EFFECT OF WELDING PROCESSES ON SUSCEPTIBILITY OF DUPLEX STAINLESS STEEL ALLOY 2205 TO SENSITIZATION USING TIG AND MMA.

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Abstract — In this study, the Gas Tungsten Arc (GTAW) and the Shielded Metal Arc (SMAW) welding processes were used to weld a 200mm x 16.53mm thick duplex alloy 2205 stainless steel pipe to determine which of the processes will cause susceptibility of the alloy to intergranular corrosion at the grain boundaries. Duplex stainless steel (DSS) Alloy 2205 containing 22%Cr, 5%Ni, ferritic-austenitic material is an emerging class of stainless steel currently being selected for a variety of applications especially where corrosion is of major concern. They have good mechanical properties and high resistance to all forms of corrosion combined with its high strength-to-mass ratio. These properties allow for savings both in terms of structural weight and maintenance costs. The welding was preceded with the writing of a Welding Procedure Specification (WPS) in accordance with the ASME IX code. The welding was then done using the parameters specified in the WPS for the two processes. Various tests were carried out on transverse specimens cut out from the welds made with both processes. These tests included compositional analysis across the weld profiles, hardness, and tensile test. The test results for the compositional analysis showed an insignificant depletion of chromium from 22.06 at the weld cap to 19.96 at the root of the TIG weld. This depletion is not enough to cause sensitization although there were likely precipitates in the weld and HAZ. The hardness across the welds profile revealed that there was a uniform distribution of hardness across the MMA weldment when compared to the TIG weld which dropped drastically at the weld metal region from 337.2 and 328.7 to 256.5 and 252.0 at the face and root respectively. The mechanical properties of both welds have not shown any major deviations from the standard Alloy SAF 2205 properties. They are within the acceptable range. The test results obtained indicated that with proper control and monitoring of the welding parameters, the SMAW can be effectively used to weld the Alloy 2205 with comparable high quality of properties.

Index Terms—Welding, Stainless Steel, Duplex Stainless Steel, Tungsten inert gas.

I. INTRODUCTION

Stainless steels are important class of engineering materials and have been used widely in a variety of industries and environments. Duplex stainless steels (DSS) are used in applications where their superior corrosion resistance, strength, or both are advantageous. They provide a broad range of corrosion resistance in various environments. They are the prime candidate for sour service application and as such, are now being used increasingly, especially in chloride or sulphide environment as an alternative to austenitic stainless steels. Their typical application is in the oil, gas and petrochemical industries. Due to their duplex microstructure and low carbon content, the wrought alloys have very excellent resistance to intergranular corrosion. Duplex stainless steels (DSS) are the preferred material for the petroleum and refining industry. They combine the characteristics of both ferritic and austenitic stainless steel SS. When properly welded, their composition ensures that austenite get reformed in the heat-affected zone (HAZ) after welding. The risk of undesirable precipitation of carbides and nitrides in the grain boundaries is such minimized. Conversely, when welded wrongly, the potential to form detrimental intermetallic phases increase drastically, and this could lead to a catastrophic failure. The corrosion resistance of a welded joint is in most cases slightly lower than the parent material. <u>The above condition can be traced to the following reasons.</u>

- The temperature cycle experience at the Weld Heat Affected Zone (HAZ)
- The shape of the weld surface
- Contaminants and possible defects generated during welding.

The use of duplex stainless steels in the welded condition is, therefore, dependent on ensuring that the material will maintain its properties after welding. This requires a variety of precise controls on the welding process, including the welding techniques, electrical parameters, preheat, and interpass temperature.

II. BACKGROUND OF STUDY

Corrosion is a major cause of weldment failures even after welding the base metal with the proper filler metal, adhering to the right industry codes and standards and having a sound weld. The wrought form of a metal or an alloy can be resistant to corrosion in a particular environment but the welded counterpart will not. In other instances, the weld can exhibit corrosion resistance superior to that of the un-welded base metal depending on the variation in both composition and metallurgical properties. Welds could be made with the addition of filler metal or done without filler metal (autogenously).

Structural discontinuities or defective structures that include cracks and cavities, inclusions, penetration and fusion can also increase the corrosion behaviour of welds. Metallurgical factors resulting from the effect of the heat cycle during the welding process could play a major role in causing microstructural differences. The difference in surface composition of welds and adjacent heat affected base metal (HAZ) make the weld region more susceptible resulting in inferior corrosion resistance of welds while the wrought base metal retain its corrosion resistant

Duplex stainless steels (DSS) are used in applications where their superior corrosion resistance, strength, or both are advantageous. They provide a broad range of corrosion resistance in various environments. They are the prime candidate for sour service application and as such, are now being used increasingly, especially in chloride or sulphide environment as an alternative to austenitic stainless steels. Their typical application is in the oil, gas and petrochemical industries. Due to their duplex microstructure and low carbon content, the wrought alloys have very excellent resistance to intergranular corrosion. Duplex stainless steels (DSS) are the preferred material for the petroleum and refining industry. They combine the characteristics of both ferritic and austenitic stainless steel SS. When properly welded, their composition ensures that austenite get reformed in the heat-affected zone (HAZ) after welding.

However, it may be noted that Stainless Steel Weldment can be affected by all the classical forms of corrosion but are particularly susceptible to those affected by variations in microstructure and composition. The forms of corrosion include galvanic corrosion, pitting, stress corrosion, intergranular corrosion, hydrogen cracking and microbiologically influenced corrosion. The most common are localize corrosion since locally sensitized zones (i.e., regions susceptible to corrosion) often develop during the welding process. The local sensitization is due to the formation of chromium carbide along grain boundaries which can result in depletion of chromium in the area adjacent to the grain boundaries. This chromium depletion produces localized galvanic cells which if the reduction drops the chromium content below 12 % wt. required in maintaining a protective passive film, the region becomes sensitized to corrosion. This is the initiation of intergranular corrosion that most often occurs in the HAZ and results in metal loss in the region parallel to the weld deposit. Intergranular corrosion is referred to as weld decay and is a common corrosion problem in stainless steel welds since chromium is one of the major alloying elements which help to prevent corrosion. Weld decay is characterized by a localized attack at an adjacent to grain boundaries with relatively little corrosion of the grains themselves and causes alloy disintegration (grains fall out) and consequent loss of strength. Intergranular corrosion can also be caused by the segregation of impurities at the grain boundaries and the enrichment or depletion of one of the alloying elements in the grain boundary areas. When such a material is exposed to a corrosive environment, the grain interfaces of the sensitized alloy become very reactive compared to the grains themselves resulting in intergranular corrosion.

Therefore, this paper investigates the effect of welding processes on susceptibility of Duplex Stainless Steel Alloy 2205 to Sensitization using TIG and MMA.

III. RESEARCH PROBLEM

The Gas Tungsten Arc Welding (GTAW) is often recommended for all stainless steels and quality welds, but it is very expensive, more complicated and challenging to perform. The oil and gas sector require quality welded joints that will reduce their cost of operation. If the DSS, an emerging material, can be readily welded without problems of sensitization at the grain boundary that will result in intergranular corrosion in service by the more affordable SMAW process, then apart from the purchase cost, it can be accessible to most industries that want to minimized the cost of corrosion in their operation.

The Duplex grade of stainless steel is not popular within indigenous companies except the big multinationals in spite of their numerous cost saving advantages due to both their high cost of purchase and fabrication.

IV. AIM AND OBJECTIVES OF THE STUDY

The aim of this work is to investigate the effect of the TIG and MMA welding processes on the susceptibility of duplex stainless steel alloy 2205 to sensitization at the weld Heat Affected Zone (HAZ) resulting in intergranular corrosion. To achieve this, these are the specific objectives;

- To carry out a chemical composition analysis to confirm both the parent and filler material respectively.
- To weld a duplex stainless steel alloy 2205 pipe using the GTAW and GMAW welding processes with a standard welding procedure Specification.
- To conduct an assessment of the various weld sections within the duplex stainless steel weldment through mechanical test. The composition and mechanical properties will be assessed.
- To evaluate the various test results and determine if any of the processes has caused Susceptibility to Intergranular corrosion as a result of Sensitization at the grain boundaries of the Heat Affected Zones (HAZ).

V. MATERIAL AND METHOD

MATERIAL:

The materials and equipment used in this research work includes; Two 200mm x 16.53mm x360mm length of a commercial type hot rolled pipe of UNS S31803 duplex stainless steel (DSS) (Trade name SAF2205), Two –12.5kg cylinders of 99% Argon Gas, Electrodes: AWS Class, ER-2209- 2.4mm and 3.2mm-5mm, Stainless steel; wire brush, grinding discs and cutting stones, Hand grinding machine, Black & Decker, Milling machine. Ajax Model 100, ESAB AB Welding Equipment: Model-SE-69581 Laxa Sweden, S/N- 91701077202 42volt, 50-60Hz, Vickers hardness tester: Model-DVRB-M, S/N- 0109, Volts; 220/240, Max load-250kgs, Min Load- 30kgs' Make –CV Instruments Ltd-Eseway, 32 Leeds Old Road England, Tensile testing machine: UTM, Model-602, capacity- 2000KN, P/N; 03070036-230V, 50Hz, 7kva, S/N: 305570, Manufacturer - Tinius Olsen Testing Machine Company, Willow Grove Pa. USA, Composition Analysis: Direct Optical Light Emission Polyvac Spectrometer E980, Etchant: ETHANOL, HCL, CuCl (100ml, 100ml, and 5grams), cotton wool, beaker, tong, water, electronic weighing balance, Colloidal suspension of 0.04um silicon diode.

METHODS:

General Procedures:

The initial process was the characterization of the parent material by compositional analysis using the Direct Optical Light Emission Polyvac Spectrometer E980C after etching with Colloidal suspension of 0.04um silicon diode. Confirming the material to be a duplex stainless steel of type Al 2205, a welding procedure was then written for its welding. The welding procedure is in accordance with ASME IX, the boiler and pressure vessel code. After welding the material, then various mechanical test was conducted on the welded material.

Specimen Preparation and Welding:

The pipe was beveled as indicated below in the joint design of Fig. 1. The preparation was done by machining and fitting carried out by tack welding in accordance with the WPS. The fitted pipes were welded together with both the Gas Tungsten Arc Welding (GTAW) and the Manual Metal Arc Welding (MMAW) processes. The ESAB AB multipurpose welding machine was used to weld following the welding Technique and parameters described in the WPS.

Back gouging was carried out in the case of the GTAW during the root pass using argon gas to enhance root penetration. In each case, proper cleaning was carried out after each pass before subsequent beads were deposited. The weld temperature was allowed to cool to between 125^{o}C and150^{o}C for both processes before carrying the deposition of another bead since the recommended maximum interpass temperature is

150^{o}C. The weld deposits comprise a root run, hot pass, filling and capping in both cases. The ESAB AB machine is a multi-process welding machine that can be used to carry out three different welding processes depending on the equipment setup.

After the root run, the weld was allowed to cool to below 150^{o}C before the next run was deposited. It was ensured that there was proper penetration at the root before the subsequent deposition. Cleaning was carried out using a stainless steel grinding disc and wire brush. The weld area temperature was measured using an industrial type thermometer to determine when to commence the next weld deposition (when the weld temperature drops below 150^{o}C).

After the capping, the pipe was allowed to cool naturally and then visually inspected to see if there were any surface flaws. Once certain that there were no serious discontinuities or defects, the welded pipe was parted into smaller stripes transversely for further preparation for the various tests.

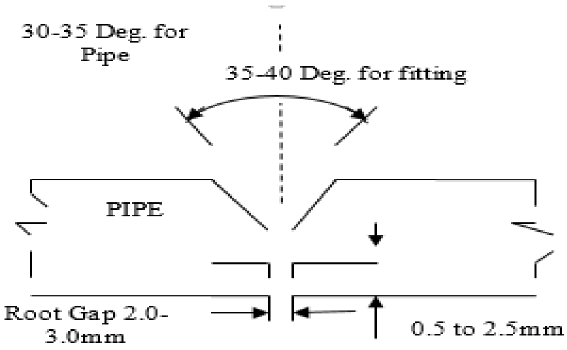

Figure 1: Sample of the specimen

TESTING METHODS:

Different mechanical testing methods were carried out on the as welded material using the transverse specimens cut out from the as welded pipe.

Preparation of Test coupons:

Parting of the pipe into small pieces was carried out by machining. Flame cutting was not used to reduce the heat input to the already welded material. Milling was also used in finishing up the specimen preparation ready for testing. Further polishing was done before etching was carried out for some of the specific test specimen.

Hardness Testing:

Vickers hardness testing was carried out across the weldment profile; i.e. Parent material, HAZ, Weld Cap, and Weld Root regions. For the various positions to be clearly visible, etching was carried out before the actual test. A ten kgf load was applied using 136o Diamond Pyramid at the test positions.

Tensile Testing:

Transverse specimens prepared from the two processes were subjected to tensile load until fracture occurred with a UTM, Model-602 Tensile Testing Equipment. The specimen were prepare in accordance with ASME IX test requirement.

Compositional Analysis:

Compositional analysis was carried out to detect if there was depletion of any of the alloying elements in the course of welding with any of the welding processes across the weldment profile. The Direct Optical Light Emission Polyvac Spectrometer E980C Equipment was used. The samples were analyzed under High Chromium Program with 22 analytical channels. The setting standard used was SUS-Al with HCR12 standard.

VI. RESULTS AND ANALYSIS

RESULTS:

The characterization of the parent material by compositional analysis using the Direct Optical Light Emission Polyvac Spectrometer E980C after etching with Colloidal suspension of 0.04um silicon diode reveals the material to be a duplex stainless steel of type Al 2205. See below in Table 1a and 1b the result of the composition Analysis (wt. %) for both the parent and filler material.

Table 1a: Parent Material

Alloying Elements	% Composition
C	0.0205
Mn	1.580
Cr	22.02
Cu	0.126
Ni	5.550
N	0.150
Mo	3.250
Si	0.470
P	0.023
S	0.006
Ti	<0.001
V	0.114
Al	0.016
Fe	66.7

Table 1b: Filler Material

Alloying Elements	% Composition
C	0.03
Mn	2.00
Cr	22.50
Ni	9.00
N	0.15
Mo	3.20
Si	0.90
P	0.03
S	0.03
Cu	0.75

HARDNESS TEST RESULT

Table 2 shows the hardness value across TIG weld and hardness is less at the weld region than any part of the weldment and also for the MMA weldment generally. The MMA weld hardness only dropped at the HAZ and generally has a more uniform distribution of hardness values across weld profile when compared to the TIG weld. The results indicate that there was a more uniform heat distribution across the MMA weld during the process. The TIG weld had a non-uniform hardness across the weld profile. The lower hardness at the weld region of the TIG could mean more cumulative heat input was involved because interpass temperature for both processes was in the range of 120 to 150^{o}C. The hardness value could be due to the effect of the multi-run weld and the deep penetration associated with the process. All hardness values for both processes are within the expected range since the expected hardness value for the alloy is 260HV although the hardness of the TIG weld region were 256.5 for the face and 252.3 at the root.

Table 2: Hardness test Results for both Processes.

MATERIAL TYPE		**Parent Metal**	**Heat Affected Zone**	**Weld Metal**	**Heat Affected Zone**	**Parent Metal**
WELD FACE	TIG	337.2	286.2	256.5	340.0	337.0
	MMA	330.8	312.6	306.2	303.5	342.7
WELD ROOT	TIG	328.7	290.5	252.0	343.3	348.2
	MMA	333.7	288.5	286.3	268.8	291.8

TENSILE TEST RESULT

The tensile test results of the specimens are as given in Table 3. Tensile test was carried out on transverse specimen of weldment. Both tensile test specimens fractured at the weld centre. The fracture load for the TIG welded specimen is 821Mpa while that for the MMA is 819Mpa. The elongations the specimens for both processes are lower than the 25 mm for the standard alloy 2205. The minimum expected Tensile strength of the alloy is between 680Mpa and yield strength 450MPA for the Sandvik duplex stainless steel.

Table 3: Tensile Test Result

Material Type	**Yield Load (KN)**	**Yield Stress (MPa)**	**Tensile Load (KN)**	**Tensile Strength (MPa)**	**(%) Elongation**
TIG	129.8	805.7	132.3	821.2	21.1
MMA	125.4	726.9	132.0	819.4	20.5
SAF 2205		450-500		680-880	

COMPOSITIONAL ANALYSIS:

Table 4: Result of Compositional Analysis

SPECIMEN TYPE	**POSITION OF TEST**	**CHEMICAL COMPOSITION BY WEIGHT**															
		C	**Ni**	**Mn**	**Cr**	**Mo**	**N**	**P**	**S**	**Al**	**Cu**	**Co**	**Si**	**W**	**Ti**	**V**	**Fe**
PARENT METAL	Parent Metal	0.0205	5.545	1.58	22.02	3.245	0.150	0.023	0.006	0.015	0,126	0.0013	0.47	0.0485	<0.01	0.115	66.7
MMA	Weld Cap	0.036	8.79	1.080	22.73	3.33	0.123	<0.096	0.019	0.0097	0.103	0.047	0.59	0.051	0.019	0.096	62.9
	Weld Interface	0.025	5.96	1.48	21.84	3.33	0.100	<0.096	0.013	0.015	0.181	0.092	0.51	0.056	0.0039	0.118	66.1
	HAZ	0.023	5.50	1.51	21.72	3.27	0.105	<0.096	0.011	0.015	0.198	0.096	0.459	0.049	0<0.0010	0.119	66.8
	Root	0.038	8.37	1.10	22.18	3.28	0.090	<0.096	0.019	0.012	0.109	0.047	0.493	0.055	0.025	0.091	64.0
TIG	Weld Cap	0.022	8.29	1.67	22.06	3.38	0.130	<0.096	0.013	0.0098	0.136	0.085	0.379	0.057	0<0.0010	0.073	63.7
	Weld Interface	0.027	5.55	1.53	21.81	3.33	0.124	<0.096	0.010	0.016	0.196	0.095	0.480	0.052	0<0.0010	0.120	66.6
	HAZ	0.025	5.72	1.56	21.73	3.40	0.123	<0.096	0.010	0.015	0.205	0.100	0.483	0.053	0<0.0010	0.122	66.4
	Root	0.032	9.76	1.79	19.96	2.98	0.107	0.020	0.015	0.0097	0.097	0.062	0.412	0.162	0.015	0.080	64.6

Table 4 shows the composition analysis of the weld profiles. The table showed that the root of both welds maintained the carbon content of the filler material but chromium was depleted from 22.06 at the cap to 19.96 at the root of the TIG weld. There was also the depletion of N from 0.13 at the cap to 0.107 and 0.123 at the cap to 0 0.09 at the root of the TIG and MMA respectively. The depletion of Chromium and nitrogen at the root of the TIG weld could result in the formation of chromium nitride in the weld root. The higher depletion of nitrogen at the root of the MMA weld can be attributed to lack of shielding with shielding gas which can lead to volatilization occur . Normally even with shielding gasses, loss are expected and 2% Nitrogen is added to the argon to compensate for the expected loss. This can be attributed to the reduction in loss of N in the TIG weld that was back gouge with argon gas. There was depletion of Nickel from 8.79 at the weld cap of the MMA to 5.96 and 5.50 at the weld interface and HAZ respectively. The depletion is expected and is provided for in the filler metal having more Nickel than the parent metal but this will amount to the formation of more Ferrite at those regions. The Nickel has not depleted lower than the 5.5 of the parent metal. There was no appreciable depletion of molybdenum except at the root of the TIG Weld. The depletions at the root of the TIG weld indicates that the process experienced more heat and could affect the mechanical properties of the weldment.

COMPARATIVE ANALYSIS OF WELDING PROCESSES:

Table 5: Comparison of TIG and MMA Processes on 2205 Duplex Stainless Steel

PARAMETERS	PROCESS		REMARKS
	MMA	TIG	
Composition	Nitrogen depletion at Root (0.090) and Interface (1.00) from1.23 at Weld Cap.	Chromium depletion to 19.96 at the root. Slight depletion of molybdenum at root.	Nitrogen depletion in MMA root can be avoided by using shielding gases with 2% Nitrogen inclusion. There is the possibility of volatilization.
Tensile Strength	Fracture at center of the weld.	Fracture at centre of weld.	Comparable strength.
Hardness	Even distribution of hardness values across weld profile.	Uneven distribution of hardness values across weld profile and significantly low value at weld and HAZ.	MMA afforded better heat distribution around weld profile

VII. CONCLUSION

From the test results it can be concluded that there are insignificant depletion of chromium from 22.06 at the weld cap to 19.96 at the root of the TIG weld. This depletion is not enough to cause sensitization although there were likely precipitates in the weld and HAZ from the other analysis carried out. Also, it can be seen that;

- The results of all mechanical test carried out are within the acceptable properties of the Duplex Alloy 2205. There were no major variations as a result of a process.
- Effective monitoring of heat levels is necessary when using the TIG process since it is a slower process to prevent leaving the material at high temperature for more than necessary. A lower maximum interpass temperature than the recommended 150^{o}C should be used especially for multipass welds.
- The Duplex Stainless Steel can be effectively welded with the Shielded Metal Arc Welding process but needs stringent control of the welding parameters. The TIG process achieved a better root penetration.

VIII. RECOMMENDATION

Based on the findings of the research work, the following recommendations are hereby made:

- The use of the Duplex Stainless Steel DSS Alloy 2205 which is regarded as the workhorse of the Duplex class of stainless steel should be encouraged by making it available in the country. This will enable the indigenous oil and gas industry to take advantage of its numerous distinctive properties since it can be readily welded with the more affordable SMAW process without sensitization at the grain boundary that will result in intergranular corrosion while in service.
- Further investigation needed to be carried out on the effect of dual process characteristics on weldment properties to justify its usage i.e. TIG for Rooting and MMA for Filling and Capping since the TIG process afforded a better root penetration.
- The type of micro-segregations formed as a result of the use of either of the processes in welding the alloy needs to be understood to be able to identify the process characteristics that can lead to the formation of those inclusions and the factors responsible for their formation.
- The weldments need to be subjected to a corrosive environment to further ascertain the process variation on the corrosion properties of the material since service characteristics can alter material conditions.

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REFERENCES

[1] American Welding Society (2004), Welding Handbook, welding processes Part 1. Miami Florida:
[2] API Technical Report 938-C. (2005). Use of Duplex Stainless Steels in the Oil Refining Industry: American Petroleum Institute: First Edition. Washington, D.C.
[3] Arnold C A (1980), "Galvanic Corrosion Measurement of Weldments," presented at NACE Corrosion/80, Chicago,
[4] ASM International® Corrosion (2000) Understanding the Basics, editor, p427-474DOI: 1361/cutb2000p427Copyright © All rights reserved. www.asminternational.org
[5] ASME BPVC IX (2010) Boiler and Pressure Vessel Code Section IX –Welding and Brazing Qualification
[6] Avesta Welding A B Outokumpu Stainless (2004) Welding Parameters for Duplex Stainless Steels AB, Avesta Research Centre Box 74, SE-774 22 Avesta, Sweden
[7] Bergström O., Kangas, P., Klockars, M., Chai, G. (2004): US20046749697B2
[8] Cary H. B., Helzer S. C. (2005) Modern welding technology Upper Saddle River, Pearson Education. New Jersey:
[9] Cassagne T., Busschaert F (2007). Experience in duplex stainless steel in oil and gas production. In: Proc. 7th Duplex 2007 Int. Conf. & Expo, Grado, Italy.
[10] Charles J. (1991), Super duplex stainless steels: Structure and properties. In: Proc. Duplex

[11] Corrosion Resistance, Duplex Stainless Steel, ASM International, p 169–189.
[12] Davis, J R (2006), Corrosion of Weldments: ASM International® Materials Park, OH 44073-002.
[13] Davison R. (2000), Practical Guidelines for the Fabrication of Duplex Stainless Steel, International. Technical Marketing Resources, USA TAPPI journal 2000, volume 83, No.9. New York.
[14] DeBold TA, Martin J W, and Tverberg J. C. (1983) Duplex Stainless Offers Strength.
[15] Fanica A, Bonnefois B, Gagnepain J. C. (2007). Welding duplex stainless steels: recent improvements. In: Proc. 7th Duplex 2007 Int. Conf. & Expo, Grado, Italy. AIM
[16] Gideon B, Ward L and Biddle G (2008) Duplex Stainless Steel Welds and their susceptibility to Intergranular Corrosion. Journal of Minerals & Materials Characterization & Engineering, Vol. 7, No.3, pp 247-263, jmmce.org Printed in the USA.
[17] Kotecki D. J., (1987) Ferrite Control in Duplex Stainless Steel Weld Metal, Weld. J, Vol. 65 (No. 10), p273s–278s.
[18] LECO Corporation Metallography Principles and Procedures 3000 Lakeview Avenue • St. Joseph, MI 49085 www.leco.com
[19] Lin, W. Lippold, J. C., and Baeslack, W. A. 1993. An investigation of heat-affected zone liquation cracking, 1: a methodology for quantification, Welding Journal, 71(4): 135s–153s
[20] Lippold J. C. and Damian J. Kotecki (2005); Welding Metallurgy and Weldability of Stainless Steels, ISBN 0-471-47379-0 Copyright © 2005 John Wiley & Sons, Inc.
[21] Messler, Robert W. (1999): Principles of welding Troy, John Wiley & Sons, Inc. New York.
[22] Mishra B, Olson D L and Lensing C (1998) The Influence of Weld Microstructural Features on Corrosion Behavior, The Third Pacific Rim International Conference on Advanced Materials and Processing (PRICM 3), TMS, 1998, p 2303–2308
[23] Molybdenum Association (IMAO) (2001), Pennsylvania USA.
[24] Nowacki J, Lukojc A (2005). Structure and properties of the heat-affected zone of duplex steels welded joints. J Mater Proc Tech 164-165: 1074-1081.
[25] Nowacki J, Lukojc A (2006) Microstructural transformations of heat affected zones in duplex steel welded joints. Mater Character; 56, 4-5: 436-441.
[26] Ogawa T and T. Koseki (1989), Effect of Composition Profiles on Metallurgy and Corrosion Behavior of Duplex Stainless Steel Weld Metals, Vol. 68 (No. 5), p 181s–191s
[27] Ogawa T. and T. Koseki (1990), the Influence of Microstructure on the Sensitization Behavior of Duplex Stainless Steel Welds, Corrosion J, Vol. 46 (No. 5), p 410–417
[28] Patterson and Sven-Åke Fager (1995) Welding practice for the Sandvik duplex 181s–191s 81Sandviken, Sweden.
[29] Pohl M, Storz O. Glogowski T (2007). Effect of intermetallic precipitations on the properties of Duplex stainless steel Science Engineering 58 65-71.
[30] Steklov (1972) Method of Evaluating the Influence of Non-Uniformity of Welded Joint Properties on Corrosion, Svar Proiz., Vol. 19 (No. 9), p 34–36 Sweden (Revised August 1995)
[31] Weman, Klas (2003). Welding processes handbook CRC Press LLC Pearson Education New York