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焊接參數對超級雙相不銹鋼熔接焊道抗孔蝕影響之研究

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An Investigation into the Welding Variable on the Pitting Corrosion Resistance of Super Duplex Stainless Steel Weldments

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摘　要

本研究以實驗量測的方式，來探討焊接參數(例如焊料進給方式及熱進給量-Heat Input)對於超級雙向不銹鋼焊道及熱影響區(Heat Affected Zone)之抗孔蝕能力之影響。為了在同一時間內有效控制只有一個焊接參數被改變，本研究將設計使用一半自動銲接製程模組，以完成一連串的銲道銲接。

而雙相鋼焊接後之焊道及熱影響區(Heat Affected Zone)，其抗孔蝕性量測方法，主要是參考ASTM G48-76、ASTM A923-94 等準則及TWI (The Welding Institute) 所推薦使用Ferric Chloride 浸泡量測技術進行。

實驗結果顯示，使用一個太高(1.8KJ/mm)或過低(1.1KJ/mm)的熱進給量或從焊池背後搖擺進料的方式傾向降低超級雙向不銹鋼之臨界孔蝕溫度(抗孔蝕能力)。而使用一適中的熱進給量(1.4KJ/mm)及傳統焊接進料的方式(從焊池前方進料的方式)可提供超級雙向不銹鋼最佳之抗孔蝕性質。

關鍵字：孔蝕性質、超級雙向不銹鋼、焊接參數

ABSTRACT

This work was carried out to investigate the effect of welding variables, such as wire feeding technique and heat input, on the pitting corrosion resistance in the multi-pass weld and heat affected zone (HAZ) of a super duplex stainless steel. To enable control of welding variables such

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that one parameter can be varied at a time, a series of weldment using semi-automatic welding process 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).

It is evident from the test results that the use of a low (1.1 kJ/mm) or an excessive high heat input (1.8kJ/mm) or oscillated filler wire entering into the back of the weld pool tends to decrease the critical pitting temperature. The best corrosion resistance was 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 weld pool) was used.

Keywords: Pitting Corrosion, Super Duplex Stainless Steels, Welding Variables.

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 that 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 duplex and super duplex steels has led to the requirement of welded joints with acceptable corrosion resistance and mechanical properties[3]. Understanding that controlling phase balance becomes crucial for achieving the goals.

From the past experience, phase balance has been shown as a function of a number of variables[4]. It has been well known that the best phase balance (50/50 phase) can be achieved by optimizing the composition and thermal behaviors with a given welding process. Experience has also shown that the most important factors that control the chemical composition and thermal behavior in the weldment are filler deposition rate and wire feeding technique, and heat input, respectively.

This study has been carried out to investigate the effect of these variables on the corrosion resistance in the heat affect zone (HAZ) and weld. To enable control of welding variables such that one parameter can be varied at a time, a series of weldment using semi-automatic welding process were completed. The critical pitting temperatures (CPT's) of the weldment was then determined in 10% $FeCl_3.6H_2O$ solution, essentially following the ASTM Standard G48-76[5], ASTM standard A923-946 and recommended practice for pitting corrosion tests for duplex stainless steel weldments by the use of ferric chloride solution from The Welding Institute (TWI)[7]. From these results, various empirical correlations were proposed to relate the pitting corrosion to the welding variables.

1. Experiment Equipment and Equipment Procedure

1.1 Welding Equipment and Procedure

To satisfy the requirements of quasi-stationary state heat flow, the welding arc must continue to move at constant velocity as weld metal solidification and temperature changes are being measured[8]. Apparatus was designed and built to accomplish this requirement which is shown as Figure 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 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 deposition rates can be achieved[9]. In this study, a simple ***U*** butt joint (see Figure 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 weldment above the root of the pipe.

To establish the effect of welding variables on the pitting corrosion resistance, welding processes 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 Table1. The first run was made with a range of different heat inputs, without any filler and at room temperature (25℃). This heated up the weld area. The second pass was started when the temperature had dropped to an acceptable interpass temperature, 100℃ using the same heat input as the first pass.

2.2 Method Used for Pitting Resistance Tests

The method used for pitting resistance tests was the basic ASTM G48-76[5] standard (Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by the Use of Ferric Chloride Solution), with reference to the ASTM A923-94[6] 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 TWI7.

Following the completion of the welding process, two samples were cut from pipe using appropriate radial cuts (see Figure 3a). The test specimens were machined with a test face size of 50 ×25 mm (see Figure 3b). 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 ±1mg accuracy.

The tests were performed using ferric-chloride solution (made up from 100g of $FeCl_3.6H_2O$ and 20g of $Na_2EDTA.2H_2O$ per 99ml of distilled water) with a volume based on the larger ($20ml/cm^2$) of the specimen surface areas. Each specimen and solution was contained in a tall-form glass beaker with a capacity of 1000ml. The beaker and solution were covered with a watchglass and placed in a water bath pre-heated to within ± 0.5℃ 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[7], 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℃ subsequent temperature being at 2.5℃ intervals. The critical pitting temperatures were established by holding samples in the solution for 24hr periods at progressively higher temperatures until samples failed to conform to acceptance values of pitting resistance.

3. Test Results and Discussion

The critical pitting temperatures (CPT's) of the weldment was determined in 10% $FeCl_3.6H_2O$ solution, essentially following the ASTM Standard G48-76, ASTM standard A923-94 and recommended practice for pitting corrosion tests for duplex stainless steel weldments by the use of ferric chloride solution from The Welding Institute (TWI). The results of ferric chloride CPT tests performed on parent material and welds are summarized in Table 2 below. From Table 2, various welds were carried out using different heat inputs, filler additions and wire feeding techniques. These weldments were then subjected to pitting corrosion tests. The observations are as follows:

3.1 Ferric Chloride Solution Temperature at 45℃

From Table 2, the effect of heat input, filler addition and wire feeding technique on the pitting resistance at solution temperature 45℃ has been developed as an empirical relationship in graphic form, as shown in Figure 4. It is evident from the data in Figure 4 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 Figure 5) when a solution temperature of 45(C was applied.

Many investigations[3,10,11,12] show that the critical pitting temperature can be reduced with lower heat inputs, i.e. achieving fast cooling rates and higher ferrite contents (see Figure 6). 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 can influence corrosion resistance as area of the surface can act as crevices which have a decisive influence on pitting corrosion resistance [3,10,11]. 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 undercooled regions on the weld surface (see Figure 7). These surface effects were slightly improved by increasing the energy input (1.8 kJ/mm). With reference to the flow pattern diagram (see Figure 8), 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].

3.2 Ferric Chloride Solution Temperature at 50 ℃

With reference to Table 2 the effect of heat input, filler addition and wire feeding technique on the pitting resistance at a solution temperature of 50℃ was obtained. Results are shown in Figure 9.

It is evident from the data in Figure 9 that increases the solution temperature up to 50℃, 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 metal. 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 Figure 10). Therefore, when the specimens were subjected to a critical pitting temperature of 50℃, the Set 18 (samples with a 1.8 kJ/mm energy input and a 100(C interpass temperature) corroded (see Figure 11) 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 Figures 4 and 8 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. Conclusion

The results of ferric chloride CPT (critical pitting temperature) tests performed on multi-pass welds and HAZ's are concluded as follows:

1. A very low heat input decreased the corrosion resistance on the weld surface due to the fast cooling resulting in a very high ferrite content and non-ideal partitioning of elements between the austenite and ferrite on the weld cap.
2. Surface effects such as coarse surface (this acted as crevices) caused by the filler wire fed into the back of the weld pool, had a decisive influence on the pitting corrosion resistance.
3. When an excessive heat input (and hence a slower cooling rate) was applied, the corrosion resistance decreased due to the appearance of intermetallic phases in the weld and HAZ.
4. The best corrosion resistance was obtained when 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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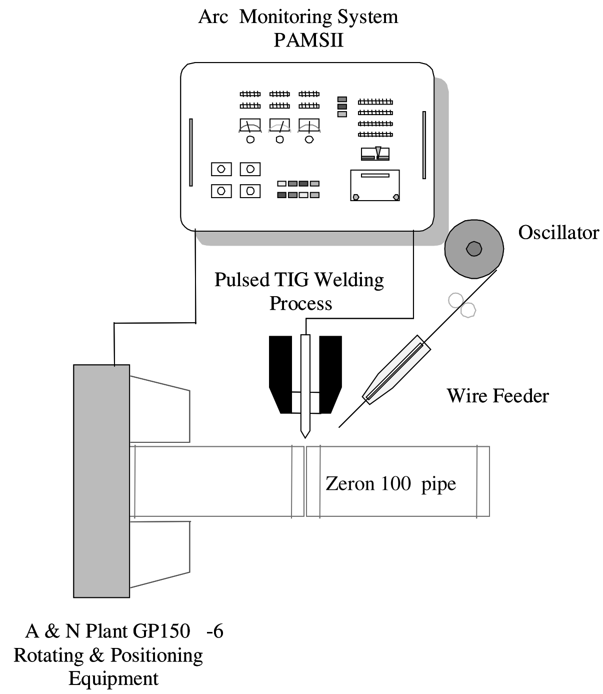


Figure 1 The equipment set-up for multi-pass welding.

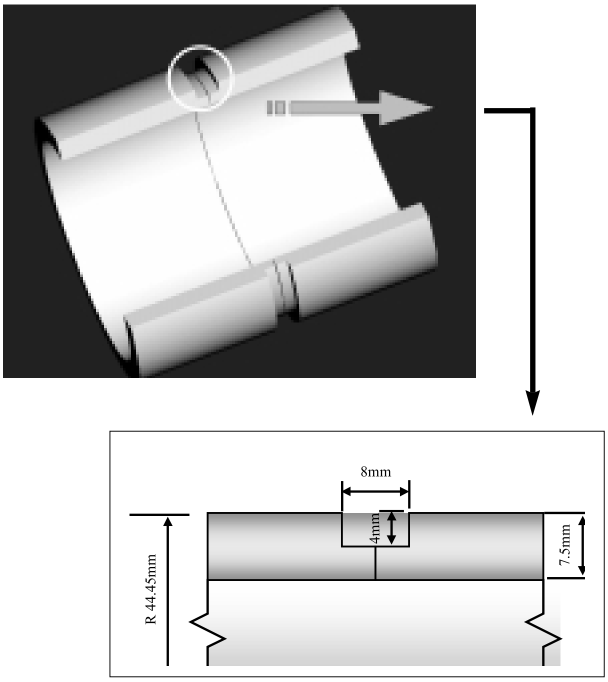


Figure 2 Joint geometry design for multi-pass welding measurement.

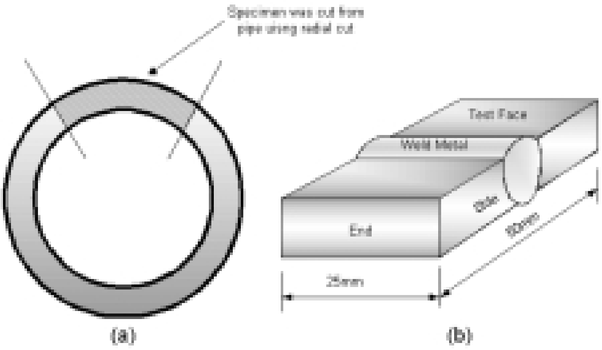
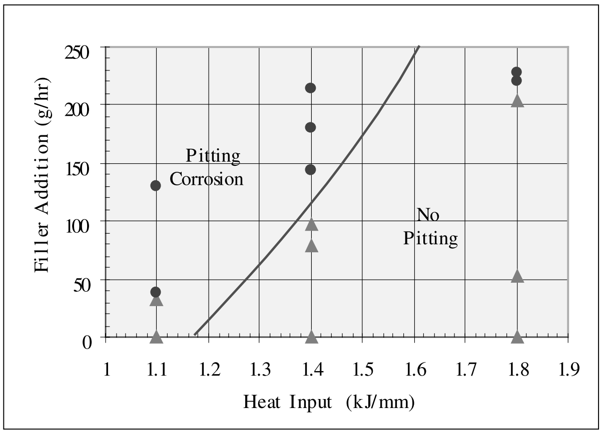


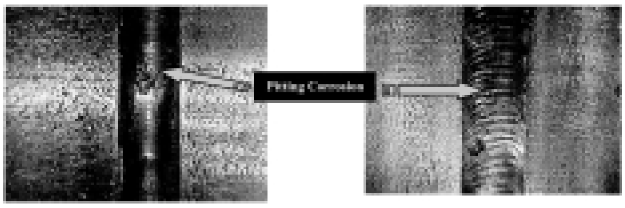
Figure 3 (a) samples cut from pipe using appropriate radial cuts. (b) test specimens machined with a test face size of 50(25 mm.



▲ Filler wire fed into the front of the weld pool or no filler wire was applied

● Filler wire fed into the back of the weld pool and oscillated

Figure 4 Effect of heat input, filler addition and wire feeding technique on the pitting resistance at solution temperature, 45℃.



heat input at 1.1 kJ/mm

heat input at 1.4 kJ/mm

Figure 5 Corroded samples showing pitting on the weld surface.

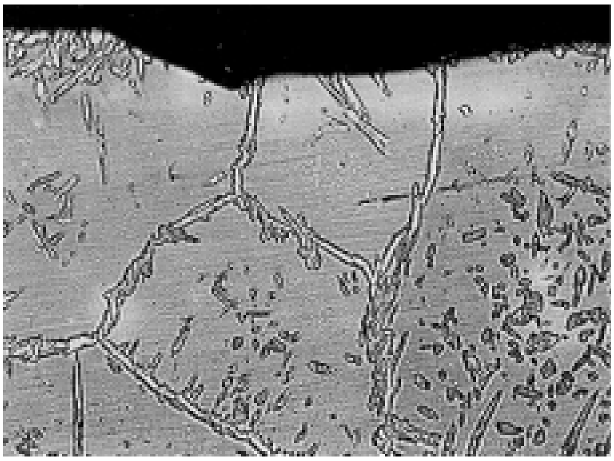


Figure 6 Higher ferrite content formed at the weld surface. (×200 Magnification)

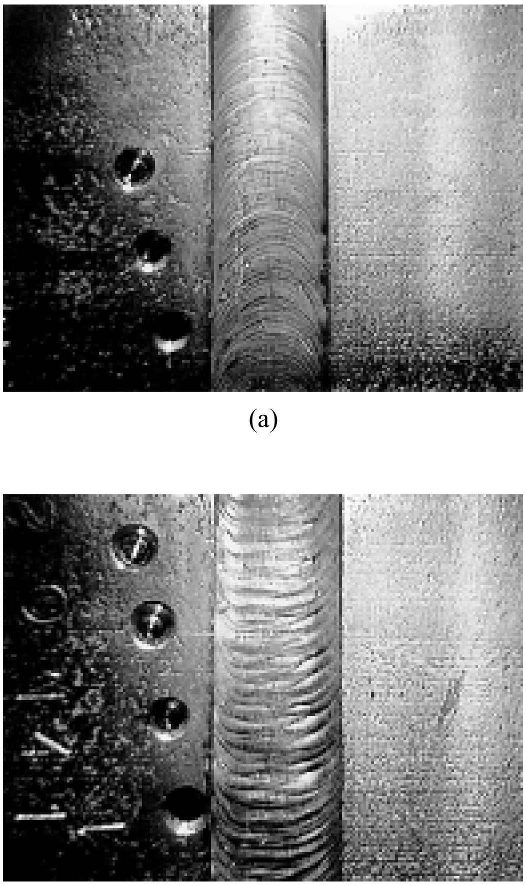


Figure7. (a) Weld completed using filler wire fed into the front of weld pool. (b) Surface effects such as coarse and undercooled surface caused by the filler wire fed into the back of weld pool.

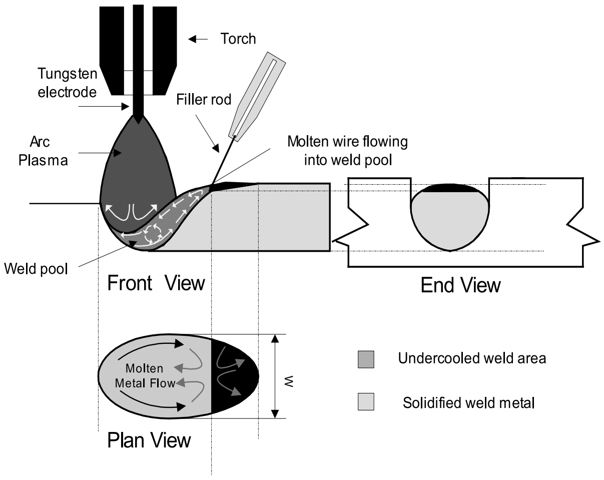
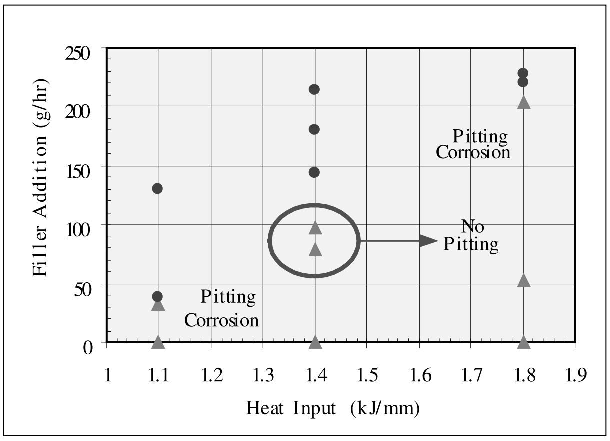


Figure 8 The flow pattern in the TIG welding pool when filler wire is fed into the back of the weld pool and oscillated .



▲ Filler wire fed into the front of the weld pool or no filler wire was applied

● Filler wire fed into the back of the weld pool and oscillated

Figure 9 Effect of heat input, filler addition and wire feeding technique on the pitting resistance at solution temperature 50℃.

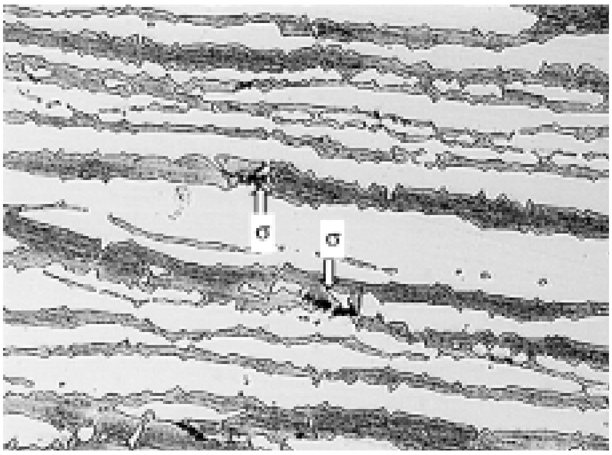


Figure 10 Precipitation of sigma, (phase observed in the low temperature heat affected zone. (× 400 Magnification)

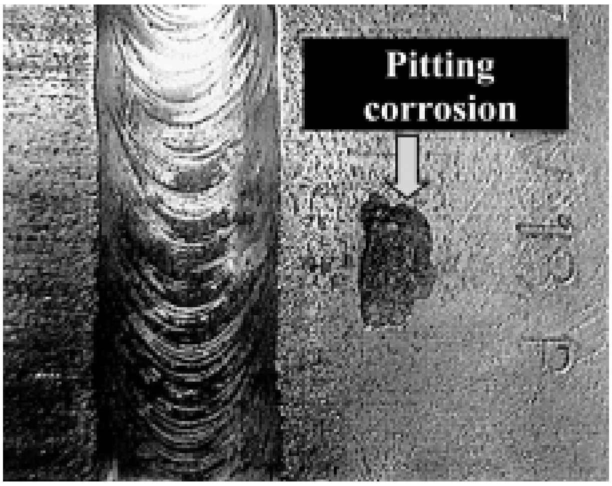


Figure 11 Pitting corrosion at the low temperature heat affected zone (LTHAZ).

Table 1 The parameters used for this study

Sample No.	Wire Feeding Method	Deposition Rate (g/hr)
Heat input at 1.1 kJ/mm		
11a	N	0
11b	F	32
11c	OB	38
11d	OB	130
Heat input at 1.4 kJ/mm		
14a	N	0
14b	F	79
14c	F	97
14d	OB	143
14e	OB	181
14f	OB	214
Heat input at 1.8 kJ/mm		
18a	N	0
18b	F	52
18c	F	184
18d	OB	221
18e	OB	228

Wire Feeding Method:
N - No filler wire was added during the welding process.
F - Filler wire fed into the front of the weld pool.
OB- Filler wire fed into the back of the weld pool and oscillated.

Table 2 Test results of critical pitting temperature

Sample No.	Position	Ferric Chloride Solution Temperature (˚C)				
		40	42.5	45	47.5	50
11a	W.M	NP	NP	PC	-	-
	P.M	NP	NP	NP	-	-
11b	W.M	NP	PC	-	-	-
	P.M	NP	NP	-	-	-
11c	W.M	NP	PC	-	-	-
	P.M	NP	NP	-	-	-
11d	W.M	NP	PC	-	-	-
	P.M	NP	NP	-	-	-
14a	W.M	NP	NP	NP	NP	PC
	P.M	NP	NP	NP	NP	NP
14b	W.M	NP	NP	NP	NP	NP
	P.M	NP	NP	NP	NP	NP
14c	W.M	NP	NP	NP	NP	NP
	P.M	NP	NP	NP	NP	NP
14d	W.M	NP	NP	PC	-	-
	P.M	NP	NP	NP	-	-
14e	W.M	NP	PC	-	-	-
	P.M	NP	NP	-	-	-
14f	W.M	NP	NP	PC	-	-
	P.M	NP	NP	NP	-	-
18a	W.M	NP	NP	NP	NP	PC
	P.M	NP	NP	NP	NP	NP
18b	W.M	NP	NP	NP	NP	PC
	P.M	NP	NP	NP	NP	NP
18c	W.M	NP	NP	NP	NP	PC
	P.M	NP	NP	NP	NP	NP
18d	W.M	NP	NP	NP	PC	-
	P.M	NP	NP	NP	NP	-
18e	W.M	NP	NP	NP	PC	-
	P.M	NP	NP	NP	NP	-

W.M = weld metal; P.M= parent material; PC = pitting corrosion; NP = no pitting