, $\Delta t_{8/5}$. It was also observed that $\Delta t_{8/5}$ value can be further enhanced with increased the preheat temperature.

3.2 Microstructure analysis

This work was carried out using a Buehler Omnimet Image Analysis System and a manual point counting technique with reference to ASTM E562-89 (Standard test method for determining volume fraction by systematic manual point count).²⁷⁾

Fig. 9 Effect of heat input and preheat temperature on measured cooling time, $\Delta t_{8/5}$ (The 1st pass weldment) for super duplex stainless steel welds.

In this work, the microstructure of the multi-pass weld and heat affected zone (HAZ) is investigated. For the HAZ, it may be more appropriate to discuss the HAZ in terms of a high temperature HAZ (HTHAZ) and a low temperature HAZ (LTHAZ) for duplex stainless steels. The HTHAZ can be defined as a zone next to the fusion boundary with a thermal cycle resulting in an almost completely ferritic structure on heating. The LTHAZ is further away from the fusion boundary. The heating temperature is insufficient to substantially alter the ferrite-austenite balance but high enough to cause the formation of intermetallic phases.³⁾

From this work, a schematic diagram illustrating the relative positions of the different microstructures in the weld and heat affected zone (HAZ) is shown in Fig. 10. The microstructures in relation to each of these regions are described as follows:

3.2.1 Region one

The region marked as “Region One” is the area, which is not reheated. In general, this area has a primary microstructure.²⁸⁾ The microstructure can be explained as a result of the chemical composition and its combined thermal history. For a given heat input, increasing wire feeding rates result in a lower ferrite content. The increased wire feeding rate gives a higher level of Nickel content and encourages the formation of austenite. Increasing the heat input (this creates a slower cooling rate) tends to decrease the ferrite content in this region (see Table 5).

Fig. 10 A schematic diagram illustration of the relative positions of microstructure regions.

Table 5 Ferrite contents in the HTHAZ and weld area.

Set No.	H.I at 1.1, kJ/mm				H.I. at 1.4, kJ/mm						H.I. at 1.8, kJ/mm				
Sample No.	11a	11b	11c	11d	14a	14b	14c	14d	14e	14f	18a	18b	18c	18d	18f
α in HTHAZ (%)	56.2	54.5	53.3	56.8	49.5	49.8	47.6	48	47.5	47.3	41.4	43	43	43.6	43.5
α in weld cap (%)	68	66	63.9	63.1	66.4	60.1	55.4	61.2	55.9	52	64	61	54	52	47
α in first pass (%)	—	49	48	48	—	46.2	46	45	43	45	—	45	44	42	44

Fig. 11 Precipitation of chromium nitride occurring in the weld cap area $\times 400$.

Precipitation of chromium nitride was seen in the weld cap area (see Fig. 11) when fast cooling rates were achieved. This is attributed to a high ferrite content and an increase in the distance across the ferrite to the austenite islands that act as nitrogen sinks.^{3,5)} This shows the importance of high wire feeding rates in order to maximise austenite reformation.

3.2.2 Region two

In Region Two of the reheated microstructure, the thermal cycle is sufficient to ensure that complete transformation to delta (δ) ferrite occurs. In these regions, the thermal cycles are very much like those of the HTHAZ, as most of the reactions occurring are similar²⁹⁾ although on weld not base material. This region does not feature very clearly because the morphology of the structure in this region is very similar to Region Three.

3.2.3 Region three

In Region Three of the reheated microstructure, intra-granular and acicular austenite forms.²⁹⁾ In this study, the total volume fraction of austenite in this region can approach 58% (see Table 5) when a higher heat input was used. The chemical composition of the first pass was the same as the parent material (weld completed without using consumable), therefore the microstructure in this region was totally dependant on the thermal history. From Table 5 it was observed that when a higher heat input (1.8 kJ/mm) was applied (this causes a slower cooling rate), a higher austenite content and larger grain size was obtained (see Fig. 12). Alternatively, if a lower heat input (1.1 kJ/mm) was applied (this causes a faster cooling rate), it tends to produce a lower austenite content and smaller grain size (see Fig. 13).

Precipitation of secondary austenite (γ_2) and sigma (σ) phases were also observed in this region in the multi-pass study.

The γ_2 was observed especially when a lower heat input (1.1 kJ/mm) was applied. The formation of γ_2 has been

Fig. 12 A higher austenite content and larger grain size was obtained from higher heat input (slower cooling rate) $\times 200$. Fig. 13 A lower austenite content and smaller grain size was obtained from lower heat input (faster cooling rate) $\times 200$.

reported⁵⁾ to occur particularly in low heat input weld runs followed by subsequent runs deposited with relatively high arc energy. It has been reported^{5,7)} that the γ_2 precipitated in an interpass region contains lower Chromium (Cr), Molybdenum (Mo) and Nitrogen (N), than the primary austenite formed at higher temperature.

Precipitation of sigma (σ) phase can occur in weld as well as in the Low temperature heat affected zone (LTHAZ, Region Five). From the earlier experimental results, it was observed that small amounts (around 0.9%) of sigma (σ) phase was found when a higher heat input (1.8 kJ/mm) was applied (this causes a slower cooling rate). The formation of

sigma (σ) phase has been reported⁵⁾ for exposures in the temperature range 700–900°C.

3.2.4 Region four

The area marked as “Region Four” is the high temperature heat affected zone (HTHAZ). The microstructure in the HTHAZ is mainly controlled by the imposed thermal history. From Table 5, it was observed that increasing the heat input (this produces a slower cooling rate) causes a decrease of ferrite content in the HTHAZ. Also, the ferrite content in the HTHAZ was not significantly affected by wire feeding rates since the cooling rate was not significantly affected.

In the HTHAZ, lower temperature reactions may occur in rapidly cooled welds (when a heat input 1.1 kJ/mm was used), such as chromium nitride formation.⁵⁾ Similarly, in Region Three, secondary austenite may precipitate along the first weld pass.

3.2.5 Region five

Region Five is subjected to thermal cycles very much like those of Region Three, which is highly depended on the thermal history. Precipitation of intermetallic phases, especially sigma phase, can occur along the interface of the second pass weld when a high heat input and maximum interpass temperature is used.

3.3 Evaluation of corrosion resistance

The results of ferric chloride CPT tests performed on parent material and welds are summarized as follows:

3.3.1 Ferric chloride solution temperature at 45°C

The effect of heat input, filler addition and wire feeding technique on the pitting resistance at solution temperature

Fig. 14 Effect of heat input, filler addition and wire feeding technique on the pitting resistance at solution temperature, 45°C.

45°C has been developed as an empirical relationship in graphic form, as shown in Fig. 14. It is evident from the data in Fig. 14 that the use of the low heat inputs (Set 11, a heat input 1.1 kJ/mm was used) and oscillated filler wire entered into the back of the weld pool (Sample 14d, Sample 14e and Sample 14f) tended to decrease the critical pitting temperature. It was observed that all corroded samples showed pitting on the surface of the weld (see Fig. 15a and Fig 16a) when a solution temperature of 45°C was applied.

Fig. 15 (a) Corroded samples showing pitting on the weld surface (faster cooling rate) (b) Higher ferrite content formed at the weld surface ×200.

Fig. 16 (a) Smooth profile was obtained when the filler wire fed into the front of the weld pool; no pitting corrosion was found (b) Coarse profile (crevices) was obtained when the filler wire fed into the back of weld pool (c) Surface act as crevices which have a decisive influence on corrosion resistance.

Fig. 17 Effect of heat input, filler addition and wire feeding technique on the pitting resistance at solution temperature 50°C.

Many investigations *e.g.*^{3,30–32} show that the critical pitting temperature can be reduced with lower heat inputs, *i.e.* achieving fast cooling rates and higher ferrite contents (see Fig. 15b). This is due to non-ideal partitioning of elements between the austenite and ferrite thereby locally reducing corrosion resistance.

Other effects such as surface profile (see Fig. 16) can influence corrosion resistance as area of the surface can act as crevices (see Fig. 16b) which have a decisive influence on pitting corrosion resistance.^{3,31,32} It was noticeable that a particularly coarse profile was obtained when the filler wire was fed into the back of weld pool because of the under-cooled regions on the weld surface. These surface effects were slightly improved by increasing the energy input (1.8 kJ/mm). With reference to the flow pattern diagram (see Fig. 6), the size of rear pool can be enlarged and elongated using a higher energy input which produced a smoother weld surface. This eliminated the effects of the creviced surface and, together with the higher levels of austenite, improved corrosion resistance in the tests.³⁾

3.3.2 Ferric chloride solution temperature at 50°C

The effect of heat input, filler addition and wire feeding technique on the pitting resistance at a solution temperature of 50°C was obtained. Results are shown in Fig. 17.

It is evident from the data in Fig. 17 that increases the

solution temperature up to 50°C, more samples tend to be corroded by the ferric chloride solution. It was observed that pitting may show on the surface of the weld or low temperature heat affected zone (LTHAZ). LTHAZ corrosion was found only in the samples when a higher heat input (1.8 kJ/mm) was applied. In this work, the thermal cycles experienced by the multi-pass welds did not produce significant levels of sigma (σ) phase in the HAZ or weld. For example, none of the specimens subjected to thermal cycle—Set 11 (a heat input of 1.1 kJ/mm was applied) and thermal cycle Set 14 (a heat input 1.4 kJ/mm was applied) contained detectable sigma (σ) phase. Only when a higher heat input (1.8 kJ/mm) was applied (*i.e.* slower cooling rate), did small contents of sigma (σ) phase appear (see Fig. 18a). Therefore, when the specimens were subjected to a critical pitting temperature of 50°C, the Set 18 (samples with a 1.8 kJ/mm energy input and a 100°C interpass temperature) corroded (see Fig. 18b) in the low temperature heat affected zone (LTHAZ).

The best corrosion resistance was therefore obtained when an intermediate heat input (1.4 kJ/mm, providing a suitable cooling rate) with the conventional wire feeding technique (filler wire fed into the front of the weld pool) was used.

The normal weakness in a weld is the root region. These welds have no true root and therefore the failures are in the regions that are not normally exposed to service. It is well known that the weld cap can suffer from low ferrite readings and reduced corrosion resistance. This study was looking at boundary conditions which make the situation worse and lead to the conclusions drawn from Figs. 14 and 17 although they have no true practical effect in service. The conclusion that can be drawn is that a higher heat input needs to be used on the weld cap but that this is not a general rule for all areas of the weld.

4. Conclusions

This study has been carried out to experimentally investigate the effect of the welding variables (includes heat inputs, wire feeding techniques and wire feeding rates) on the cooling rate in the HAZ and welds. Also, supporting tests, including pitting corrosion resistance and microstructure analysis were investigated to relate the cooling rates to the welding variables. From the test results, the following general conclusions can be drawn:

Fig. 18 (a) Small content of sigma (σ) phase appears in low temperature heat affected zone (LTHAZ). (b) Pitting corrosion at the LTHAZ.

1. Heat input is an important variable which plays a key role in governing the cooling time, $\Delta t_{8/5}$. It was also observed that $\Delta t_{8/5}$ value can be further enhanced with increased the preheat temperature.
2. The cooling time $\Delta t_{8/5}$ and peak temperature achieved were not significantly affected by the wire feeding rate. This may be caused by the similarity of thermal properties between the parent material and consumable.
3. The wire fed into the back of weld pool provided an undercooled area in the weld cap.
4. Cooling rate plays a key role on the phase balance in the HAZ and weld. It also significantly affects the formation of intermetallic phases and corrosion resistance.
5. The best corrosion resistance was obtained when a suitable cooling rate (using an intermediate heat input of 1.4 kJ/mm) with the conventional wire feeding technique (filler wire fed into the front of the weld pool) being used.

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